FOUNDATIONS OF ENGINEERING GEOLOGY

TONY WALTHAM | THIRD EDITION

Spon Press

Foundations of
Engineering Geology

Foundations of Engineering Geology

TONY WALTHAM
BSc, DIC, PhD

Third Edition

Preface

Civil engineering is an exciting combination of science, art, professional skill and engineering achievement which always has to rely on the ground on which its structures stand. Geology is therefore vital to success in civil engineering, and this book brings to the reader those many aspects of the geological sciences specifically relevant to the profession.

This book is structured primarily for the student of civil engineering who starts with no knowledge of geology but is required to understand the ground conditions and geological processes which, both literally and metaphorically, are the foundations of his future professional activities. It also provides an accessible source of information for the practising civil engineer.

All the material is presented in individual double-page spreads. Each subject is covered by notes, diagrams, tables and case histories, all in bite-sized sections instead of being lost in a long continuous text. This style makes the information very accessible; the reader can dip in and find what he needs, and is also visually guided into relevant associated topics. There is even some intended repetition of small sections of material which are pertinent to more than one aspect within the interrelated framework of a geological understanding.

The contents of the book follow a basic university course in engineering geology. The freestanding sections and subsections permit infinite flexibility, so that any lecturer can use the book as his course text while tailoring his programme to his own personal style. The single section summarizing soil strength has been included for the benefit of geology students who do not take a comprehensive course in soil mechanics within a normal civil engineering syllabus.

The sectionalized layout makes the information very accessible, so that the practising engineer will find the book to be a useful source when he requires a rapid insight or reminder as he encounters geological problems with difficult ground. Reference material has therefore been added to many sections, mainly in tabulated form, to provide a more complete data bank. The book has been produced mainly in the inexpensive soft-bound format in the hope that it will reach as large a market as possible.

The mass of data condensed into these pages has been drawn from an enormous variety of sources. The book is unashamedly a derived text, relying heavily on the world-wide records of engineering geology. Material has been accumulated over many years in a lecturing role. A few concepts and case histories do derive from the author's personal research; but for the dominant part, there is a debt of gratitude acknowledged to the innumerable geologists and civil engineers who have described and communicated their own experiences and research. All the figures have been newly drawn, and many are derived from a combination of disparate sources. The photographs are by the author.

Due thanks are afforded to the Department of Civil and Structural Engineering at the Nottingham Trent University where the engineering and teaching experience was gained, to Neil Dixon for his assistance with the gentle art of soil mechanics, to the staff of Blackie in Glasgow who made the innovative style of the book possible, and to the many colleagues and friends without whom nothing is possible.

T.W., 1994.

Preface to the Third Edition

The third edition of this book has again retained the format and structure that has proved so accessible and so popular, but it has been carefully updated and improved with additional paragraphs that reflect ongoing changes within the profession of civil engineering.

Progress within the printing industry has allowed this edition to enjoy the benefits of full colour without any immediate increase in cover price. Diagrams have been improved now that they can be in full colour; some have retained the earlier line structure, but many have been redrawn to show extra features. Geology is a very visual subject, so some extra pages have been introduced to present selections of the author's photographs, with the intention of drawing the reader out into the world of reality, where the endless variations within terrain conditions make an understanding of the geology so very important to all civil engineers.

This book was never intended to be a handbook with all the answers and all the procedures. It aims to introduce the critical aspects of geology to the student of engineering, though it does appear to act as a convenient reminder for the practising engineer. To enhance its role as a source book, a long list of further reading is appended. This cites the useful key texts in each subject area, and also refers to the primary papers on case studies used within the text, in both cases without any need to include conventional references that can disrupt a text.

As in the earlier editions, cross references to other pages are not used in order to explain terms. The index is intentionally comprehensive, so that it can be used as a glossary. Each technical term in the text does appear in the index, so that the reader can check for a definition, usually at the first citation of a term.

Sincere thanks are recorded to Rob Gill of Geosec Slides (Mull) who provided the photomicrographs in plain light to demonstrate rock textures, and also to Ian Jefferson, John Arthur, Simon Cooke, Jenny Walsby, Keith Westhead, Richard Cartlidge, George Tuckwell, Peter Fookes and various others who have contributed to the revisions within this third edition.

It is then appropriate to again thank David McGarvie, one-time editor at Blackie, who was the author's key support, in the face of some opposition, in making possible this slightly unconventional style of textbook. The success of the concept is reflected in the forthcoming book by Ian Jefferson and colleagues on the *Foundations of Geotechnical Engineering*, which will be a companion book in the same format. It is hoped that both volumes will make the pressured lives of students of civil engineering just a little bit easier.

T.W., 2008.

# Contents

01 Geology and Civil Engineering

THE GEOLOGICAL ENVIRONMENT

Earth is an active planet in a constant state of change.
Geological processes continually modify the Earth's surface, destroy old rocks, create new rocks and add to the complexity of ground conditions.

Cycle of geology encompasses all major processes, which are cyclic, or they would grind to an inevitable halt.

> **Land:** mainly erosion and rock destruction.
> **Sea:** mainly deposition, forming new sediments.
> **Underground:** new rocks created and deformed.

Earth movements are vital to the cycle; without them the land would be eroded down to just below sea level.
Plate tectonics provide the mechanism for nearly all earth movements (*section 09*). The hot interior of the Earth is the ultimate energy source, which drives all geological processes.
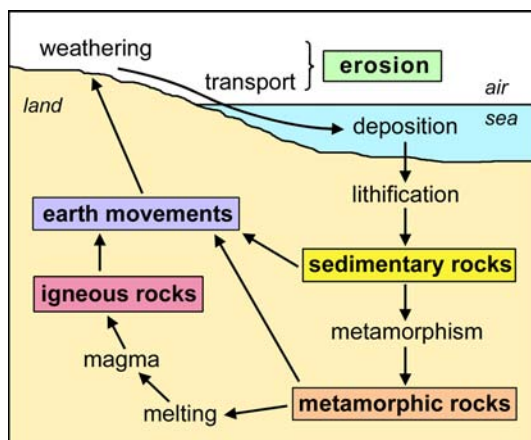
Geological time is an important concept. Earth is 4000M years old and has evolved continuously towards its present form.
Most rocks encountered by engineers are 10–500M years old. They have been displaced and deformed over time, and some are then exposed at the surface by erosional removal of rocks that once lay above them. Underground structures and the ground surface have evolved steadily through geological time.
Most surface landforms visible today have been carved out by erosion within the last few million years, while older landforms have been destroyed.
This time difference is important: the origin of the rocks at the surface may bear no relationship to the present environment. The classic example is Mt Everest, whose summit is limestone, formed in a sea 300M years ago.
Geological time is difficult to comprehend but it must be accepted as the time gaps account for many of the contrasts in ground conditions.

> **Concepts of scale** are important in geology:
> Beds of rock extending hundreds of kilometres across country.
> Rocks uplifted thousands of metres by earth movements.
> Rock structures reaching 1000 m below the ground surface.
> Strong limestone crumpled like plasticine by plate tectonics.
> Landslides with over 100M tons of falling rock.
> Earthquakes a million times more powerful than a nuclear bomb.
> And the millions of years of geological time.

Endless horizontal rocks exposed in Canyonlands, USA.

SIGNIFICANCE IN ENGINEERING

Civil engineering works are all carried out on or in the ground. Its properties and processes are therefore significant – both the strengths of rocks and soils, and the erosional and geological processes that subject them to continual change.
Unstable ground does exist. Some ground is not 'terra firma' and may lead to unstable foundations.
Site investigation is where most civil engineers encounter geology. This involves the interpretation of ground conditions (often from minimal evidence), some 3-D thinking, and the recognition of areas of difficult ground or potential geohazards.
Unforeseen ground conditions can still occur, as ground geology can be almost infinitely variable, but they are commonly unforeseen simply due to inadequate ground investigation.
Civil engineering design can accommodate almost any ground conditions that are correctly assessed and understood prior to and during construction.

> ### Components of Engineering Geology
>
> | The main field of study: | Sections in this book |
> |---|---|
> | Ground materials and structures | 02–06 |
> | Regional characteristics | 09–12 |
> | Surface processes and materials | 13–18 |
> | Ground investigations | 07, 08, 19–23 |
> | Material properties | 24–26, 39 |
> | Difficult ground conditions | 27–38 |
>
> Other aspects of geology – fossils and historical studies, mineral deposits and long-term processes – are of little direct significance to the engineer, and are not specifically covered in this book.

SOME ENGINEERING RESPONSES TO GEOLOGICAL CONDITIONS

Geology	Response
Soft ground and settlement	Foundation design to reduce or redistribute loading
Weak ground and potential failure	Ground improvement or cavity filling; or identify and avoid hazard zone
Unstable slopes and potential sliding	Stabilize or support slopes; or avoid hazard zone
Severe river or coastal erosion	Slow down process with rock or concrete defences (limited scope)
Potential earthquake hazard	Structural design to withstand vibration; avoid unstable ground
Potential volcanic hazard	Delimit and avoid hazard zones; attempt eruption prediction
Rock required as a material	Resource assessment and rock testing
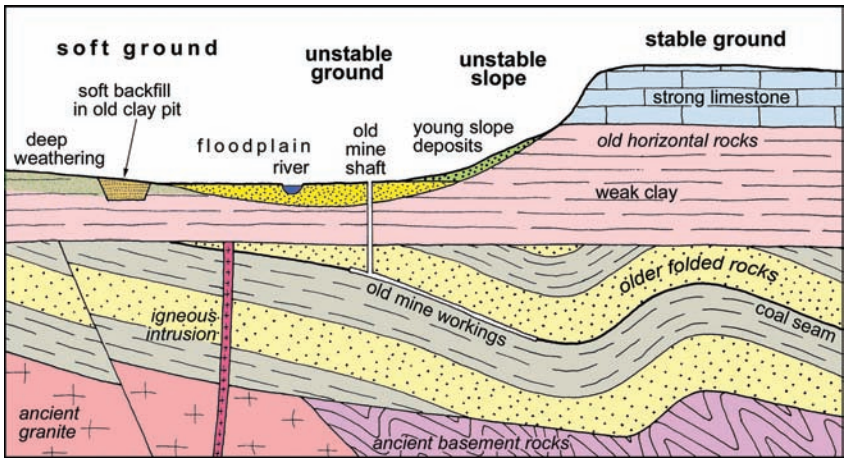
Ground profile through some anonymous region within the English Midlands.

Most rocks were formed 200–300M years ago, when the area was near the equator in a deltaic swamp, disturbed by earth movements then left in a shallow sea.

The ground surface was shaped by erosion within the last million years, when the slope deposits and the alluvium partly filled the valley that was largely cut by river erosion.

The more difficult ground conditions are provided by the floodplain, soft sediments, the areas over deep rockhead, unstable slopes, old mines and the backfilled quarry.

Folded rocks in the Hamersley Gorge, Australia.

Strong Rocks	Weak Rocks
UCS > 100 MPa	UCS < 10 MPa
Little fracturing	Fractured and bedded
Minimal weathering	Deep weathering
Stable foundations	Settlement problems
Stand in steep faces	Fail on low slopes
Aggregate resource	Require engineering care

STRENGTH OF THE GROUND

Natural ground materials, rocks and soils, cover a great range of strengths: granite is about 4000 times stronger than peat soil.

Some variations in rock strength are summarized by contrasting strong and weak rocks in the table.
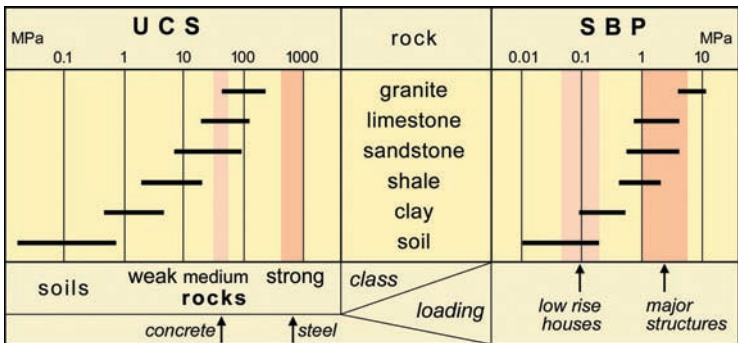
Assessment of ground conditions must distinguish:

• Intact rock – strength of an unfractured, small block; refer to UCS.
• Rock mass – properties of a large mass of fractured rock in the ground; refer to rock mass classes (*section 25*).

Note – a strong rock may contain so many fractures in a hillside that the rock mass is weak and unstable.

Ground conditions also vary greatly due to purely local features such as underground cavities, inclined shear surfaces and artificial disturbance.

UCS:
Unconfined (or uniaxial) compressive strength: load to cause failure of a cube of the material crushed between two flat plates with no lateral restraint. (Strong and weak limits are simplified; *see section 24 for BS criteria*.)

SBP:
Safe (or acceptable) bearing pressure: load that may safely be imposed upon rock in the ground: the estimated (or measured) ultimate bearing pressure to fail the rock (allowing for fractures and local zones of weakness) divided by a safety factor of between 3 and 5.

ROCKS AND MINERALS

Rocks: mixtures of minerals: variable properties.
Minerals: compounds of elements: fixed properties.

Rock properties broadly depend on:

• strength and stability of constituent minerals;

• interlocking or weaknesses of mineral structure;

• fractures, bedding and larger rock structures.

All rocks fall into one of three families, each with broadly definable origins and properties.

Most rock-forming minerals are silicates – compounds of oxygen, silicon and other elements.

Rock properties can show extreme variations. It is useful to generalize, as in the table below, in order to build an understanding of geology, but it must be accepted that rocks are not engineered materials and their properties do vary from site to site.

For example, most sedimentary rocks are quite weak, and limestone is a sedimentary rock, but some of the limestones are very strong.

Rock family	Igneous	Sedimentary	Metamorphic
Material origin	Crystallized from molten magma	Erosional debris on Earth's surface	Altered by heat and/or pressure
Environment	Underground; and as lava flows	Deposition basins; mainly sea	Mostly deep inside mountain chains
Rock texture	Mosaic of interlocking crystals	Mostly granular and cemented	Mosaic of interlocking crystals
Rock structure	Massive (structureless)	Layered, bedded, bedding planes	Crystal orientation due to pressure
Rock strength	Uniform high strength	Variable low; planar weaknesses	Variable high; planar weaknesses
Major types	Granite, basalt	Sandstone, limestone, clay	Schist, slate

Rocks and Structures

Strong, massive granite forming cliffs at Yosemite, California.
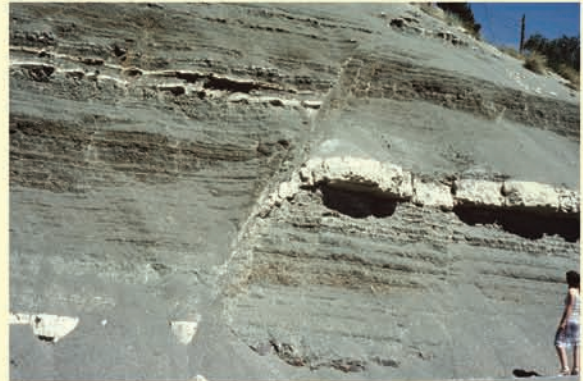
Small normal fault in shales and limestones, in a Utah road cut.

Basalt lava in Hawaii, with rubble layers and an open tube.

Coal Measures with seams between yellow sandstones, Alaska.

Swarm of dolerite dykes intruded in granite, in southern Jordan.

Interbedded limestones and shales of the Lias, Dorset coast.

Folded limestones at Lulworth, Dorset.

Explosive eruption of Stromboli volcano, Italy.
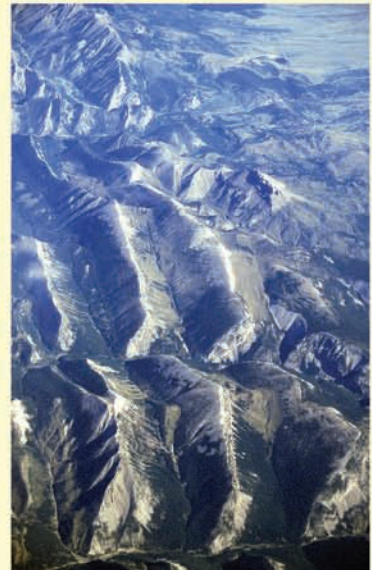
Limestone escarpments in Canada.

4

Blast zone of Mt St Helens volcano, 1980.

Small graben in banded siltstones, Oman.

Zigzag folds in sandstone/shale, Cornwall.

Faces cut by line drilling in granite, Rock of Ages quarry, Vermont.

Strong, banded and foliated, Lewisian gneiss, Outer Hebrides.

Crumpled layers of micas and quartz in Moine schist, Scotland.

Vertical cleavage and crossing joints in a slate quarry in Wales.

Gravestones made of sandstone, granite, slate and limestone.

Current bedding in coarse, pebbly, fluvial sandstone, Nottingham.

02 Igneous Rocks

Magma is generated by local heating and melting of rocks within the Earth's crust, mostly at depths between 10 and around 100 km. Most compositions of rock melt at temperatures of 800–1200°C.

When the magma cools, it solidifies by crystallizing into a mosaic of minerals, to form an igneous rock.

VOLCANIC ERUPTIONS

Eruptions may be violent and explosive if a viscous magma has a high gas pressure, or may be quiet and effusive if the magma is very fluid. There is a continuous range of eruptive styles between the two extremes, and a single volcano may show some variation in the violence of its individual eruptions.

Pyroclastic rocks (meaning fire fragmental, also known as volcaniclastic) are formed of material, collectively known as tephra, thrown into the air from explosive volcanoes. Most tephra is cooled in flight, and lands to form various types of ash, tuff and agglomerate, all with the properties of sedimentary rocks. Some tephra, erupted in turbulent, high-temperature, pyroclastic flows, lands hot and welds into ignimbrite, or welded tuff.

EXTRUSIVE IGNEOUS ROCKS

These form where magma is extruded onto the Earth's surface to create a volcano.

Lava is the name for both molten rock on the surface, and also the solid rock formed when it cools.

Fluid basaltic lavas flow easily to form low-profile shield volcanoes, or near-horizontal sheets of flood basalt.
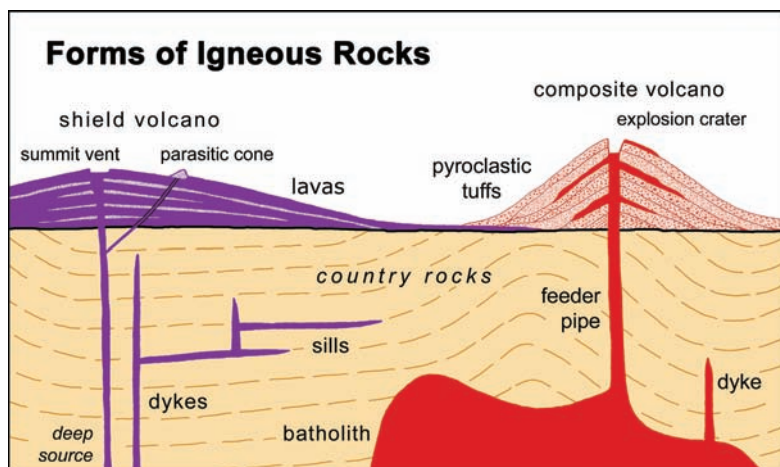
More viscous lavas, mainly andesitic, build up conical composite, strato-volcanoes, where lava is interbedded with ash and debris that are thickest close to the vent.

INTRUSIVE IGNEOUS ROCKS

These are formed when magma solidifies below the surface of the Earth. They may later be exposed at the surface when the cover rocks are eroded away.

Batholiths are large blob-shaped intrusions, roughly equidimensional and commonly 5–50 km in diameter. Most are of granite.

Dykes are smaller sheet intrusions formed where magma has flowed into a fissure. Mostly 1–50 m wide; may extend for many kilometres; generally of dolerite. **Sills** are sheet intrusions parallel to the bedding of the country rocks into which the magma was intruded.

Forms of Igneous Rocks

Molten lava flowing from a small vent on the flank of the Etna volcano.

GRANITE

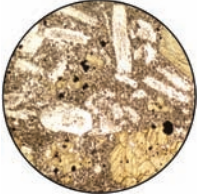|	
TYPE	Acid igneous; coarse grained, large scale intrusive (plutonic).
MINERALOGY	Coarse interlocking crystal mosaic with no textural orientation. Quartz 25%, feldspar 50%, micas 15%, mafics 10%.
OCCURRENCE	Large batholiths, exposed at surface by subsequent erosion. Cooled as large bodies 3–15 km beneath surface.
EXAMPLES	Britain: Land's End. USA: Yosemite.
STRUCTURES	Commonly massive and very uniform. Widely spaced sheet jointing, curved due to large exfoliation (caused by cooling and stress relief).
WEATHERING	Slow decay of feldspar to clay, leaving quartz to form sandy soils. Spheroidal weathering leaves rounded corestones in soil matrix.
STRENGTH	High strength with all physical properties good. UCS: 200 MPa. SBP: 10 MPa.
FOUNDATIONS	Very strong rock, except where partially decayed to clay, near the surface or along some deep joint zones.
HYDROLOGY	Groundwater only in fractures.
VALUE	Excellent dimension, decorative and armour stone and aggregate.
VARIETIES	Syenite and diorite: have less quartz and are slightly darker. Gabbro: basic, and is much darker. Larvikite: a dark coarse syenite with distinctive internal reflections. Many strong rocks are referred to as granite within construction trade.

Microscope view, 5 mm across: clear quartz, cloudy feldspar, cleaved brown biotite mica.

MAIN MINERALS OF IGNEOUS ROCKS

mineral	composition	colour	H	D	common morphology and features
Quartz	SiO_2	clear	7	2·7	mosaic; no cleavage; glassy lustre
Feldspar	$(K,Na,Ca)(Al,Si)_4O_8$	white	6	2·6	mosaic or laths; types – orthoclase and plagioclase
Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$	clear	2½	2·8 ⎫	splits into thin sheets, due to perfect cleavage,
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	black	2½	2·9 ⎭	members of the mica group of minerals
Mafics	Mg-Fe silicates	black	5–6	>3·0	long or short prisms; hornblende, augite, olivine

Mafic minerals (or mafics) is a convenient term for a group of black silicates whose individual properties are of little significance in the context of most engineering.

Cleavage is the natural splitting of a mineral along parallel planes that are dictated by weaknesses in their atomic structure.

Mineral strength is a function of hardness and lack of cleavage, along with effects of decay or orientation.

Features are generalized, and exceptions do occur; crystal faces are displayed on museum specimens of most minerals, but are rarely seen in normal rocks.

H = hardness, on a scale of 1–10, from talc the softest mineral of hardness 1, to diamond the hardest of hardness 10.

Steel and glass have hardnesses between 6 and 7.

D = density, measured in grams/cm³ or tonnes/m³.

BASALT

TYPE	Basic igneous; fine-grained, extrusive (volcanic).
MINERALOGY	Fine interlocking crystal mosaic with no textural orientation. May have open vesicles or mineral-filled amygdales (old gas bubbles). Feldspar 50%, mafics 50%.
OCCURRENCE	Lava flows in bedded sequences. Cooled after flowing from volcano.
EXAMPLES	Britain: Skye and Mull. USA: Columbia Plateau and Hawaii.
STRUCTURES	Sheets or lenses, maybe interbedded with ash or tuff. Commonly with weathered or vesicular scoria tops on each flow. Young lavas have smooth pahoehoe or clinkery aa surfaces. Compact basalt may have columnar jointing (from cooling contraction).
WEATHERING	Rusts and decays to clay soils; maybe spheroidal weathering.
STRENGTH	Compact basalts are very strong. UCS: 250 MPa. SBP: 10 MPa (less on young lava).
FOUNDATIONS	Variable strength, especially in younger lavas, due to ash beds, scoriaceous or clinkery layers, lava caves and other voids.
HYDROLOGY	Young lavas are generally good aquifers.
VALUE	Good aggregate and valuable roadstone.
VARIETIES	Andesite: intermediate lava, dark or light grey, often weathered red. Dolerite: medium grained intrusive dyke rock; looks similar to basalt. Rhyolite: pale grey acid lava, commonly associated with frothy pumice and dense black obsidian glass.

Microscope view, 5 mm across: clear feldspar laths and large brown mafics, in fine groundmass of same minerals.

CLASSIFICATION OF IGNEOUS ROCKS

This simple classification covers the great majority of igneous rocks. It is based on two parameters which are both significant and recognizable. The main types of igneous rocks can therefore be identified by just colour and grain size.

The form of occurrence determines the structure of the rock in the ground; also, lavas may cool in hours or days while a batholith may take a million years to crystallize, and the cooling rate largely determines the grain size of the rock.

Chemical composition is determined by what rocks had melted to form the original magma; silica-rich magmas are referred to as acidic (unrelated to pH) and are generally low in iron, so have few black iron minerals, and are therefore lighter in colour than basic rocks.

Porphyritic rocks have scattered larger, older crystals (called phenocrysts) in a finer groundmass.

In fine grained rocks, grains cannot be seen with the naked eye; the limit of 0·1 mm is effectively the same as the limit of 0·06 mm used in soils and sediments.

			occurrence	form	cooling	grain	size
Rhyolite	Andesite	**Basalt**	extrusions	lavas	fast	fine	<0·1 mm
Porphyry		Dolerite	small intrusions	dykes	medium	medium	0·1–2 mm
Granite	Diorite	Gabbro	large intrusions	batholiths	slow	coarse	<2 mm

70% acid viscous explosive 3% 10% light		50% basic fluid effusive 12% 50% dark	*SiO₂ content* *classification* *magma viscosity* *volcano type* *Fe content* *mafic minerals* *colour*	Granite and basalt are most abundant because magma viscosity determines the ease of migration. Acid magma is viscous, so most stays in batholiths to form granite; while basic magma is so fluid that most of it escapes to the surface to form basalt lava.

03 Sedimentary Processes

Sediment is largely material derived from weathering of rocks that are exposed on the Earth's surface (the remainder is mostly organic material).

All rocks weather on exposure to air and water, and slowly break down to form *in situ* soils.

In most land environments, the soil material is subsequently transported away from its source, and may then be regarded as sediment; this includes the solid debris particles and also material in solution in water.

Natural transport processes are dominated by water, which sorts and selectively deposits its sediment load.

Ultimately all sediment is deposited, mostly in the sea, and mostly as stratified layers or beds of sorted material.
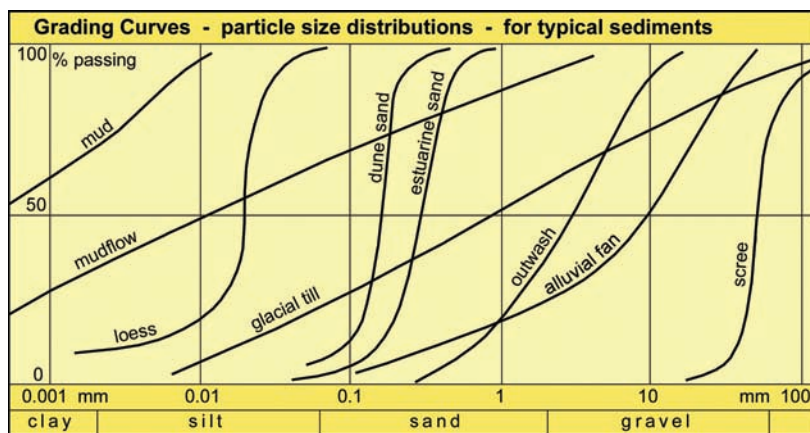
Burial of this loose and unconsolidated sediment, by more layers of material subsequently deposited on top of it, eventually turns it into a sedimentary rock, by the various processes of lithification.

The land is essentially the erosional environment; it is the source of sediment, which forms the temporary soils before being transported away.

The sea is essentially the depositional environment; sediment is buried beneath subsequent layers, and eventually forms most of the sedimentary rocks.

Subsequent earth movements may raise the beds of sedimentary rock above sea level; erosion and removal of the overlying rocks (to form the source material for another generation of sediments and sedimentary rocks) then exposes the old sedimentary rocks in outcrops in a landscape far removed from contemporary seas and in an environment very different from that of the sedimentation.

SEDIMENTARY MATERIALS Most sedimentary rocks are varieties of sandstone, clay or limestone

Mineral grains: mostly quartz, also muscovite (the physically and chemically stable minerals)
Rock fragments and volcanic debris (not yet broken down to their constituent minerals) } – SANDSTONES
Breakdown products: clay minerals (formed by reaction of water with feldspar or mafic minerals) – CLAYS
Organic debris: plant material to form peat and coal (animal soft parts form oil) – minor rocks
Organic debris: dominated by calcite from marine shell debris
Solutes: dominantly calcite precipitated from sea water largely due to biological activity } – LIMESTONES
Solutes: including gypsum and salt, and other less abundant soluble compounds – minor rocks

---

Grading Curves - particle size distributions - for typical sediments
(Mudflow and till are well graded; dune sand and scree are well sorted)

Gully erosion produces new sediment that builds a steep alluvial fan.

SEDIMENT TRANSPORT

The most abundant sediment is clastic or detrital material consisting of particles of clay, sand and rock debris.

Water is far the most important agent of sediment transport. Rivers move the majority of sediment on land. Coarser debris is rolled along the river beds; finer particles are carried in suspension. Water's ability to transport sediment depends on its velocity – larger particles can only be moved by faster flows. Sediment is therefore sorted (to one size) during water transport.

Sediment is also moved in the sea, mainly in coastal waters where wave action reaches the shallow sea bed. Other transport processes have only limited scope:

- Gravity alone works mainly on the steeper slopes, producing landslides and colluvium.
- Wind moves only fine dry particles.
- Ice transport is powerful, but restricted by climate.
- Volcanoes may blast debris over limited distances.

Some minerals are transported by solution in water. Organic sediment is rarely carried far from its source.

SEDIMENT DEPOSITION

Water on land Sorted and stratified, mostly sand and clay. Alluvium in river valleys is mostly temporary, later eroded away, except in subsiding deltas. Lake sediment includes salts precipitated due to desert evaporation.

The sea Final destination of most clastic sediment. Sorted and stratified in beds, mostly in shallow shelf seas. Turbidity currents carry sediment into deeper basins. Shell debris in shallow seas, with no land detritus, forms the main limestones.

Slopes Localized, poorly sorted scree and slide debris.

Wind Very well sorted sand and silt, mostly in or near dry source areas, so only significant in desert regions.
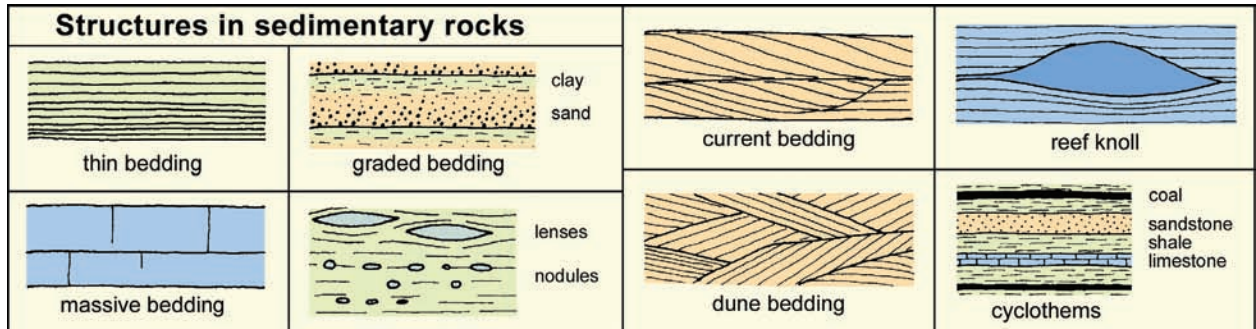
Ice Unsorted debris dumped in the melt zones of glaciers. Localized today but extensive in past Ice Ages.

Volcanoes Fine, sorted airfall ash, wind-blown over large areas; also coarse unsorted flow and surge deposits, mostly on volcano slopes. Collectively known as pyroclastic sediments (= fire fragmental).

MAIN MINERALS OF SEDIMENTARY ROCKS

Units and terms as for igneous minerals in section 02

mineral	composition	colour	H	D	common morphology and features
Quartz	SiO_2	clear	7	2·7	granular; no cleavage; glassy lustre
Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$	clear	2½	2·8	thin sheets and flakes on perfect cleavage, mica
Kaolinite	$Al_4Si_4O_{10}(OH)_8$	white	the clay minerals,		stable type; includes china clay
Illite	$KAl_4AlSi_7O_{20}(OH)_4$	white	maximum crystal size		dominant type; similar to fine muscovite
Smectite	$(Na,Ca)Al_4Si_8O_{20}(OH)_4.nH_2O$	white	only microns across		unstable (variable water); montmorillonite
Calcite	$CaCO_3$	white	3	2·7	mosaic; shell debris; rhombic cleavage on 3 planes
Dolomite	$CaMg(CO_3)_2$	white	3½	2·8	mosaic and rhombs
Gypsum	$CaSO_4.2H_2O$	white	2	2·3	bladed selenite; massive alabaster; fibrous satinspar
Hematite	Fe_2O_3	red	6	5·1	widespread colouring agent
Limonite	$FeO.OH$	brown	5	3·6	widespread colouring agent; rust, may be yellow
Pyrite	FeS_2	yellow	6	5·0	metallic brassy lustre (fool's gold); common as cubes

Structures in sedimentary rocks

thin bedding

graded bedding — clay, sand

massive bedding

lenses, nodules

current bedding

dune bedding

reef knoll

cyclothems — coal, sandstone, shale, limestone

LITHIFICATION

The processes by which a weak, loose sediment is turned into a stronger sedimentary rock. Induced by burial pressure and slightly increased temperature beneath a kilometre or more of overlying sediment. The processes of lithification are also known as diagenesis by geologists, referring to the changes which take place after deposition. The results of lithification, notably the increase in strength, are referred to as consolidation by engineers. Three main processes of lithification:

Cementation The filling of the intergranular pore spaces by deposition of a mineral cement brought in by circulating groundwater. Rock strength is largely dependant on the type of cement, which may be silica (strongest), iron oxides, calcite or clay (weakest). The dominant process in sandstones.

Recrystallization Small scale solution and redeposition of mineral, so that some grains become smaller and some larger. Result may be similar to cementation, but may produce stronger mosaic texture. Can also include change of state and growth of new, more stable minerals. The dominant process in limestones.
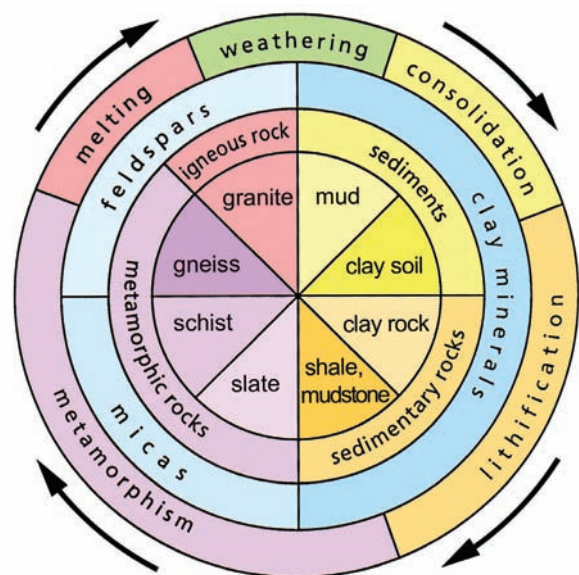
Compaction Restructuring and change of grain packing, with decrease in volume, due to burial pressure, with consequent reduction of porosity as water is squeezed out. Increase in strength is due to more grain to grain contact. The dominant process in clays.

CONSOLIDATION generally refers to the increase in strength in clays, due to their restructuring, improved packing, loss of water and reduced porosity caused by compaction under load; it also includes some cementation and new mineral growth.

Normally consolidated clays have never been under a higher load than their existing overburden; these include most clay soils.

Over-consolidated clays have been under a higher load in the past, imposed by cover rocks since removed by erosion; these include nearly all clays within rock sequences. They have lower porosity and higher strength due to their history of burial and exposure.

THE CLAY ROCK CYCLE

weathering — consolidation — clay minerals — lithification — sedimentary rocks — micas — metamorphism — melting — feldspars

igneous rock — granite — mud — sediments — clay soil — clay rock — shale, mudstone — gneiss — schist — slate

metamorphic rocks

Clay soils and clay rocks related to their metamorphic and igneous derivatives. The eight rocks (and sediment soils) in the core of this cyclic diagram are related by processes (shown in the outer ring), which act in the clockwise direction. Bulk composition is roughly constant, except for the water content, which decreases from mud to granite. Only weathering increases the water content, and weathering of any rock may short-circuit the processes by producing mud. Only the main changeable minerals are shown; quartz is present in all the rocks and soils.

(Consolidation also refers to the effect of soil compaction under structural loading, and may be applied specifically to changes taking place when clays are compacted.)
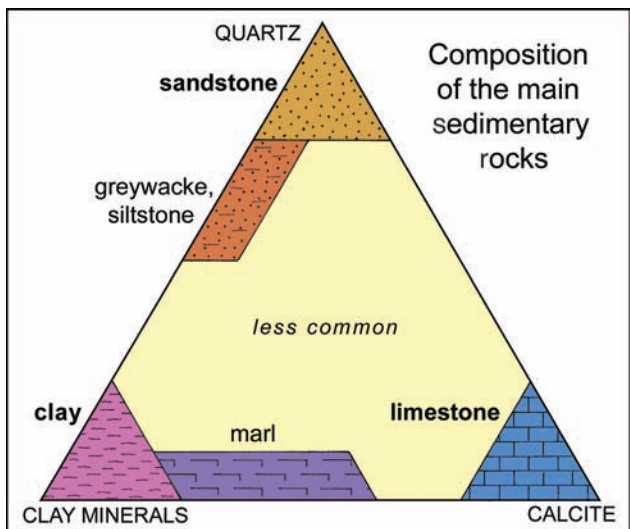
9

04 Sedimentary Rocks

CLASSIFICATION OF SEDIMENTARY ROCKS

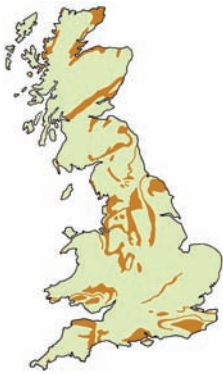| A CLASTIC ROCKS	B NON-CLASTIC ROCKS

1. Rudaceous: coarse grained   <2 mm
   Conglomerate – rounded fragments
   Breccia – angular fragments
 	
2. Arenaceous: medium grained   0·06–2 mm
   Sandstone and allied rocks
 	
3. Argillaceous: fine grained   <0·06 mm
   Siltstone – quartz particles
   Clay and allied rocks
	1. Carbonates, consisting mainly of calcite
	   Limestone and allied rocks
	
	2. Non-carbonates
	   Flint and chert – nodular or banded silica
	   Coal and lignite – lithified peat and plant material
	   Ironstone – any iron-rich sedimentary rock;
	                     sand, clay or oolite texture
	   Salt and gypsum – monomineralic rocks deposited
	                     by evaporation of water

Electron microscope view of sandstone with quartz grains and weak flaky clay mineral cement. An original, partial, calcite cement has been removed by weathering.

Composition of the main sedimentary rocks

QUARTZ — sandstone — greywacke, siltstone — less common — clay — marl — limestone — CLAY MINERALS — CALCITE

LIMESTONE

TYPE	Sedimentary, organic or chemical carbonate.
MINERALOGY	Variable-sized calcite mosaic, usually with shell fragments. Calcite 95%, dolomite 3%, clay minerals 2%.
OCCURRENCE	Marine shell debris and chemical precipitate, lithified by recrystallization. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: Pennine dales. USA: Mammoth Cave plateau.
STRUCTURES	Massive or thin bedded; commonly with thin shale partings. May include large lenticular reefs of massive strong limestone. May contain nodules and lenses of silica: flint in chalk, chert in limestones.
WEATHERING	Soluble in rainwater, leaving minimal or no soil, and allowing formation of open fissures, sinkholes and caves. Forms distinctive karst landscapes with underground drainage, dry valleys and, commonly, many bare rock outcrops. Karstic collapse into caves may occur, but as rare events; limestone gorges are common, but most are not collapsed caves.
STRENGTH	Older limestones are more completely recrystallized and stronger. UCS: 20–100 MPa. SBP: 0·5–4 MPa.
FOUNDATIONS	Extreme variability; strong rock with open fissures and cavities. May shear along thin shale beds.
HYDROLOGY	Efficient aquifer with diffuse and conduit flow.
VALUE	Valuable dimension and aggregate stone. Burn with clay to make cement.
VARIETIES	Oolite: consists of sand-sized spherical calcite concretions. Chalk: weak, friable, pure, white limestone. Travertine, tufa: soft, porous, banded calcite precipitated in flowing water. Dolomite: recrystallized with magnesium content (in dolomite mineral). Calcilutite: compact, strong, fine grained limestone.

Microscope view, 5 mm across: calcite forming large shell fragments, in coarse and fine cement matrix.

SANDSTONE

|	
TYPE	Sedimentary, clastic, arenaceous.
MINERALOGY	Medium grained, with sand grains mostly of quartz, set in cement of quartz, calcite, clay or other mineral. Quartz 80%, clay minerals 10%, others 10%.
OCCURRENCE	Sand of marine, river or desert origin, lithified by cementation. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: Pennine moors and edges. USA: Canyonlands.
STRUCTURES	Massive or thin bedded; commonly interbedded with shale. May have cross bedding inherited from deltaic or dune origin.
WEATHERING	Crumbles to sand, forming sandy well-drained soils.
STRENGTH	Older sandstones tend to be better cemented and stronger. Clay cements are notably weak; quartz cements are generally strong. UCS: 10–90 MPa SBP: 1–4 MPa.
FOUNDATIONS	Generally strong material, unless poorly cemented or with weak cement.
HYDROLOGY	Productive aquifer with diffuse flow.
VALUE	Most sandstones abrade too easily for use as aggregate; some may yield good dimension stone.
VARIETIES	Flagstone: thinly bedded due to partings rich in mica flakes. Grit: imprecise colloquial term for strong sandstone. Greywacke: old, partly metamorphosed, strong; interbedded with slate. Flysch: young and weak; interbedded with shale or clay. Tuff: volcanic ash of sand grain size; lithified or unlithified.
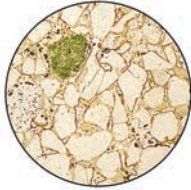
Microscope view, 5 mm across: mostly quartz grains, in cement that is partly of coloured iron oxide.

Eroded remnants of once-continuous beds of sandstone, Monument Valley, northern Arizona, USA. A massively bedded sandstone forms the vertical sided buttes, and overlies a series of thinly bedded sandstones with many shale layers.
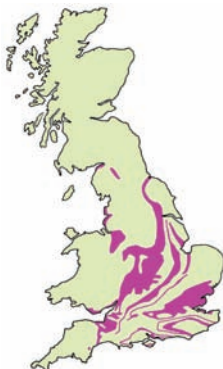
CLAY

TYPE	Sedimentary, clastic, argillaceous.
MINERALOGY	Fine-grained structureless mass of clay minerals, commonly with a proportion of small silt grains of quartz. Illite 60%, kaolinite 20%, smectite 10%, others 10%.
OCCURRENCE	Mud, mainly of marine origin, lithified by compaction and water expulsion. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: London Clay. USA: South Dakota Badlands.
STRUCTURES	Commonly featureless and unbedded, but may be bedded with variable silt and organic content. May have nodules (hard rounded lumps) with stronger mineral cement.
WEATHERING	Reverts to mud, forming heavy clay soils.
STRENGTH	Older, more lithified and unweathered clays have higher strength. Younger clays have properties transitional to those of low strength soils. UCS: 1–20 MPa. SBP: 0·1–1 MPa.
FOUNDATIONS	Weak material with low, variable strength related largely to water content; prone to slow creep and plastic deformation; high potential compaction may cause high and differential settlement under structural load.
HYDROLOGY	Aquiclude.
VALUE	Watertight fill, bricks, cement.
VARIETIES	Mudstone: more lithified, massive and stronger. Shale: more lithified, laminated and fissile. Marl: clay or mudstone with significant calcite content. Siltstone: mainly quartz grains, essentially a fine grained sandstone.

Microscope view, 5 mm across: very fine clay groundmass, but some layers have more clear quartz silt.

05 Metamorphic Rocks

Metamorphic rocks are created by changes induced at high temperature (up to about 600°C) and/or high pressures (around 500 MPa at 20 km depth). These changes (metamorphism) take place in the solid state. The type of metamorphic rock produced depends on the original rock material that was metamorphosed, and also on the temperature and pressure conditions that were then imposed on it.

METAMORPHIC CHANGES IN ROCK

Recrystallization forms a strong mosaic of minerals, notably in marble.

New minerals grow at the expense of less stable minerals in the new conditions of high temperature and pressure. Most important changes are in the sequence:

clay minerals → micas → feldspars and mafics

Micas are the most significant minerals in metamorphic rocks, and they only change to feldspars at the highest grade of metamorphism.

A green colour is typical of low grade metamorphic rocks that contain significant chlorite and epidote.

Directional pressure within the solid state creates mineral orientation within the regionally metamorphosed rocks. New minerals grow in the line of least resistance – perpendicular to the maximum pressure – to cause foliation, or banding, within these rocks.

Planar weaknesses in the foliated metamorphic rocks are created by the parallel micas splitting along their mineral cleavage – causing rock cleavage (also known as slaty cleavage) and schistosity – both of which are independent of any original bedding.

Non-foliated metamorphic rocks have stronger isotropic structure. These include hornfels, formed by thermal metamorphism of clay without high pressure; also marble, and gneiss with little or no mica.

TYPES OF METAMORPHISM

Regional metamorphism involves high temperature and pressure. Occurs in mountain chains due to continental collision on plate boundaries. Extends over large areas.

Thermal or **contact** metamorphism involves high temperature only. Occurs in metamorphic aureoles, each 1 m – 2 km wide, around igneous intrusions where rock has been baked.

Dynamic metamorphism at high pressure only is rare.
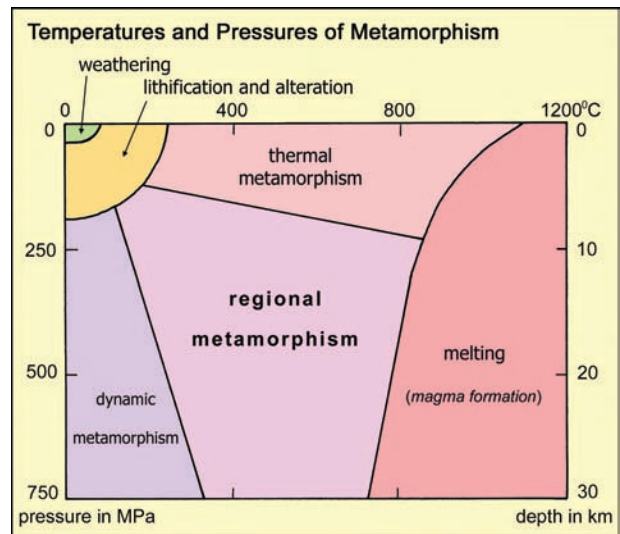
Grade of metamorphism is the overall extent of change, notably in the sequence (within regional metamorphism) from slate to schist to gneiss. The sequence of changes can be seen in the rock cycle diagram (*section 03*).

METAMORPHISM OF DIFFERENT ROCKS

Limestone → marble: by recrystallization of calcite, forming strong mosaics.
Sandstone → quartzite: by recrystallization of quartz, forming very strong mosaics.
Basalt → greenstone: by limited growth of new green minerals.
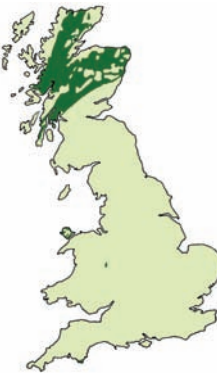Granite shows little change: it is largely stable in metamorphic conditions.
Clay (and rock mixtures) → hornfels, slate, schist or gneiss: depending on type and grade of metamorphism.

MAIN METAMORPHIC ROCKS derived from clay or mixtures of rocks					
name	*grain size*	*main minerals*	*structure*	*strength*	*UCS (MPa)*
Hornfels	fine	mica, quartz, clay minerals	uniform	very strong	200
Slate	fine	mica, quartz, clay minerals	cleavage	low shear, high flexural	20–120
Schist	coarse	mica, quartz	schistosity	very low shear	20–70
Gneiss	coarse	quartz, feldspar, mafics, mica	foliation	strong	100

ROCK ALTERATION

Alteration includes various processes that affect rocks, usually involving water at lower temperatures and pressures than metamorphism.

Weathering involves rainfall water coming from above; a near-surface feature (*section 13*).

Hydrothermal alteration involves hot water rising from below, commonly from volcanic source.

Metasomatism involves chemical replacement by elements carried in solution.

Alteration is commonly localized within a few metres of major faults or fractures; it may occur throughout zones a kilometre or more across.

New, hydrated, weak minerals are the main product of alteration processes; normally the altered rock is therefore significantly weaker than the original.

Alteration may be indicated by local colour changes, notably green or yellow.

Chloritization: very low grade metamorphic growth of weak, green chlorite.

Kaolinization: alteration of feldspars to kaolinite (clay mineral).

Sericitization: alteration of feldspars to flakes of sericite (similar to fine grained muscovite).

Iron alteration: rusting and decay of iron minerals to yellow or brown limonite.

MAIN MINERALS OF METAMORPHIC ROCKS

mineral	composition	colour	H	D	common morphology and features
Quartz	SiO_2	clear/white	7	2·7	mosaic; no cleavage; glassy lustre
Feldspar	$(K,Na,Ca)(Al,Si)_4O_8$	white	6	2·6	mosaic or short prisms
Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$	clear	2½	2·8	thin sheets and flakes; perfect cleavage,
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	black	2½	2·9	members of the mica group of minerals
Chlorite	$Mg_5Al_2Si_3O_{10}(OH)_8$	blue-green	2	2·7	small flakes; perfect cleavage
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}.OH$	green	6	3·3	small laths
Calcite	$CaCO_3$	white	3	2·7	mosaic; rhombohedral cleavage on 3 planes
Kaolinite	$Al_4S_{i4}O_{10}(OH)_8$	white	2	2·6	fine, powdery clay mineral
Limonite	$FeO.OH$	brown	5	3·6	rusty staining

Other metamorphic minerals, such as hornblende, garnet and andalusite, may be present, but have little influence on rock properties. Units and terms as explained for igneous minerals in *section 02*.

SCHIST

TYPE	Regional metamorphic, medium grade, foliated.
MINERALOGY	Coarse-grained mosaic, with banding and conspicuous parallel orientation. Micas 35%, chlorite 20%, quartz 25%, others 20%.
OCCURRENCE	Regional metamorphism of clays and mixed rocks at high temperature and pressure, in structurally complex cores of mountain belts on convergent plate boundaries.
EXAMPLES	Britain: Scottish Highlands. USA: Inner Gorge of Grand Canyon.
STRUCTURES	Prominent schistosity due to parallelism of abundant mica, commonly with foliation banding and complex folding and crumpling.
WEATHERING	Slow alteration to clays.
STRENGTH	Anisotropic: compressive strength varies by factor of 5 across or oblique to schistosity. Very low shear strength; weakest with higher chlorite or mica content. UCS: 20–70 MPa. SBP: 1–3 MPa.
FOUNDATIONS	Commonly weak, easily sheared.
HYDROLOGY	Aquiclude.
VALUE	Minimal.
VARIETIES	Slate: finer grained, with excellent rock cleavage. Phyllite: intermediate between slate and schist. Gneiss: less mica, more quartz, and higher strength.

Microscope view, 5 mm across: sub-parallel mica flakes deflected round pink garnet crystals.

HORNFELS

|	
TYPE	Thermal metamorphic, non-foliated.
MINERALOGY	Fine-grained mosaic, with no mineral orientation or foliation. Micas 30%, quartz 30%, others 40%.
OCCURRENCE	Thermal (contact) metamorphism of clay at high temperature, in metamorphic aureoles up to 1 km wide around major igneous intrusions.
EXAMPLES	Britain: Dartmoor margins. USA: Sierra Nevada margins.
STRUCTURES	Commonly closely jointed with sharp fractures and local irregularities. May have inherited structures from original rock.
WEATHERING	Very slow alteration to clays.
STRENGTH	Fine-grained materials are generally very strong. UCS: 250 MPa. SBP: 4 MPa.
FOUNDATIONS	Strong rock.
HYDROLOGY	Aquiclude.
VALUE	Good aggregate stone of high strength and low abrasion.
VARIETIES	Marble: metamorphosed limestone, consists of recrystallized calcite. Quartzite: metamorphosed sandstone, consists of recrystallized quartz. Greenstone: metamorphosed basalt, with some new green minerals.

Microscope view, 5 mm across: fine groundmass of quartz and micas, with large andalusite crystals.

06 Geological Structures

FRACTURES

Earth movements involve plastic folding and brittle fracture of rocks, as well as uplift and subsidence. These are tectonic features, caused by large scale movements of crustal plates (*section 09*). Under the high confining pressures at kilometres of depth, and over the long time scales of tectonic processes, most rocks may show plastic deformation, and fractures occur when and where the plastic limits are exceeded.

Outcrop is an exposure of rock at the surface; or the area of a rock lying directly beneath a soil cover.
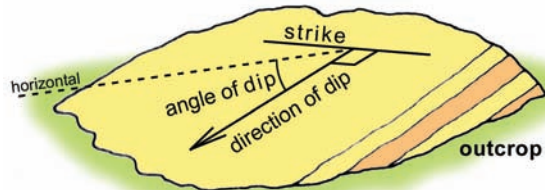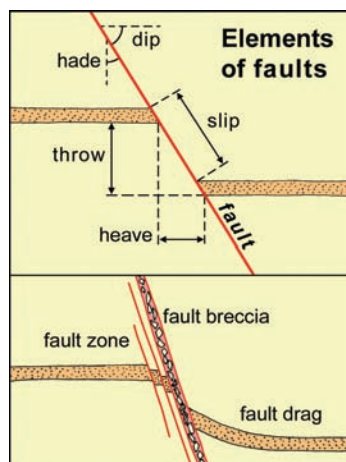

Dip is the angle in degrees below the horizontal. Direction of dip is down the dip.
Strike is direction of horizontal line on a dipping surface. These refer to bedding or any geological structures. Rock dip is used to avoid confusion with ground slope.

Faults are fractures that have had displacement of the rocks along them.
Throw is the vertical component of fault displacement. Faults are described by reference to their downthrow side; this is relative movement and may be due to the other side having moved up.

Strongly folded and faulted rock in Greek road cutting.

Joints are rock fractures with no movement along them. They are formed by tectonic stressing and are developed in nearly all rocks.
Joint densities and joint lengths are infinitely variable. Groups of sub parallel joints form joint systems.

Bedding planes are usually the dominant fractures within sedimentary rocks. Many bedding planes are very thin bands or partings of shale or clay between units of stronger rocks. Others are clean breaks, or joints, developed tectonically along the slightest of contrasts within the deposition sequence.
Slaty cleavage and schistosity are also types of joints.
All joints are structural weaknesses, whose density, extent and orientation are major influences on rock mass strength (*section 25*).
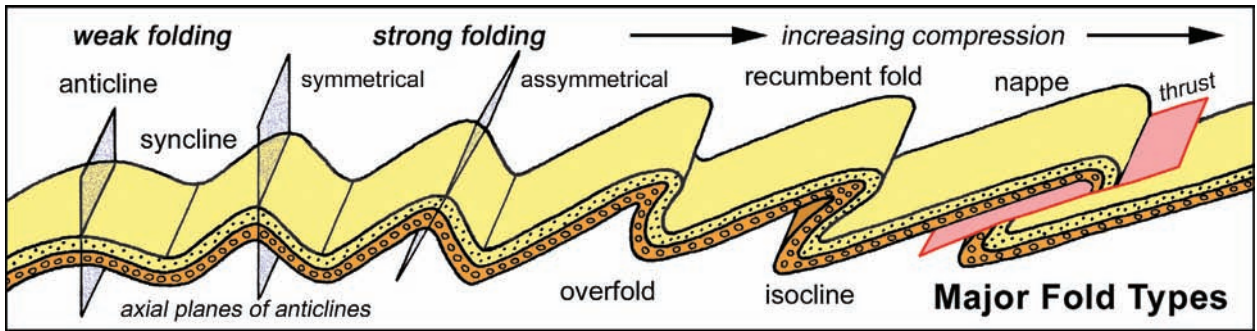Massive rocks are those that have less fractures, joints or structural weaknesses of any kind.

Fault types are recognized by relationship of downthrow to dip of the fault plane.
• Normal faults form under tension; downthrow is on downdip side.
• Reverse faults form under compression; downthrow side is opposite to dip.
• Vertical faults are not easily distinguished as either normal or reverse.
• Thrust faults, or thrusts, are reverse faults with low angles of dip.
• Strike-slip (or tear) faults moved horizontally (*nb* apparent throw in dipping rocks).
• Grabens are downfaulted blocks between two normal faults.

FEATURES OF FAULTS

Faults commonly create zones of badly broken ground – that are weaker and less stable than the adjacent rock – with implications for foundation bearing capacity, slope stability and tunnel roof integrity.
Sudden movements along faults (when tectonic stresses accumulate to overcome frictional resistance) cause earthquakes – vibrations transmitted through the surrounding ground (*section 10*).
Old faults (including all those in Britain) cannot displace ground surface that has evolved subsequent to any fault movement. Fault line scarps and valleys may appear in a landscape due to differential erosion across the fault zone and adjacent contrasting rocks.

Fault breccia: coarse angular broken rock debris in zone (0.1–100 m wide) along a fault; commonly a zone of enhanced groundwater flow.
Fault gouge: finely ground rock paste within a thin zone along a fault plane.
Fault drag: disturbance and folding of rock near a fault.
Slickensides: scratches and polishing on fault planes, and on bedding plane faults within tight folds.
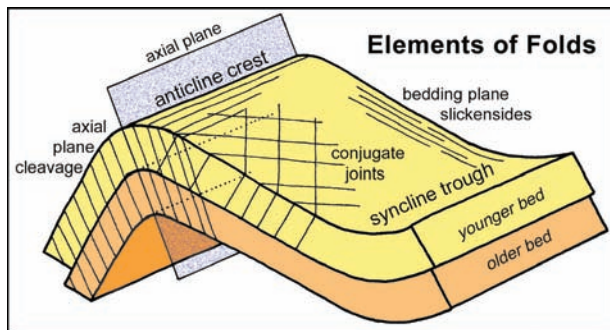**Veins**: sheets of mineral infill deposited by hydrothermal water in fractures or fissures in rock. They occur in joints or faults. Most veins are of quartz or calcite – white streaks in rock faces. Larger veins (mostly on faults) can contain valuable minerals – may have been mined out.
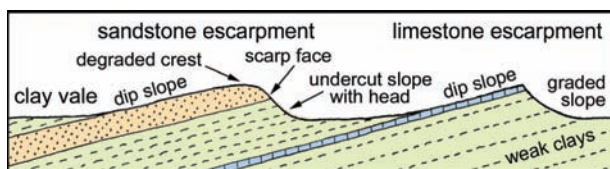
Major Fold Types

weak folding — anticline, syncline — axial planes of anticlines
strong folding — symmetrical, assymmetrical — overfold — *increasing compression* — recumbent fold — isocline — nappe — thrust

FOLDS

Folds are upward anticlines ⌒ or downward synclines ⌣ .

They may be gentle ⌒, moderate ⌒ or strong ⩘.

Folds may be rounded ⌒⌒ or angular ⩘ .

Overfolds and recumbent folds have dips past vertical.
Isoclines have parallel dips on both sides.
Nappes are recumbent folds sheared along the central line with the development of a thrust fault, usually with large displacement.


Elements of Folds — axial plane, anticline crest, axial plane cleavage, bedding plane slickensides, conjugate joints, syncline trough, younger bed, older bed

Escarpments, or cuestas, are asymmetrical hills of dipping beds of strong rock, exposed by differential erosion of weaker rocks above and below.

sandstone escarpment — limestone escarpment — degraded crest — scarp face — clay vale — dip slope — undercut slope with head — dip slope — graded slope — weak clays

Succession of rocks Older rocks generally lie below younger rocks, and are only exposed by erosion.
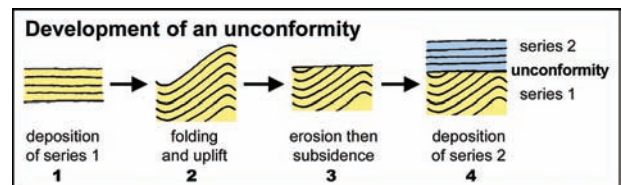
Reference to old and young rocks by age avoids any confusion with high and low outcrops that refer only to their topographical positions.

Inlier is an outcrop of old rocks surrounded by the outcrops of younger rocks; its presence on a map indicates either an eroded anticline or a valley.

section — inlier — valley | map — inlier | section — inlier — anticline
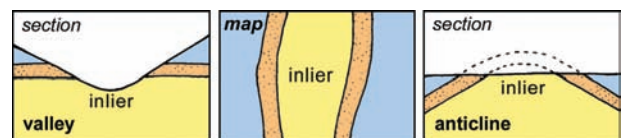
Outlier is an outcrop of young rocks surrounded by old, due to either an eroded syncline or a hill.

Unconformity is the plane or break between two sequences of rocks with different dips. It indicates a period of earth movements and tectonic deformation between the times of sediment deposition. It forms a major structural break – the older rocks must be more lithified and folded, and perhaps more metamorphosed, than the younger rocks above the unconformity.

Development of an unconformity — series 2, unconformity, series 1 — deposition of series 1 (1), folding and uplift (2), erosion then subsidence (3), deposition of series 2 (4)

NON-TECTONIC STRUCTURES

Localized structures formed in shallow rocks and soils, by erosion processes and shallow ground deformation, unrelated to regional tectonic structures.
Camber folds develop in level or low-dip rocks where a clay (or soft shale) underlies a strong sandstone or limestone. The clay is plastically squeezed out from beneath the hill due to the differential loads upon it.
Valley bulge is the floor lift (since eroded away) and the structural disturbance left beneath it.
Most clay is squeezed out from close to the valley side (or scarp edge), so that overlying stronger rocks sag and camber towards the valley.
Gulls are open or soil-filled fissures in the strong rocks of cambered valley sides, opened by camber rotation and perhaps also by sliding.
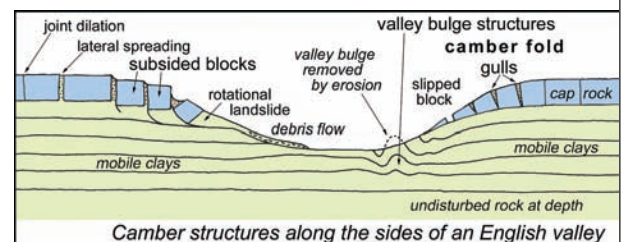
Post-glacial cambered ground, or foundered strata, is common in the sedimentary rocks of England; it causes fissured rock masses and potential landslides along many valley sides and scarp faces.

Glacial drag: shallow local disturbance, with folds, overfolds and faults in soils and weak rocks that were over-ridden by Pleistocene glaciers.
Unloading joints: stress-relief fractures close to and parallel to ground surface due to erosional removal of overburden cover rocks.
Landslip fissures: open fissure and normal faults developed in head zones of slopes prior to failure.
Contraction joints: cooling joints in igneous rocks, including columnar basalt.

joint dilation — lateral spreading — subsided blocks — rotational landslide — debris flow — mobile clays — valley bulge removed by erosion — valley bulge structures — camber fold — gulls — slipped block — cap rock — mobile clays — undisturbed rock at depth

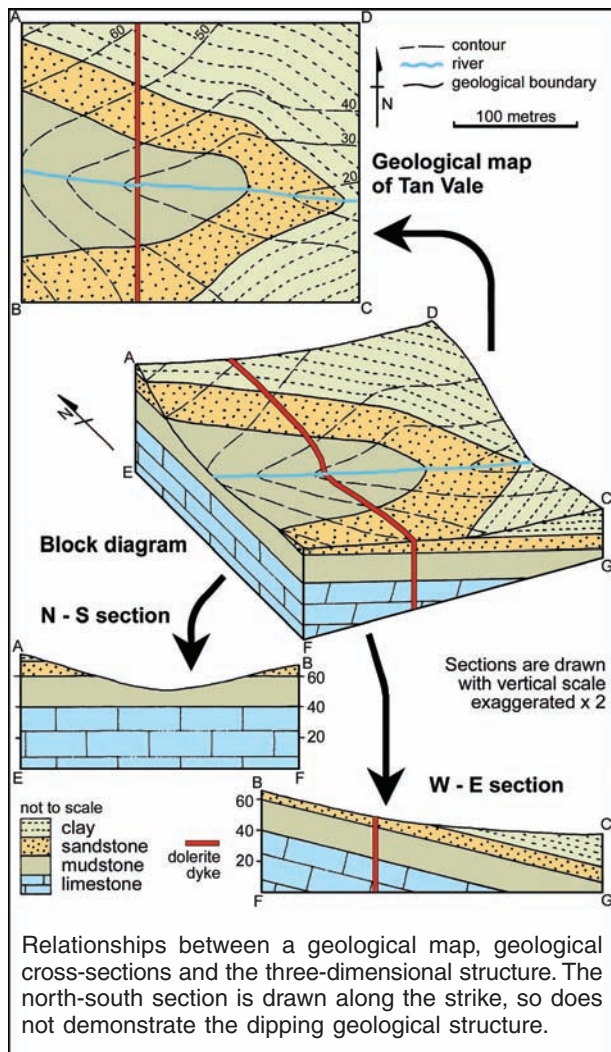*Camber structures along the sides of an English valley*

07 Geological Maps and Sections

Geological maps show outcrops (where the rocks meet the surface). Shapes of outcrops depend on the shape of the surface and the shape of the rock structure. Surface shape is known (from topographic contours): therefore rock structure can be interpreted.

An important rule: where more than one interpretation is possible, the simplest is usually correct.

Map interpretation is therefore logical and straightforward if approached systematically. Maps remain the best way of depicting 3-D rock structure on a piece of paper.

Geological map of Tan Vale

Block diagram

N - S section

Sections are drawn with vertical scale exaggerated x 2

W - E section

not to scale
clay
sandstone
mudstone
limestone
dolerite dyke

Relationships between a geological map, geological cross-sections and the three-dimensional structure. The north-south section is drawn along the strike, so does not demonstrate the dipping geological structure.

STAGES OF MAP INTERPRETATION

1. Identify faults and unconformities (structural breaks).
2. Identify dips by the V in Valley Rule.
3. Determine succession (unless already given).
4. Identify fold axes (from dips and outcrop bends).
5. Draw stratum contours (if detail is required).
6. Draw cross-section to show sub-surface structure.

GEOLOGICAL MAP SYMBOLS

→ 5 dip, direction, and amount in degrees
+ horizontal beds   ─┼─ vertical beds
─┬─ fault, tick on downthrow side
─◆─ anticline   ─✕─ syncline
alluvium   till (glacial)
sandstone   shale or clay
limestone   igneous rock

OUTCROP PATTERNS

Six basic concepts cover all outcrop patterns, and enable most geological maps to be interpreted successfully.

Horizontal beds have outcrops that follow the contours because they are at constant altitude (*limestone on the Scar Hill map*).

Vertical beds have straight outcrops that ignore the contours (*the dyke on the Tan Vale map*).

Dipping beds have curved outcrops that cut across, and respond to, the contours – because outcrops shift down-dip as erosion lowers the surface (*sandstone on both maps*).

Dip direction is recognized by the ***V in Valley Rule***: an outcrop of a dipping rock bends round a V shape where it crosses a valley, and the V of the outcrop points (like an arrowhead) in the direction of dip, regardless of the direction of valley slope and drainage.

This works because the outcrop is shifted furthest down-dip at its lowest point, where it crosses the valley floor (*as on the Tan Vale map and diagram*).

(The rule does not apply in areas of low dip, where outcrops nearly follow contours, so point upstream.)

On level ground, dipping beds have straight outcrops along the direction of strike.

Succession is recognized by younger rocks coming to outcrop in direction of dip. Conversely, if succession is known, the dip is in the direction of younger outcrops – the easiest way to recognize dip on most maps.
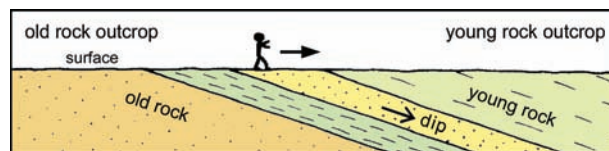

**Width of outcrop** is greater at lower dips – and on thicker beds.
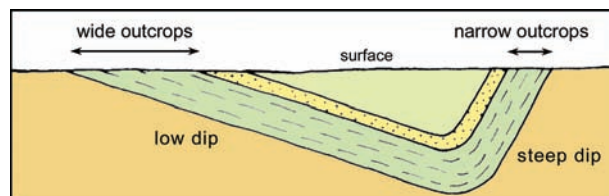
RECOGNITION OF STRUCTURES

Unconformity is recognized where one outcrop (of a younger bed) cuts across the ends of outcrops of older beds (*as does the limestone on the Scar Hill map*).

Faults are usually marked and keyed on maps. They may cut out, offset or repeat outcrops of beds. Fault dip is recognized by V in Valley Rule. Downthrow side of a fault is the side with younger outcrop because the older rocks have been downthrown to beneath surface level.
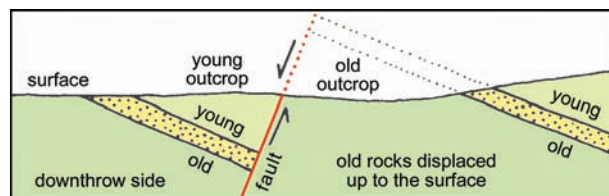
Folds are recognized by changes in dip direction, and also by outliers and inliers not due to topography. Most important, folds are recognized by bends in outcrop: any outcrop bend must be due to either a fold or a topographic ridge or valley. Each outcrop bend should be interpreted (*as on the Scar Hill map*).
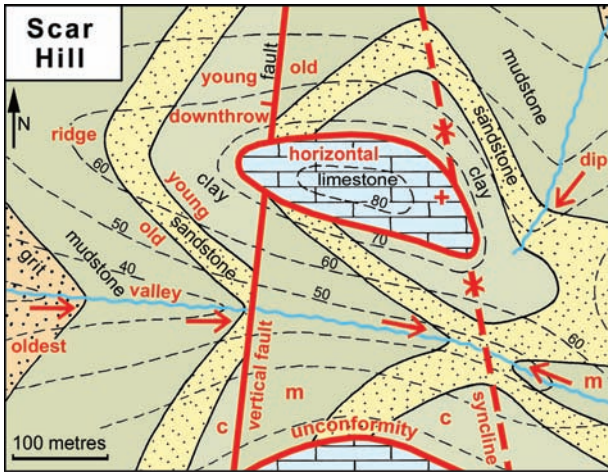
Interpretation of the Scar Hill map

Bends in outcrop are used to identify:
1. topographic features, where dip is uniform;
2. direction of dip where crossing a valley; or
3. fold axes if not due to any topographic feature.

STRATUM CONTOURS

These are lines drawn on a map joining points of equal height on a bed (or stratum). They are like topographic contours, except that they show the shape of buried geological structures. Each contour is labelled with its altitude and the bed boundary to which it refers.

They are drawn by joining points of known equal height on one geological boundary – where its outcrop crosses a topographic contour. The surface information of the map is therefore used to construct the stratum contours, which provide data on the underground geology.

With uniform dip, stratum contours are straight, parallel and equidistant.

Stratum contours have been drawn (*below*) on part of the Tan Vale map. Note that:
- they extend right across the map;
- some apply to two boundaries and are double labelled;
- every boundary/contour intersection has a stratum contour drawn through it;
- labels refer to the base of a bed.
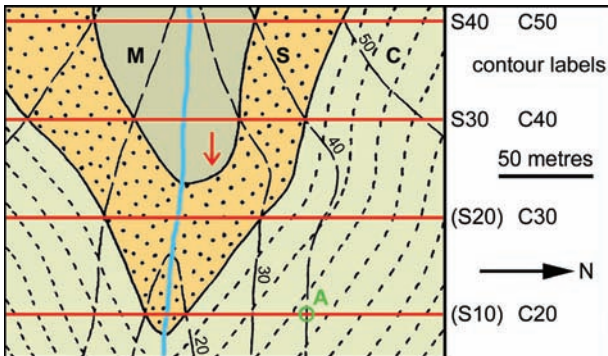
Stratum contours on part of the Tan Vale map

Information can be read from the stratum contours:
- Dip direction is E, 090 (90° from stratum contours);
- Dip amount is 1 in 5 (10 m contours are 50 m apart);
- Sandstone has vertical thickness of 10 m (sandstone base 30 is same contour as clay base 40);
- True thickness = vertical thickness × cosine dip.

Depths to any rock can be read off at any point. The stratum contours indicate that a borehole drilled at point A would pass through 20 m of clay, and then reach the sandstone, which would continue to a depth of 30 m, below which lies the mudstone.

DRAWING A CROSS-SECTION

A cross-section is drawn by projecting the data from a single line on the map onto a profile of the same scale (or with vertical exaggeration if required).

The topography and each geological boundary are constructed individually from the relevant contours, whose intersections on the section line are projected to their correct altitudes on the profile.

Three stages in drawing a cross-section through the geology on the Scar Hill map are shown below.

The purple projection lines, and the large rings around their end points, are only included to demonstrate the construction of stages 1 and 2.
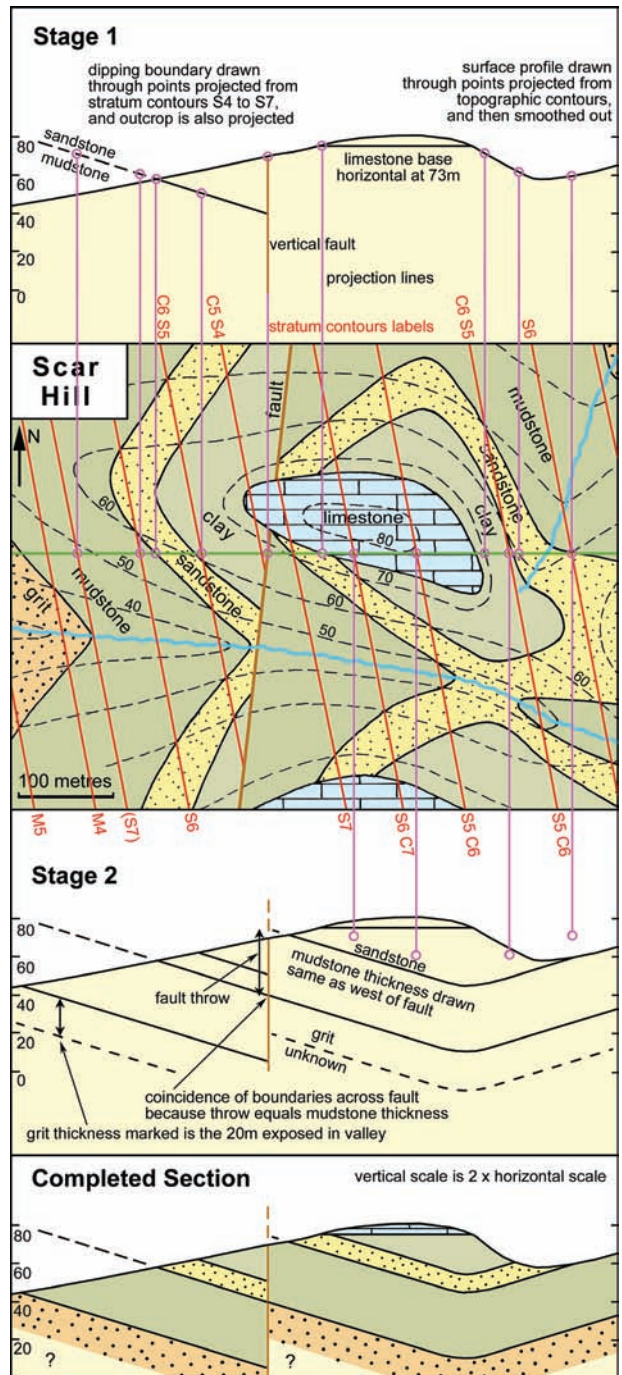
Note two important features of the stratum contours that are drawn on the Scar Hill map:
- they do not cross the fault;
- they apply to the lower, folded beds, and do not relate to the limestone that lies above the unconformity.

17

08 Geological Map Interpretation

Most published geological maps have scales that are between 1:10,000 and 1:100,000.
Low relief cannot be shown accurately at these scales, and therefore stratum contours cannot be drawn to show the geology.
Principles of outcrop shape, bed relationships and structure recognition (*from section 07*) still apply, but the interpretation and section drawing cannot rely on stratum contours.

SOME BASIC CONCEPTS

Most outcrops are laterally uniform sedimentary rocks.
These are in parallel beds of roughly constant thickness.
They are folded and crumpled into parallel curves.
Bed thinning and splitting is rarely seen in small areas.
Beds do not form patternless wedges and blocks.
Heavily faulted areas can provide local complexity.
Intrusions and volcanic rocks have more varied shapes.
Drift sediments form thin, but variable, surface layers.

Geological Map of Oakunder

This is an example of a typical geological map: it shows all rock outcrops, and has some dip arrows to show structure; its stratigraphic column shows the succession and bed thicknesses; simplified topography only shows river valleys.
It is based on the Ashover area; the real map can be seen on BGS Sheet 112 (Chesterfield) at 1:50,000 or 1:63,360.
(All maps should have a bar scale, which retains integrity when copied to different sizes.)
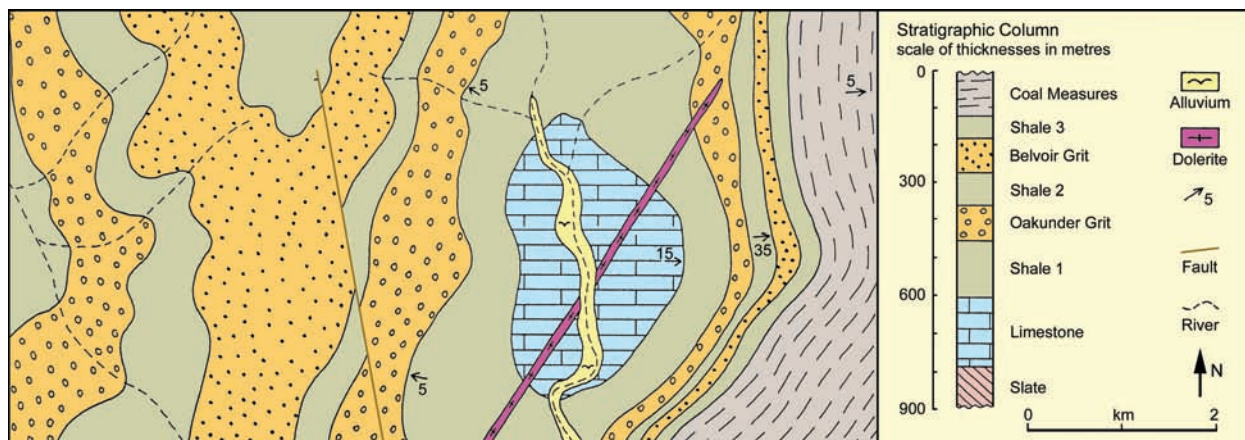
INITIAL INTERPRETATION

Follow stages 1–4 (*in section 07*).
Add interpretation data to map.
Find dips from V in Valley rule.
Find dips from succession rule.
Outcrop widths indicate dip.
Width / thickness = dip gradient.
Three shale beds are distinguished: numbered in stratigraphic column, and labelled on map.
Fault and dyke are both straight, so they are vertical.
Fault is minor – dies out to north, has small outcrop displacements.
Bed sequences are mirrored across the axes of each fold.
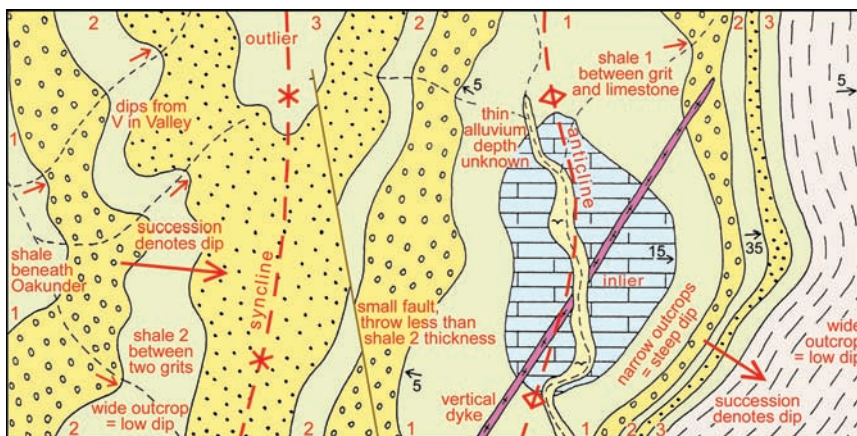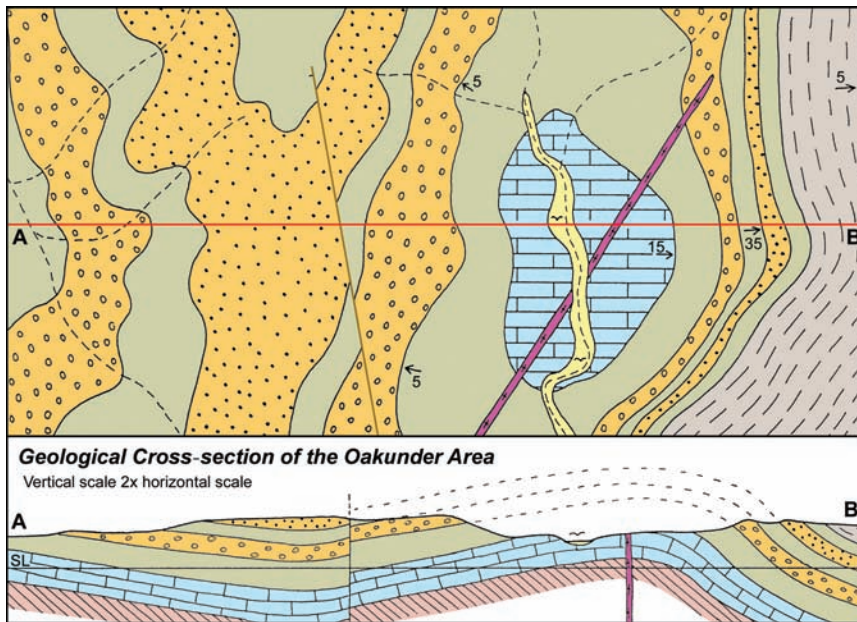

THREE-POINT INTERPRETATION

Sub-surface structure can be interpreted from a minimum of three isolated points (usually in boreholes) on a single horizon.
Assume locally uniform dip to draw stratum contours.
Along lines drawn between any pair of boreholes, distribute uniformly altitudes of the selected boundary or bed. Lines joining these interpreted points of equal altitude are therefore stratum contours.
With three boreholes, can only interpret and draw straight stratum contours.
With more than three boreholes, can draw curved and converging stratum contours to show folding and non-uniform dips. Reliability depends on borehole spacing in relation to structural complexity.
Useful for initial interpretation of site investigation data.
Applicable to any rock or drift layer, rockhead or fault.

Drawing stratum contours from borehole data
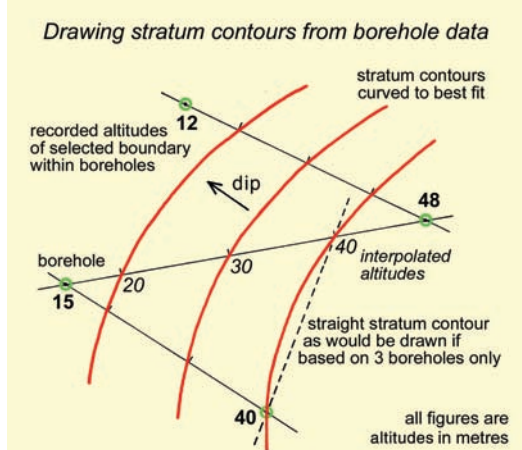
DRAWING THE SECTION

Sequence of stages for the Oakunder map is as follows:
1. Ground profile is given (or is drawn from topographic map).
2. Outcrops are projected onto ground surface (*as in section 07*).
3. Dips are obtained by using the given bed thicknesses (*as on right*).
4. Fault can be ignored at first, because it is interpreted as minor.
5. Oakunder Grit is drawn across both folds, linking the three outcrops.
6. Fault is added so that base of Belvoir Grit does not have an outcrop.
7. Within the syncline, Oakunder Grit is adjusted across the fault.
8. Other beds are added parallel, with constant thicknesses.
9. Parallel curves are fitted to changing dips east of anticline.
10. Slate is added below limestone of thickness as in stratigraphic column.
11. Rocks in core of anticline are unknown beneath given slate thickness.
12. Dolerite is added as vertical dyke cutting through beds.
13. Alluvium is given sensible thickness in valley floor.
14. Optional broken lines in the sky clarify the geological structure.

1 Dip is to the right, so the base of the grit is the outcrop on the left.
2 Project outcrops down to points 1 and 2 on the section.
3 Take thickness from the key, to plot the base at point 3, directly below the top at point 2.
4 Draw the base of the grit through points 1 and 3, and dip is correct.

Geological Cross-section of the Oakunder Area
Vertical scale 2x horizontal scale

INTERPRETATION OF A STRATIGRAPHIC COLUMN

Data is symbolized to cover variations across the area on the map.
Drift deposits are at the top; their thicknesses are not shown.
Main rock sequence is drawn to scale to show mean thicknesses.
Sandstone E lies unconformably on the Carboniferous rocks.
Middle Coal Measures include sandstones and coals marked individually.
Undifferentiated MCM is a mixture of shales, mudstones and thin sandstones (these lithological facts are only obtained from an accompanying handbook).
Sandstone D is locally absent where it is cut out by the unconformity.
Sandstone C varies from 6 to 16 m thick, but is present everywhere.
Sandstone B locally splits into two, and the upper unit may thin out.
Sandstone A varies from 0 to 12 m thick, and is missing in part of map area.
Coal 2 locally splits, but the upper leaf may be cut out by sandstone.
Coal 1 has two leafs, with 5 m of shale between, over most of the map area.
Base of MCM is not seen on the map, an unknown thickness continues down.
Igneous rocks are at the bottom, even though they intrude into higher rocks.
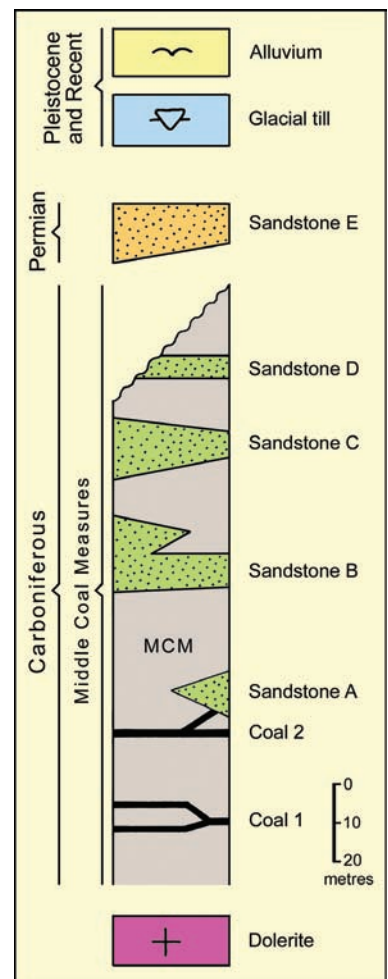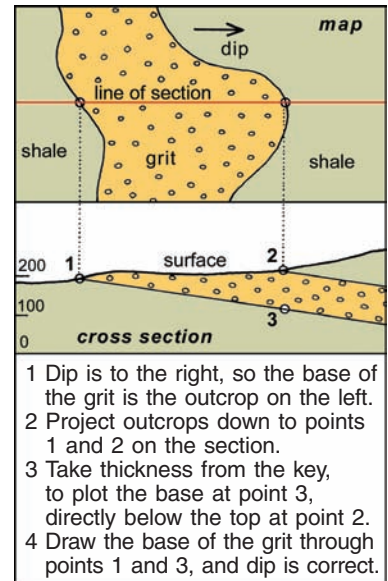
STANDARD GEOLOGICAL MAPS

Maps primarily record data observed at outcrops (or in boreholes). Interpretation is only added where needed; doubt is shown by broken lines. It is largely left to the reader to interpret structure from the outcrop data.
Drift boundaries (*section 13*) are distinguished from rock boundaries. Rock outcrops beneath drift may lack their map colour or ornament, but are labelled so that their boundaries are unambiguous.
Major areas of landslide and camber may be identified.
Larger scale maps may include underground data, borehole records, drift thickness and mine shafts, etc.

ENGINEERING GEOLOGY MAPS

Extra data is available for some locations, with multiple map sheets covering the same area and individually showing selected features; these may include major rock properties, slope stability, subsidence potential, mine workings, drift thickness, drift bearing capacity, rock resources and groundwater conditions.
Generalized engineering geology maps may be summary compilations; these show secondary, interpreted, data to give useful broad pictures of ground conditions, but serve only as guidelines towards specific ground investigations for engineering projects.

09 Plate Tectonics

Planet Earth consists of three concentric layers:
Outer crust, <100 km thick, various solid silicate rocks;
Mantle, 2800 km thick, hot plastic iron silicates;
Inner core, 3500 km radius, largely of molten iron.

CONTINENTS AND OCEANS

Oceanic crust is mainly basalt and dolerite, 5–10 km thick, forming all the ocean floors; it is created and destroyed at plate boundaries.

Continental crust is mainly granite and gneiss, 20–80 km thick; of lower density than oceanic crust, it floats higher on the mantle and forms all the continents, submerged continental shelves and adjacent islands. It is too light to be subducted, so is almost indestructible; it may be eroded or added to by accretion of sediment and rock scraped off subducting oceanic plates.
Individual plates may be either or both crustal types.
Continent coasts may or may not be plate boundaries.

> ### THE MOHO
>
> The boundary between the crust and the mantle is known as the Mohorovicic discontinuity (or the Moho) recognized by refraction of seismic waves. No one has yet seen the rock beneath it. The American drilling project, Mohole, was abandoned early, and Russia's borehole in the Kola Peninsula reached 12.3 km deep in 1993, when further drilling became impracticable.

PLATES AND PLATE MOVEMENT

Lithosphere is the relatively brittle outer rock layer, consisting of the crust and upper mantle; it is broken into large slabs known as plates.
Convection currents circulate within the mantle – because it is heated from below – and the convection cells have horizontal movements across their tops.
Plate tectonics are the relative movements of the plates as they are shifted by the underlying mantle flows.
Each plate is relatively stable, but disturbances along the plate boundaries cause most geological processes. The formation of igneous, sedimentary and metamorphic rocks, and their subsequent deformation or erosion, can all be identified on the cross-section diagram (*opposite*) through two plate boundaries.
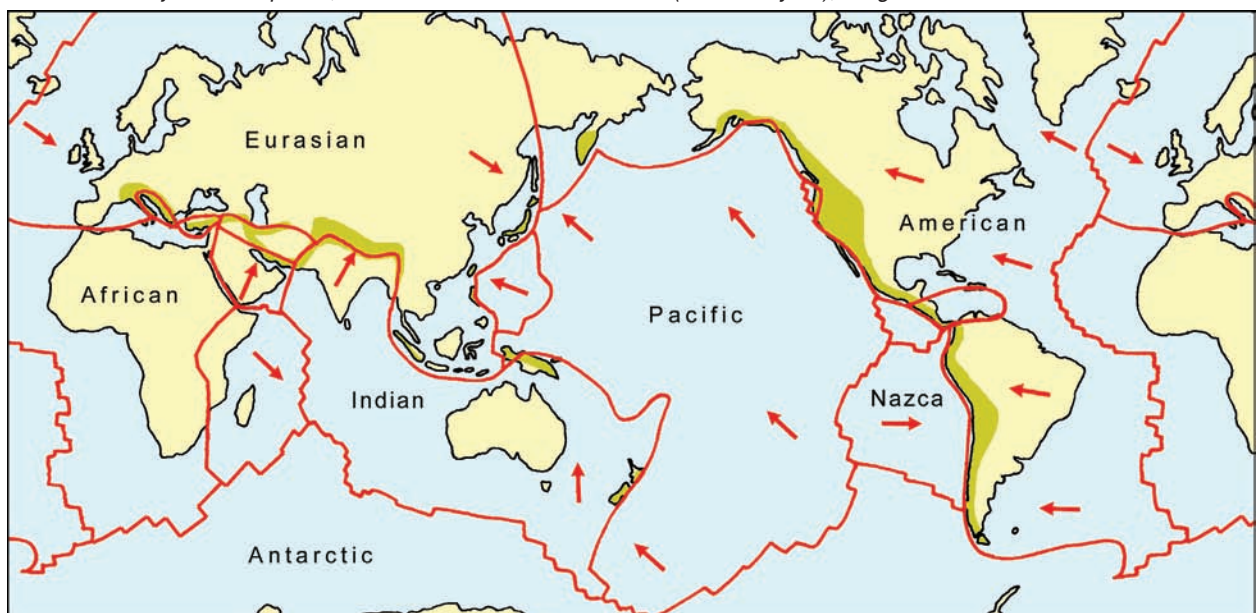
PLATE BOUNDARY TYPES

Conservative boundary has sideways movement only, e.g. San Andreas Fault in California. Major strike-slip faults are formed, and intermittent movements create major earthquakes.

Divergent boundary is constructive, as new oceanic plate is formed, e.g. Mid Atlantic Ridge. Basaltic magma is produced as a silicate liquid separated from iron-rich mineral solids in partially melted mantle; this produces numerous dykes and submarine volcanoes. Excess magma creates islands, e.g. Iceland, with effusive basalt volcanoes and high geothermal heat; small earthquakes occur as rocks part under tension.

Convergent boundary is destructive, as oceanic plate is subducted and melted, e.g. beneath the Andes along western edge of South America. The over-riding continental plate is crumpled and thickened to form a mountain chain, involving a great range of geological processes, collectively known as orogenesis (from the Greek for mountain building).
Type of convergence determines style of orogenesis:
Continent-ocean: normal orogenic belt, where oceanic plate is subducted and destroyed, e.g. Andes.
Ocean-ocean: one plate is destroyed, magma creates island arc volcanoes, e.g. Java.
Continent-continent: collision, with orogenic maximum, where plates are welded together, e.g. Himalayas.

MOUNTAIN CHAINS

Uplift of mountain chains occurs because the lightweight granitic crust, thickened within the orogenic belt, floats to a higher level on the mantle in order to maintain the isostatic balance of equal loading all around the rotating sphere of Earth.
The highest mountain chains are the youngest. The Himalayas are <10M years old, formed largely of folded sedimentary rocks; the top of Mount Everest is limestone. Old mountain chains are eroded down. The Scottish Highlands have been eroded for 400M years; they consist of granites and gneisses, rather similar to the rocks on the floors of the deepest Himalayan valleys.

The world's major crustal plates; arrows show relative movement (a few cm/year), orogenic mountain belts are shaded.

GEOLOGICAL ENVIRONMENTS

The overall geological character of a region – whether or not it has metamorphic rocks, active volcanoes and/or earth movements, whether the sedimentary rocks are thick or thin, folded or unfolded – relates to the plate tectonic processes.

These are the background to the ground conditions of concern to the engineer.

Stable environments are on the plates; thin sedimentary rocks, slow erosion, gentle folding, only rare earthquakes and generally no volcanoes.

The oldest continental plates are the shields of strong metamorphic rocks, known as basement, including those that form Scotland's Outer Hebrides and most of eastern Canada. Most of Britain and the eastern USA are both on younger stable plates.

Unstable environments are on or near the plate boundaries, and the geology relates to the boundary movement: sideways, divergent or convergent.

OROGENESIS

Involves all the main geological processes except basaltic volcanoes.

Strong folding, overfolds and nappes; weaker folds away from the boundary.

Faults and thrusts under compression, and major earthquakes when they move.

Regional metamorphism developed by heat and pressure at depth.

Partial melting of continental crust creates granite batholiths within cores of metamorphic belts.

Melted oceanic basalt mixes with continental material to form viscous andesite and rhyolite magmas and explosive volcanoes.

Mineralization by migrating fluids in hot active zones.

Uplift of orogenic mountain chains; consequent rapid erosion and sediment production.

Thick sedimentation in adjacent subsidence zones; turbidites extend into oceans.
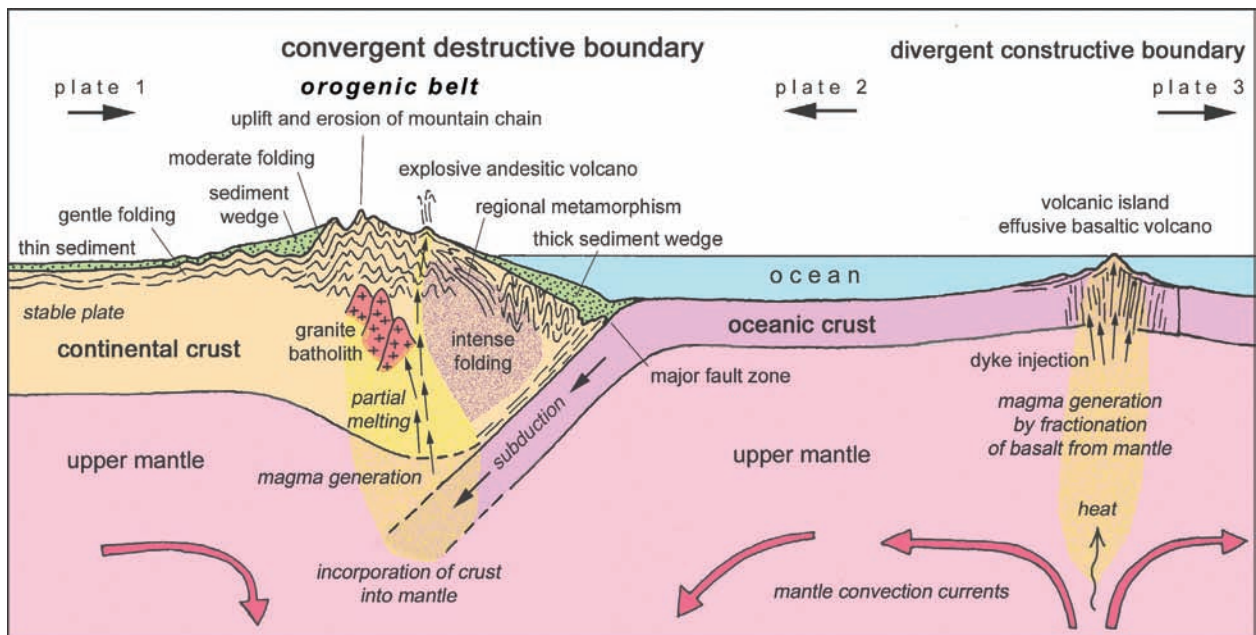
Plate boundary processes, shown on a diagrammatic section through parts of three tectonic plates.

GEOLOGICAL TIME

Processes evolve and plate patterns change over geological time. New oceans open up; continents collide and weld into one. Any one place can therefore be in a series of geological environments through its history.

Time is an extra dimension that must be appreciated to fully understand the geology of any area; the geological history of a site accounts for the structures and rock relationships, which are relevant to ground engineering.

The significance of rock age to an engineer: in any one area, e.g. Britain, older rocks are generally stronger, better lithified, maybe metamorphosed, and more complexly folded than younger rocks. However, rocks of the same age may be very different in areas of different plate tectonic histories, e.g. the contrasts between the rocks of the east and west coasts of the USA.

Quaternary sediments are so young that most have not been deeply buried; they are largely unconsolidated and minimally deformed.

The stratigraphic column divides geological time into periods, and the same names apply to the systems of rocks formed in those periods.

The names are international, except that Carboniferous is replaced by Mississippian and Pennsylvanian in the USA.

THE STRATIGRAPHIC COLUMN

period/system	era	age
Holocene = Recent Pleistocene (= Ice Ages)	Quarternary	*My* 1.8
Pliocene ⎱ Neogene Miocene ⎰ Oligocene ⎱ Eocene ⎰ Paleogene Paleocene ⎰	Tertiary	
Cretaceous Jurassic Triassic	Mesozoic	65
Permian Carboniferous ⎰ Pennsylvanian ⎱ Mississippian Devonian Silurian Ordovician Cambrian	Paleozoic	250
Proterozoic Archean (origin of the Earth)	Precambrian	545 *4600*

21

10 Boundary Hazards

Earthquakes

Caused when relative movement of plates or fault blocks overcomes shear resistance of a fault. Movement builds up elastic strain in rocks; fault rupture and rock rebound release strain energy as ground shock waves.
Most earthquakes originate at focus <20 km deep.
Surface displacement may be a few metres or absent.
Fault breaks may extend over lengths 1–100 km.

SIZE AND SCALE OF EARTHQUAKES

Ground movements are measured on seismographs.
Magnitude (M) defines the size of an earthquake on the Richter scale: $\log_{10}$ of the maximum wave amplitude in microns on a Wood Anderson seismograph 100 km from the epicentre (point on the surface above the focus).
Moment magnitude (M_W) relates to fault area, movement and rock rigidity; it gives a better indication of an earthquake's energy, and is numerically close to M.
Intensity is the scale of earthquake damage at any one point, described on the modified Mercalli scale, and declining away from the epicentre. (MSK and EMS-98 scales are similar to Mercalli, but with more detail.)
Damage relates largely to peak ground acceleration, also to peak velocity, frequency and duration.
Duration usually <10 secs for magnitude 5, may last for 40 secs at magnitude 8; increases away from epicentre.

Mercalli Earthquake Intensity (and peak acceleration)	
I Not felt	VII Adobe damaged (~0.1g)
II Felt at rest	VIII Masonry damaged
III Felt indoors	IX Foundations damaged
IV Windows rattle (<0.02g)	X Buildings destroyed (>0.6g)
V Felt outdoors	XI Railways buckled
VI Frightening	XII Total destruction

Types of Earthquake Waves
P and S are small, fast interior waves, from which form Love and Rayleigh, which are larger, slower, and more destructive, surface waves.
Velocity difference of P and S creates a time lag on a seismograph, so distance to epicentre is calculated at about 9 km/sec of the lag.

EARTHQUAKE PREDICTION

Most are on plate boundaries, 90% on subduction zones.
Some occur on intra-plate faults: Britain has up to M5, and Mississippi Valley earthquakes were M7.8 in 1811.
Also due to magma movement under volcanoes.
Some faults slip smoothly: the Cienega Winery in California has its foundations displaced 15 mm/year by the San Andreas Fault – but no earthquake damage.
Prediction: research is now greatly reduced, in favour of research into structural survivability in earthquakes.
Side effects of ground strain before some quakes may include foreshocks, uplift, dilation, gas emissions, groundwater changes and increase in seismic velocity, but monitoring reveals inconsistent patterns.
Past records may indicate seismic gap (with no recent slip) on an active fault, where a future quake is more likely.
Control: raised water pressures reduce shear strength, and cause fault movement before large strain energy accumulation. Pumping water into deep wells does trigger premature small quakes, but legal complications make serious earthquake control impossible.

China's earthquakes: Tangshan, 1976 (M7.5), probably killed >600,000. New building codes were introduced, but were widely ignored. Then, many among the 70,000 killed in Sichuan, 2008 (M7.9), died in collapses of new, poorly built, concrete schools.

World distribution of earthquakes
Each year there are about 20 of M7
and about 1500 of M>5
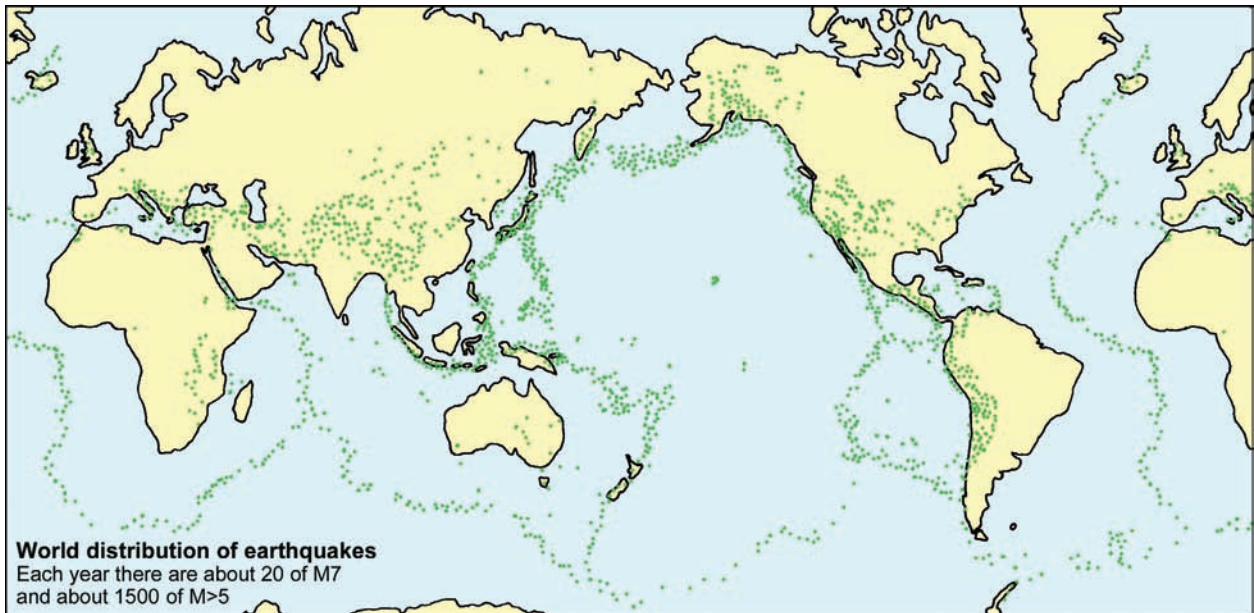
Approximate Correlations of Earthquake Magnitude, Intensity and Damage

Relative energy	Richter Magnitude	Example	Max. Intensity	Damage at epicentre	Area of influence
	1–3		I–IV	Social disturbance, no damage	Small
1	4	2008 Market Rasen M4.8	VI	Slight	Small (major earthquake for Britain)
30	5	1979 San Francisco M5.7	VII	Little damage to reinforced concrete	Minor earthquake for California
				Severe damage to adobe houses	Intensity VI slight damage to 10 km away
1000	6	2003 Bam (Iran) M6.6	IX	Severe damage to many buildings	Intensity VII damage to 10 km away
30,000	7	2005 Kashmir Pakistan M7.6	X	Major damage to most buildings	Intensity VII damage to 50 km away
1 M	8	1906 San Francisco M7.8	XII	Near-total destruction	Intensity VII damage to 200 km away
30 M	9	2004 Aceh (Sumatra) M9.1	XII	Total destruction (and the Aceh tsunami)	Intensity X severe damage to 20 km away

CONSTRUCTION IN SEISMIC ZONES

Adobe and dry stone walls fail under horizontal acceleration of 0·1g, but good low-rise timber buildings can withstand any earthquake.

Reinforced concrete structures need bracing to stop rhombohedral collapse; this can be provided by massive, resistant shear walls, or diagonal steelwork.

Rebars must be integrated across intersections of columns/beams/walls/slabs.

Pile cap failures are restrained by tie beams and integrated basement structures.

Buildings and bridges can be isolated on rubber spring blocks; and steel springs can act as energy absorbers to stabilize structures.

Precautionary provisions add 5–10% to construction costs. Later modifications are more expensive.

Avoid ornamental appendages, which can fall off.

Use land zoning to avoid areas of deep soft soils and known fault traces – any displacement of Holocene soils indicates modern activity on a fault.

New building in California is prohibited within 15 m of active faults; wider zones apply to larger buildings and less well-mapped faults.

DEEP SOILS AND EARTHQUAKES

Soft soils do not dampen ground vibrations. They amplify them. Buildings on soft soil suffer much worse earthquake damage than those on bedrock.

Wave amplitude may double in passing from rock to soil. Dominant natural period of the shock waves also increases, from about 0·3 seconds in solid rock, to 1–4 seconds on soils. The natural period further increases with soil depth, and with distance from the epicentre.

Buildings have a natural period of about N/10 seconds (N = number of stories). Maximum damage is due to resonance, when periods of building and soil match.

Deep soft soils have long periods that match those of high-rise buildings susceptible to more catastrophic damage – as in the Mexico City earthquake in 1985.

Soft soils cause damage that is typically 1–3 intensities higher than on adjacent bedrock.

Secondary earthquake phenomena

Subsidence due to liquefaction of low-density sands.
Landslides and slope failures of all sizes and speeds.
Tsunamis – oceanic seismic waves (*section 17*).
Seiches – oscillating waves on lakes.

Volcanic Eruptions

Basaltic volcanoes lie on divergent plate boundaries (e.g. Iceland), or on plates away from boundary disturbances (e.g. Hawaii), where magma is generated from mantle plumes. They produce large flows of mobile lava in quiet, effusive eruptions, with only limited fountaining or explosions.

These volcanoes are tourist attractions, which may threaten fixed structures, but offer minimal threat to life.
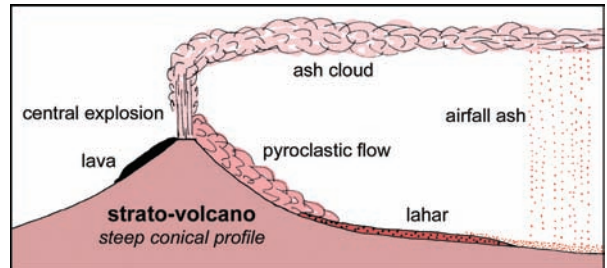

shield volcano
low and wide profile
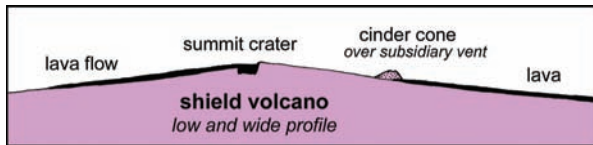
Prediction of eruptions is largely based on volcanic inflation (uplift) and seismic monitoring; there have been successful forecasts of repetitive basalt emissions.

Scale and size of explosive eruptions cannot be predicted reliably, neither can their precise timing, nor the vent location within an active volcanic area.

Explosive volcanoes all lie on the convergent plate boundaries (e.g. Krakatoa, St Helens), where magma is generated by subduction melting. Viscous magma, of andesite or rhyolite, makes gas pressures build up.

Eruptions produce high ash clouds, explosive blasts and very dangerous pyroclastic flows (of hot gas and ash) which turn into lahars (mud flows) lower down valleys; lava flows are minor and short.

Flank collapses can cause massive lateral blasts.

These eruptions are dangerous, largely unpredictable and totally uncontrollable; they must be avoided.

strato-volcano
steep conical profile

World distribution of volcanoes
There are >500 active volcanoes in the world
Typically >50 of them erupt in any one year
●● basaltic volcanoes; ▲▲ explosive volcanoes
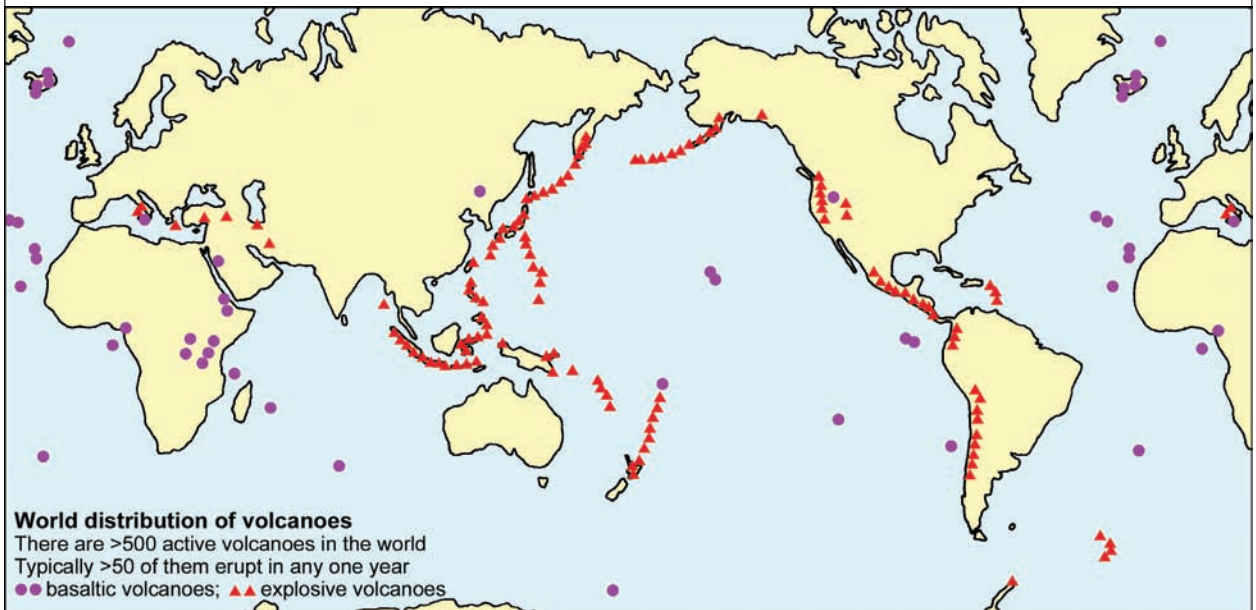
11 Rocks of Britain

Britain covers an area small enough to have its geology viewed as a single sequence of processes encompassing the whole country. With a single history, the geology of Britain is sensibly divisible by rock age, and with few exceptions the older rocks are stronger and more deformed than the younger. For such a small area there is amazing diversity within the geology, and all ages are represented within the rocks.

The tectonic framework of Britain has evolved over two successive convergent plate boundaries and then a divergent boundary; these have annealed fragments of continental crust to create the complexity of Europe, followed by the western breakaway of the Atlantic opening and the tensile thinning of the North Sea crust. This evolution has created major contrasts in ground conditions across the country.

The old rocks of the northwest:
• huge thicknesses of rock crumpled on convergent plate boundary 400 million years old;
• have formed land subject to erosion ever since;
• now strong metamorphic rocks, intensely folded;
• accept high bearing pressures;
• yield valuable stone and aggregate resources.

The young rocks of the southeast:
• thin sediment sequences formed on the edge of subsiding North Sea basin <200 million years old;
• were mostly covered by sea until 25 million years ago;
• now weak sedimentary rocks, gently folded;
• can take only low foundation loading;
• have no good aggregate resources.

The Carboniferous rocks of the middle:
• thick sediment sequences formed on wedge of plate between two boundary disturbance zones;
• include the Coal Measures of Britain's industrial heartland, formed in equatorial delta;
• now strong sedimentary rocks, well folded;
• have very varied ground conditions;
• yield valuable rock resources of all types.

Geological evolution of Britain can be seen in time sequence of changing patterns of plate boundary processes and sedimentary environments.
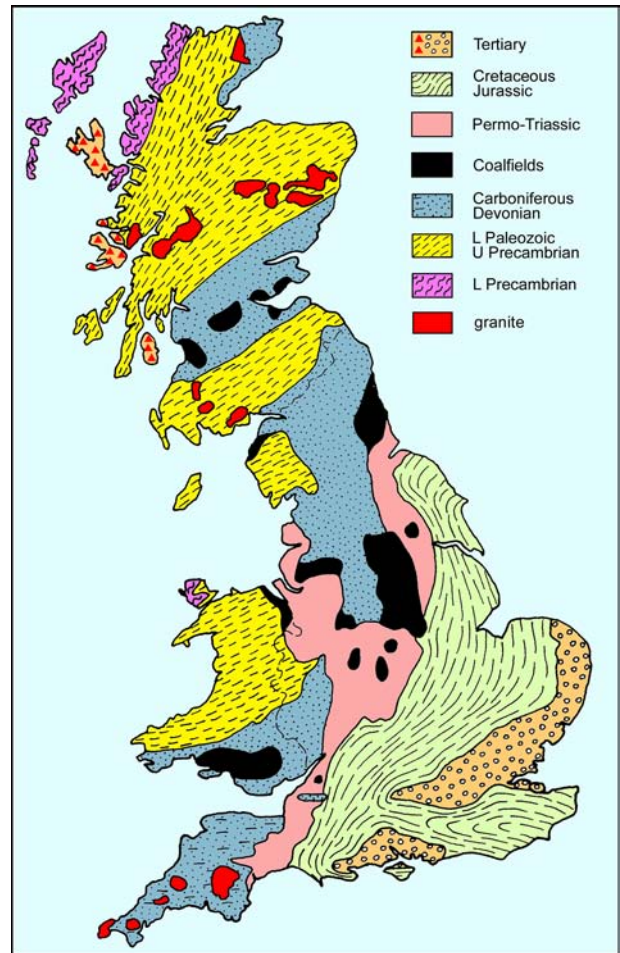
The map divides Britain into geological environments, largely related to age but primarily distinguished by the rock types and structures, which are the main concern of the ground engineer. The marked coalfields include concealed parts beneath Permian and Triassic cover.

Ireland represents a western continuation of the geology of Scotland and northern England; it is dominated by Carboniferous and older rocks, with the Antrim basalt plateau covering them in the north.

Legend (map):
- Tertiary
- Cretaceous Jurassic
- Permo-Triassic
- Coalfields
- Carboniferous Devonian
- L Paleozoic U Precambrian
- L Precambrian
- granite

Geological Evolution of Britain

| L Paleozoic 500 | Caledonian 400 | Carboniferous 330 | Hercynian 280 | Mesozoic 150 | Alpine 40 |

| 400 age in millions of years | island | fold belt | mountains | deep ocean | shallow sea | plate boundary | plate movement | river | volcano |

MAJOR ROCK UNITS OF BRITAIN	Tectonics and environment
Quaternary Unconsolidated sand and clay, alluvium and till.	Coastline as now, but land bridge to Europe in low sea levels of Ice Ages.
Tertiary Soft sediments of London and Hampshire basins. Poorly consolidated sands and clays, with London Clay 200 m thick. Also basalt lavas, volcanic centres and intrusives of western Scotland.	Gentle Alpine folding of all rocks. Deltaic sediments in bays of North Sea. Volcanoes on Atlantic divergence. Uplift forms land almost as today.

Jurassic and Cretaceous
Weak sedimentary rocks forming most of southern and eastern England.
Chalk – 200 m thick, soft limestone with flint horizons forming Downs, Chilterns.
Clays and sandstones of Weald and Midlands, with thick Oxford Clay beneath
  Fenlands, unstable Gault Clay, and Portland limestones in south.
Sandstones and ironstones of Midlands and North Yorkshire Moors.
Oolitic limestones (oolites) from Cotswolds to Lincoln Ridge.
Lias blue-grey clays with thin limestones in Midland lowlands.
	Thin sediment accumulation in
	  shallow seas over England.
	Sea forms shelf, marginal to
	  subsiding North Sea basin.
	Scotland and Wales form islands,
	  with no deposition.
	Atlantic opening starts.
	Submergence under sea.

Permian and Triassic
Red sandstones and mudstones of Midlands lowlands.
Red mudstones with beds of salt and gypsum, including Mercia Mudstone.
Yellow and red sandstones with conglomerates, including Sherwood Sandstone.
Magnesian Limestone – impure, sandy or dolomitic limestone east of Pennines.
Granites of Devon and Cornwall with associated mineralization.
	Desert sediment accumulation:
	  salt playas in low relief;
	  alluvial fans around mountains.
	Marine incursion from east.
	Magma from orogenic core.
	Hercynian folding includes
	  Pennine anticline and coal basins;

Carboniferous
Strong sedimentary rocks forming most of the high ground of Northern England,
  South Wales and Central Scotland, including all coalfield industrial areas.
Clyde Valley basalt lavas, Edinburgh volcanics, Whin Sill dolerite of Pennines.
Coal Measures – 2000 m of repetitive cyclic sequences, of sandstones,
  siltstones, mudstones, dark shales and thin coal seams (up to 2 m thick).
Millstone Grit Series – alternating sandstones (grits), shales with flagstones.
Limestone – massive limestones with cherts in S. Pennines, Wales and Mendips;
  thin bedded impure limestones and shales in Northern England and Scotland.
Slates and grits in Cornwall and Devon.
	more intense, with metamorphism,
	  towards boundary in south.
	Marginal plate boundary disturbance.
	Intermittent swamp forests
	  established on subsiding delta flats.
	Massive delta expanding from north.
	Shallow shelf seas and basins.
	Convergent plate boundary in south.
	Sediments in subducting ocean zone.

Devonian Slates, grits and limestones in Cornwall and Devon. Brown sandstones and basalt lavas of Tayside and Ochils. Red and brown sandstones and mudstones of Brecon Beacons and Orkney. Highland granites west of Aberdeen.	Marine sediments in southern ocean. Red beds in desert basins surrounded by new mountains. Melting in orogenic core. Strong metamorphism of all old rocks.

Lower Paleozoic
Mountains of Wales, Lake District and Southern Uplands; repeated greywackes
  and slates 12 km thick; include Ffestiniog slate, Wenlock limestone,
  rhyolite and andesite lavas and tuffs of Snowdon and Borrowdale Volcanics.
Dalradian schists, gneisses and marbles in southern part of Scottish Highlands.
	Caledonian folding at plate collision.
	Subduction of Iapetus Ocean plate,
	  beneath convergent boundaries,
	  with local belts of volcanics.
	Northwestern boundary more active.

Precambrian
Moine schists and gneisses forming most of Scottish Highlands.
Torridonian Sandstone of northwest Scotland.
Buried basement of England and Wales, only exposed in small inliers,
  including Charnwood, Birmingham, Long Mynd and Anglesey.
Lewisian basement gneisses of northwest Scotland and Outer Hebrides.
	Active convergent plate boundaries.
	Sand deposited on continental block.
	Old continental blocks:
	  SE block now largely buried;
	  fragment of NW block exposed.

To follow a time sequence, this table should be read from bottom to top.
Sequence of rocks is in stratigraphic order, with youngest at top.
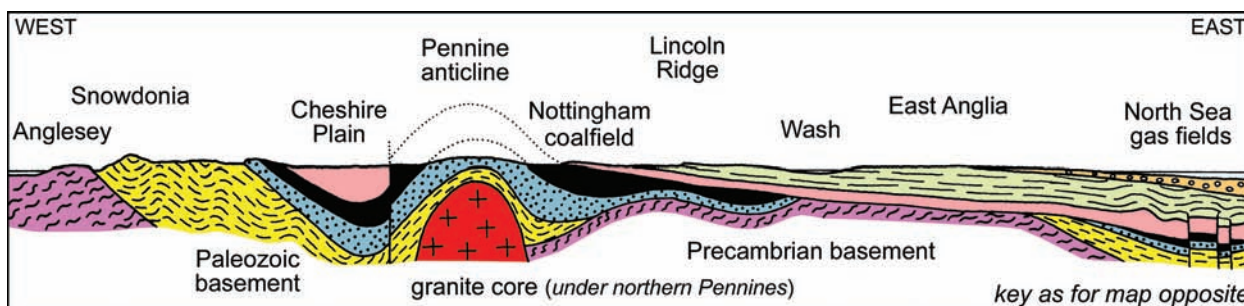
Diagrammatic section of the geology across Britain, from Anglesey to the North Sea.

12 Rocks of the United States

The USA spans an entire continent and every type of geological environment. Unlike Britain its geology cannot be viewed in a simple time sequence: at any one time, plate boundary activity on one side could be distant enough to leave the other side unaffected.

Over such a large area, age alone is meaningless for describing ground conditions; igneous and metamorphic rocks in the west are far younger than weak, barely folded, sedimentary rocks in the east.

It is sensible to divide the USA into geological provinces, each with its own character and geological history, distinguished from its neighbours by both the types and structures of its rocks.

Coast Ranges

Complex series of deformed rocks along the active plate boundary of the west coast. In California the highly folded, Mesozoic and Tertiary, Franciscan greywackes and schists include a slice adjacent to the Sierra Nevada containing the gold mineralization of the 1849 rush.

Faults include the very active San Andreas zone with its associated earthquakes, and break the ranges into fault blocks further south. In the Los Angeles area, basins have up to 5 km of oil-bearing Tertiary sediments between older mountain blocks. The Peninsular Ranges have granite intruded into the metamorphic rocks.

Further north, the Klamath Mountains are fault slices of Paleozoic sedimentary, metamorphic and igneous rocks, followed by Tertiary basalts along the Oregon coast, and Tertiary granites and schists forming the Olympic Mountains.

Central Valley of California

Faulted basin containing Mesozoic sedimentary rocks 12 km thick. Surface has up to 400 m of poorly consolidated Quaternary sands, silts and clays causing widespread subsidence problems.

The North American continent has a core of strong Precambrian basement rocks: these form the Laurentian shield of Canada, and underlie the Great Plains and Central Lowlands where thin sedimentary cover rocks were deposited when shallow seas lapped onto the basement core.

Thick sedimentary rock sequences were crumpled and metamorphosed along plate boundaries and welded onto both sides of the core: the older Appalachia on the east, and the younger Rockies and Cordillera on the west. The active western plate boundary has been complicated by the continental slab obliquely overriding the rising convection plume of the East Pacific rise, creating the tension in the Basin and Range province and adding to the volcanic activity.

Cascades

Chain of Tertiary and modern volcanoes above the active subduction zone of the convergent plate boundary. These include Lassen and St Helens with their major explosive eruptions in the last 100 years. Mainly andesite and rhyolite lavas, with locally thick pyroclastics and some basalts.

Columbia Plateau

Volcanic province dominated by horizontal Tertiary flood basalts. Eastern extension has younger Snake River Pleistocene basalts, reaching to more varied pyroclastics and lavas of the Yellowstone volcanic centre with its continuing geothermal activity.

Idaho Batholith

Strong, massive, Cretaceous granite forming the largest batholith in the Rockies.

Sierra Nevada

Cretaceous batholith of massive, strong granite, with glacial features on much of the high ground.
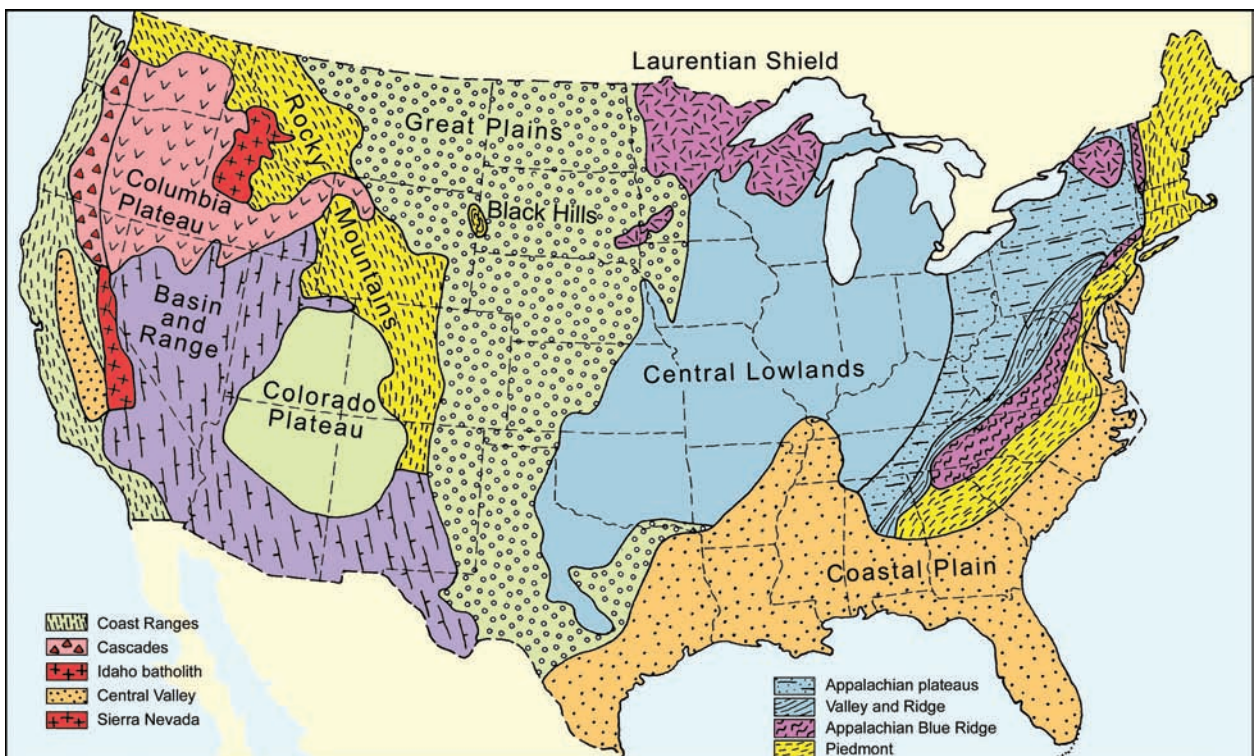
Alaska
Essentially an extension of all the units and provinces in the Western Cordillera. Interior mountain chains of folded Paleozoic rocks, older metamorphics and younger intrusions separate basins with thick sedimentary sequences. Coast ranges consist of younger metamorphics along with active volcanoes and faults (which produce earthquakes).

Hawaii
Islands are tops of huge, ocean-floor volcanoes formed in a chain where Pacific plate is moving northwest over a mantle hot spot. Rocks are nearly all basalt, with minor tuffs, alluvium and reef limestones; volcanoes are now active only on Hawaii Island.

Laurentian Shield

Southern tip of the exposed Precambrian basement which forms much of eastern Canada. Complex of strong, deformed rocks, dominated by greenstones, slates, greywackes, gneisses and granites, with an extensive cover of Pleistocene till. Includes an exposed inlier in South Dakota and the Adirondaks of New York.

Great Plains

Flat lying Mesozoic and Tertiary rocks on a Precambrian basement. Mainly shales and weak sandstones, with some coal basins and localized volcanics. Include the clays of the Badlands and the Cretaceous limestones of the Edwards Plateau. Pleistocene sands, clays and loess in the south and centre are widespread, but are replaced by glacial till in the north.

Appalachian Plateaus

Strong sandstones, shales and limestones, mostly of Upper Paleozoic age. Gently folded with low to moderate dips. Valuable coal seams in the Pennsylvanian Coal Measures are extensively mined in all of the province except New York state.

Valley and Ridge

Strongly folded Paleozoic rocks in a sequence 18 km thick. Long, steep, escarpment ridges of strong sandstone and limestone separate parallel valleys in softer shales and Coal Measure rocks.

Appalachian Blue Ridge

High-grade metamorphic Precambrian basement rocks overthrust onto younger rocks to the west. Mainly gneisses, but with thick greenstones in Shenandoah Mountains and strong metamorphosed sandstones in the Great Smokies. Includes extensions of gneisses north of New York and into Vermont.

Piedmont

Eastern flanks and foot slopes of the Appalachians, formed mostly of strongly deformed Paleozoic slates and greywackes, with igneous intrusions in the Carolinas. More highly metamorphosed rocks include the Manhattan gneiss and more extensive schist belts. Province includes New England with less metamorphosed rocks and a number of granites. Pleistocene sediments and glacial tills form Cape Cod and much of Long Island.

Black Hills

Anticlinal inlier with Mississippian limestones around a core of schists intruded by the granite of Mt Rushmore.
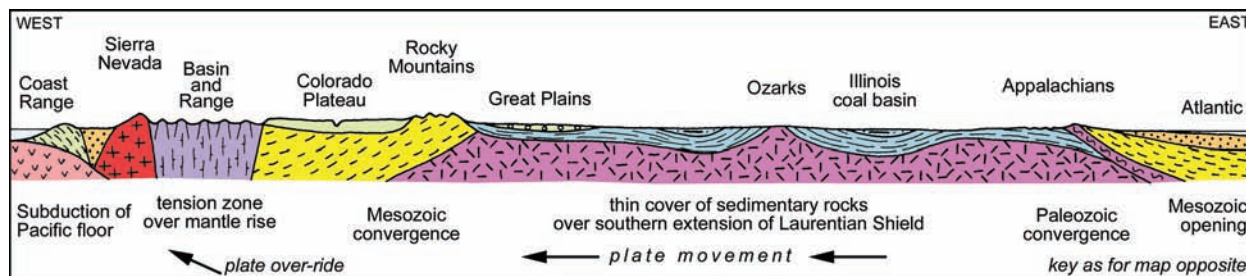
Diagrammatic section of the large-scale geology across the North American continent.

Rocky Mountains

Precambrian and Paleozoic metamorphics forming the old core of the Cordillera. Generally strong rocks include gneiss, schist, greenstone and marble, mostly well folded, with various younger intrusives and volcanics. Basins in Wyoming contain thick Tertiary sedimentary rocks with coal and oil shale.

Basin and Range

Vast province of fault blocks broken by east-west tension within the crust. Up-faulted ranges of strong igneous and metamorphic rocks of Precambrian to Mesozoic age, and also the Permian limestones of the Guadalupe Mountains. Down-faulted basins contain weaker Tertiary and Quaternary clastic sediments, along with the salt sequences of the Great Basin, Death Valley and elsewhere, and some volcanics along fault zones.

Colorado Plateau

Flat lying, Carboniferous to Tertiary, sedimentary rocks, overlying basement schists that are exposed in the Grand Canyon. Includes the strong red sandstones of Canyonlands and national parks, soft limestones at Bryce Canyon, scattered basalt volcanics, and some shallow coal basins.

Central Lowlands

Paleozoic sedimentary rocks gently folded into broad basins and domes. Limestones of the Ozarks form the largest dome, with an exposed core of Precambrian gneiss, and also contain extensive mineral deposits. Further east, strong Mississippian limestones form extensive plateaus. Pennsylvanian Coal Measures, dominated by shales, siltstones and strong sandstones, are up to 5 km thick in the main coal basins west of the Ozarks, across Illinois and in Michigan. Extensive Pleistocene cover of glacial till in the north, and loess in the southwest.

Coastal Plain

Poorly consolidated Tertiary clastic sediments provide no hard rock resources. Widespread subsidence problems occur on extensive soft clays, on some large areas of peat, and over the Tertiary limestones forming much of Florida. Mesozoic sedimentary rocks crop out along the Appalachian margin and thicken towards the coasts beneath a Tertiary cover. Beneath the Gulf Coast, sediments up to 6 km thick contain salt domes and major oilfields, together with extensive resources of lignite (brown coal) in Texas. Younger deltaic sands, clays and peats fill the Mississippi basin.

27

Surface Processes

Spheroidal weathering of granite that was beneath soil, California.

Waterfall retreat that has left Niagara Falls at the head of a gorge.

Collapse of a California marine arch that has left a sea stack.

Glacier retreat that has left moraines around a frozen lake, Nepal.

Dry salt flat with crystal growth along desiccation cracks, Bolivia.

Flood damage left after Hurricane Katrina hit New Orleans.

Barchan sand dunes, migrating towards the left, Egypt.

Gabion wall protecting a road from river erosion in Scotland.

Houses under water on the active floodplain through York.

Waves breaking onto coastal defences, Sidmouth, Devon.

Pleistocene glacial striae on gneiss in Central Park, New York.

Converging glaciers with lateral and medial moraines, Alaska.

Gully erosion of shale slope below sandstone plateau, Colorado.

Oil pipeline on refrigerated piles across permafrost, Alaska.

Shingle spit across mouth of the River Axe at Seaton, Devon.

Very large cave passage in Brazil.

Braided river on floodplain, Zanskar, India.

Fluvial slot canyon in sandstone, Utah.

13 Weathering and Soils

GROUND CONDITIONS

Top few metres of the ground profile generally consist of soil, drift and weathered rock, with engineering properties very different from those of the underlying bedrock.

Soil: mixture of weathered mineral debris and plant material, usually <1 m thick; may divide into plant-rich topsoil and clay-rich subsoil.

Weathering: the natural decay and breakdown of rock, or drift, that is in contact with air and water; generally to depths of less than 10 m.

Drift: transported, superficial sediment deposited on top of the bedrock; mostly unconsolidated clay, sand and coarser clastic debris; generally Quaternary age, hence too young to be consolidated; varies in total thickness from 0 to >50 m.

Colluvium: slope debris, moved downslope largely by gravity alone; so relative extent of sediment transport is drift > colluvium > soil; it includes debris from creep and sheetwash, also head and scree. Sheetwash by surface water increases greatly with loss of vegetation.

Rockhead: the buried drift/rock interface; commonly a conspicuous boundary between weak soils and drift and the underlying strong rock; may be less well defined in deep profile of weathered rock; formed as erosion surface before drift deposition so its topography may be totally unrelated to modern surface.

Engineering soil: weak material (UCS <600 kPa) that can be excavated without ripping or blasting, therefore including soil, drift, weak rocks and weathered rocks.

Variable ground conditions
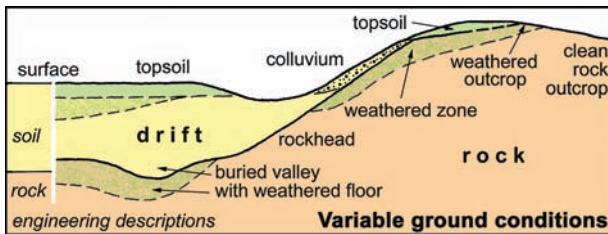
ROCK WEATHERING

Physical and chemical breakdown of rocks at or near the surface. Subsequent removal causes surface lowering:

• Weathering + Transport = Erosion •

Weathering processes depend on contact with air and/or water, so are strongly influenced by climate.

- Frost shattering is important in cooler latitudes and at higher altitudes.
- Salt crystallization is only significant in deserts with high evaporation.
- All chemical processes accelerate in hot wet climates, and are further increased by organic acids from dense plant cover.
- The most important chemical process is the production of clay minerals from other silicates.
- Temperate weathering produces illite as the dominant clay mineral.
- Hot wet weathering of igneous rocks produces the unstable smectite.
- Laterite: red soil, high iron and aluminium, low silica, formed in tropics.
- Saprolite: totally decomposed rock retaining ghosts of original structure.
- Spheroidal weathering: forms rounded boulders or corestones from angular joint blocks weathered more at edges and corners.

DEPTH OF WEATHERING

Scale and depth of weathering depends on the time scale, the rock type and the present and past climates.

Rocks only exposed for 10,000 years (i.e. since last glaciation) are less deeply weathered than those exposed for a million years in unglaciated areas.

Shales, porous sandstones and weak limestones weather to greater depths than do granites and compact metamorphic rocks.

Deepest weathering occurs in regions of climatic extremes, either with periglacial frost action or beneath equatorial rainforest.

Top of zone II is effectively rockhead, but is not sharply defined; it is usually about 1–5 m deep in Britain; but zone I fresh rock may only be found at depths >20 m in quarries that demand the best quality of rock.

In tropical areas, soils of zone IV may reach depths of 5–20 m. Decomposed granite of weathering grade III commonly reaches >30 m deep in Hong Kong.
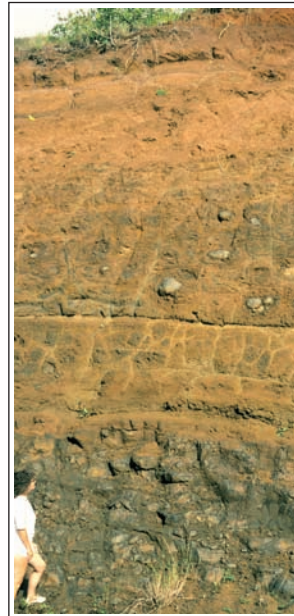
This road cutting in Hawaii shows an almost complete weathering sequence in basalt lavas.

Grade III material is not seen in this sequence, because a change of rock type is more significant than the weathering state – a layer of weak, rubbly, scoriaceous lava has weathered much more completely than the solid lava above it.

Grade I fresh rock only occurs at greater depths, below this cut face. For engineering purposes, sound rock is found near the top of zone II, about 4m below the surface at this site.

Physical Weathering

Unloading joints:	stress relief fractures, due to overburden removal.
Thermal expansion:	fracturing, due to daily temperature changes.
Frost shatter:	fracturing, as fissure water or porewater freezes and expands.
Wetting and drying:	movement, due to loss or gain of water in clays.
Root action:	tree root expansion in fissures, and rootlet growth in pores.
Crystallization:	growth of salt crystals, where groundwater evaporates.

Chemical Weathering

Solution:	mainly of calcite and gypsum, in sandstone cement, veins and limestone.
Leaching:	selective removal of solutes or specific elements.
Oxidation:	notably rusting and breakdown of iron.
Hydrolosis:	most silicates react with water to form clay minerals.

ENGINEERING CLASSIFICATION OF WEATHERED ROCK

Grade	Description	Lithology	Excavation	Foundations
VI	Soil	Some organic content, no original structure	May need to save and re-use	Unsuitable
V	Completely weathered	Decomposed soil, some remnant structure	Scrape	Assess by soil testing
IV	Highly weathered	Partly changed to soil, soil > rock	Scrape *nb* corestones	Variable and unreliable
III	Moderately weathered	Partly changed to soil, rock > soil	Rip	Good for most small structures
II	Slightly weathered	Increased fractures, and mineral staining	Blast	Good for anything except large dams
I	Fresh rock	Clean rock	Blast	Sound

(More complex schemes, for description of non-uniform and mixed rock masses, are given in BS 5930.)

WEATHERING GRADE AND ROCK PROPERTIES

Some representative values for selected materials to demonstrate physical changes in weathered rock

Grade of weathering		I	II	III	IV	V
Granite: unconfined compressive strength	MPa	250	150	5–100	2–15	<1
Triassic sandstone: unconfined compressive strength	MPa	30	15	5	2	0
Carboniferous sandstone: rock quality designation	%	80	70	50	20	<15
Chalk: standard penetration test	N value	>35	30	22	17	75
Chalk: safe bearing pressure	kPa	1000	750	400	200	
Triassic mudstone: safe bearing pressure	kPa	400	250	150	50	
Triassic mudstone: clay particle fraction	%	10–35		10–35	30–50	
Typical depth in Britain	metres		5–30	1–5	1–2	

WEATHERING PROFILES IN ROCK
Jointed Igneous   Bedded Sedimentary
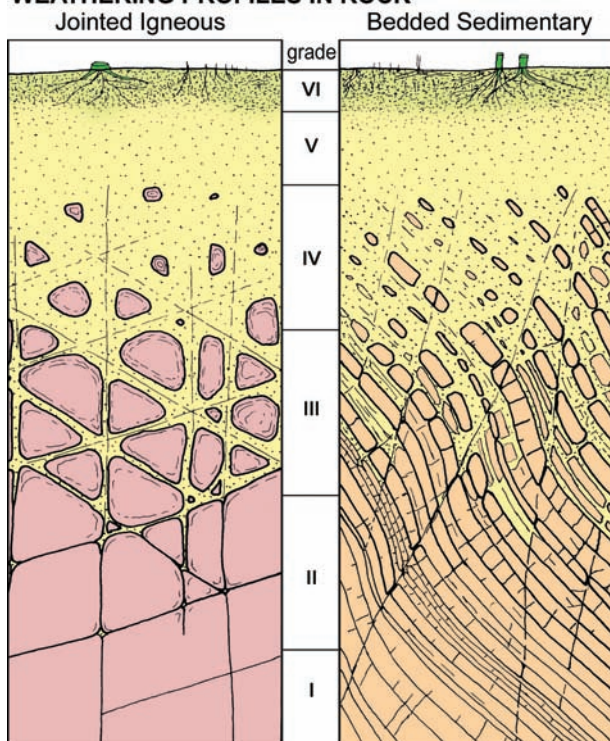
WEATHERING OF LIMESTONE

Limestone is unique because it is a physically strong rock that can be totally removed by natural dissolution during weathering.

Rainwater and soil water weather the limestone surface, and also dissolve away the rock where they seep down fractures and bedding planes, thereby creating wider fissures and caves.

This process forms very uneven ground with strong rock between large voids.

Pinnacled rockhead has deep fissures, mostly filled with soil, between weathered limestone pinnacles, all beneath soil or drift cover; it creates difficult foundation conditions prone to sinkhole subsidence (*section 29*). Limestone pavements with large flat rock surfaces are the result of recent glacial scouring which removed the weathered and dissected surface rock.

Karst is a landscape, normally on limestone, that is characterized by underground drainage, caves, sinkholes, dry valleys, thin soils and bare rock outcrops.
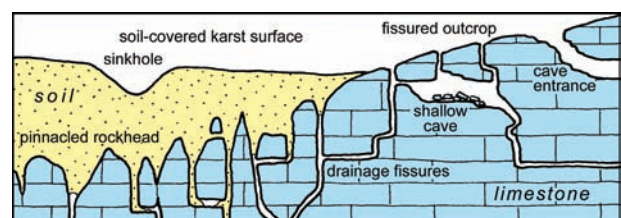
DRIFT DEPOSITS AND CLIMATE

The nature, extent, structure and properties of drift deposits are closely related to the processes by which they were deposited.

These deposition processes are, or were, determined largely by climate.

Fluvial processes – the action of rivers and flowing water – are dominant in all climatic regimes except for the permanently frozen zone beneath glaciers and the very arid zones in deserts.

Ice Ages: During the Quaternary, the Pleistocene period was marked by phases of world-wide cooling – the Ice Ages – when ice sheets covered large parts of the northern continents, and climates were severely modified across the rest of the world. The last ice sheets retreated only about 10,000 years ago.

Many drift deposits were formed in environments very different from those of today. They are therefore best understood by distinguishing them on the basis of process and climate.

31

14 Floodplains and Alluvium

WATER EROSION

Water is the main agent of erosion; its power increases greatly with velocity.

Rivers erode by downcutting, and sides degrade to form valleys with V profiles.

On low gradients, downcutting reduces, so lateral erosion dominates, notably on the outside of river bends.

Sediment is transported as rolled bed-load and in suspension; particle size increases with velocity.

Deposition is due to velocity loss, on gradient loss and inside bends, so sediment is sorted by size.
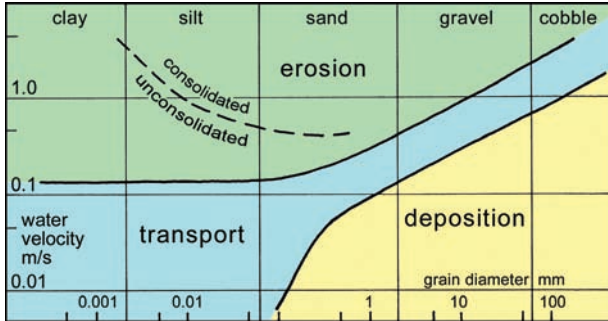
ALLUVIAL DEPOSITS

Alluvium: river-deposited sediment; sorted and bedded, but any grain size from clay to boulders; laterally and vertically variable, with wide range of engineering properties.

Floodplain: zone of alluvial deposition along valley floor, subject to periodic flooding. The alluvium builds up over time, much of it formed as over-bank flood deposits, which are mostly fine grained and horizontally bedded.

Meander scrolls: cross-bedded, crescentic lenses of sediment, mostly sand or gravel, left on insides of migrating river bends or meanders.

Channel fills: abandoned river channels filled with sediment, commonly clay or peat.

Alluvial fans: coarser, poorly sorted sediment (including fanglomerate) on steeper slopes and at mouths of hillside gullies and tributary streams.

River terraces: remnants of any older, higher floodplains, abandoned when river cut to lower level; formed of alluvium, though may be rock-cored; eroded away as modern floodplain enlarges.

Tufa and **travertine**: weak, porous calcite deposit, forming thin layer or cementing a gravel; may overlie uncemented alluvium and can be confused with rockhead. Les Cheurfas dam, Algeria, was built in 1885 on tufa crust, and failed by piping on first impoundment.

Peat: black organic soil, formed in small lenses or large areas of upland bog or lowland fen; extremely weak and compressible (*section 27*).

Lake deposits: similar to fine alluvium (*section 15*).
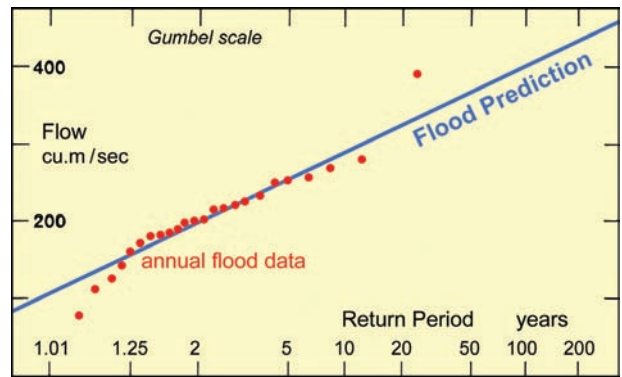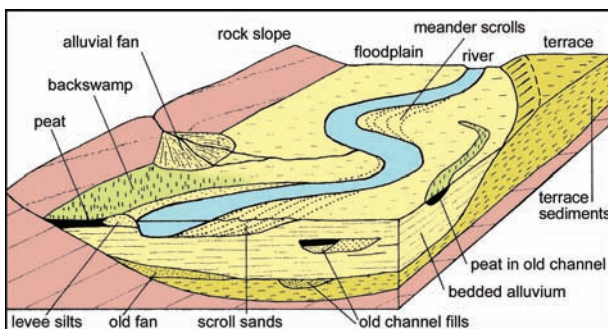
FLOODPLAINS

Maximum annual flood flows on a river over 24 years; return period = (number of records −1) / (rank).

Flooding is natural and inevitable on floodplains.

Flood size (expressed as flow, stage, height or area) is described by its statistical return period, e.g. a 50 year flood, which has 2% chance of occurring in any year.

From existing data, plot of flow against return time (based on rank) gives straight line (often except for the highest flood), which allows predictions of rarer events; so flood zones can be identified and avoided, and channel sizes can be designed.

Floodplain hydrology may be changed unintentionally; urbanization, deforestation and levee construction all raise height of flood peaks.
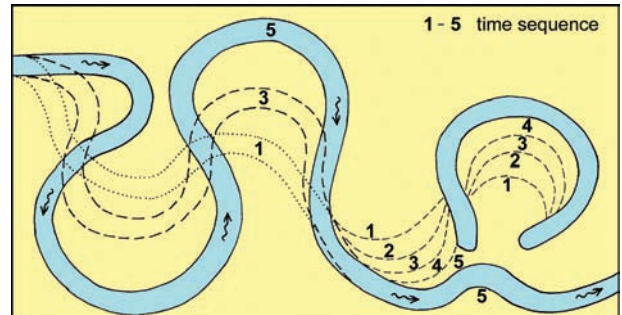
Development of river meanders.

CONSTRUCTION ON ALLUVIUM

Alluvium thickness may vary 1–>100 m; difficult to predict but generally compatible with local hill relief.

Some alluvium is laterally uniform. Other has channel fills, scrolls and fans, making site investigation and borehole correlation difficult.

Non-cohesive sand alluvium has SBP = 100–600 kPa, depending on density; quick or running sands form with high water pressures or seepage flows in loose material.

Cohesive clay alluvium generally has SBP = 0–200 kPa, depending largely on consolidation history (*section 26*).

Bearing capacity of unconsolidated alluvium can normally be increased by effective drainage and consequent accelerated consolidation.

> **Heavy structures on soft alluvium** may require end-bearing piles to rockhead, or friction piles in thicker sequences. Each phase of Yorkshire's Drax power station required over 12,000 end-bearing, pre-cast concrete piles, each 22 m long, driven through clay and silt alluvium and into sandstone bedrock or a dense alluvial sand just above rockhead.

Caption labels: protective wall, scour through bridge, wing walls, sediment bar with channels, → main flow, ∵ deposition

FLOOD CONTROL MEASURES

Levees are linear ridges alongside river channels.

Natural levees are formed by bank overflow and rapid deposition, and may build up to channel a river at a level above the main floodplain; China's Yellow River is 6 m above its floodplain for over 500 km.

Artificial levees are earth (or concrete faced) embankments built to prevent floodplain inundation. They must be continuous – roads must go over them or through floodgates; the Mississippi levees are 10 m high and more than 1000 km long.

Canalization can shorten a river course, creating a new steeper gradient to transmit flood peaks more effectively. Levees and canals prevent a river flooding its natural floodplain, and so artificially increase flood peaks downstream. Flood control dams can capture floodwater and act as a substitute for lost floodplain storage.

Floodways are zones of undeveloped land between levees designed to transmit floodwater when required.

CONSTRUCTION ON FLOODPLAINS

Protection by levees permits wider use of floodplains.

On undefended floodplains, construction is normally avoided inside the 100 year flood zone (in Britain, the 1947 flood limit provides a useful guideline) – but flood frequencies will change with any global warming.

The flood of 1972 in Rapid City, South Dakota, cost 237 lives; all the destroyed buildings were on the floodplain, recognizable on existing maps as the area of alluvium; reconstruction has left the floodplain as a park.

Encroachment is construction on the floodplain which hinders flood flows; it causes upstream ponding, and increased flows and scour round the structures, which are therefore self-destructive and must be avoided.

Parkland and buildings with unenclosed ground floor carparks do not encroach, and are acceptable on active floodplains and in floodways.

Transport routes need to cross floodplains; bridges must have extra flood arches to avoid encroachment; flat bridges with no parapets can survive overflooding with no damage and only short-term loss of use.
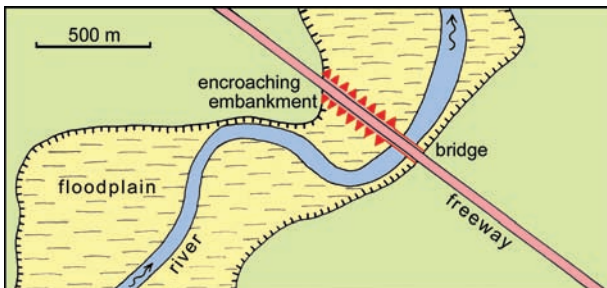
Freeway bridge over Schoharie Creek, New York, failed in 1987; approach embankment had encroached on floodplain and thereby increased flood flow beneath bridge, so extra scour undermined pad foundations on gravel.

RIVER CHANNEL ENGINEERING

The natural processes of river flow include:
 • Erosion on the outside of bends;
 • Channel migration due to bend erosion;
 • Bed scour between encroaching bridge piers;
 • Sediment deposition in slack water, notably inside bends and downstream of obstacles;
 • Catastrophic channel re-routing across floodplains, during rare flood events that overtop levees.

Bank erosion may exceed 1 m per year, and protection may be essential, using walls of concrete or gabions (loose rock in wire baskets), and wing dams to trap sediment.

Repeated dredging may be needed to counter mid-channel deposition, notably on oblique bars.

Mississippi River has continuous levees to protect New Orleans and other cities. Floodway sluices can be opened to take flood peaks that threaten to overtop the levees. The 1993 flood overtopped the 100 year levees. Since then, more farmland has been left unprotected – a limit to sustainable economic floodplain development is now recognized. River levees were not overtopped in 2005, when the flooding of New Orleans was by seawater surge caused by Hurricane Katrina.
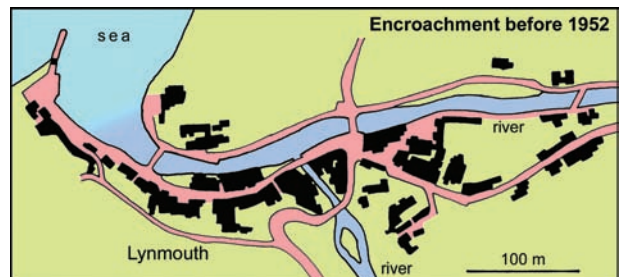
Lynmouth, Devon, flood disaster in 1952 was due to encroachment by bridges and buildings that diverted floodwater down the streets and through the village. New larger channel has longer bridges and floodway park.

33

15 Glacial Deposits

Pleistocene Ice Ages

Ice Ages were created by a series of phases of worldwide cooling, when average temperatures fell 8°C.

In each Ice Age, the largest ice sheets centred over Canada (reaching into USA) and Scandinavia (extending over most of Britain). Smaller ice caps formed on most high mountain ranges. Glaciated landforms and deposits still remain over these very large areas.

Last Ice Age ended about 15,000 years ago; known as Promit Devensian in Britain and Wisconsin in USA; features dominate mountain landscapes today, and it left extensive deposits on glaciated lowlands.

Earlier Ice Ages had ice sheets more extensive than during the last Ice Age, leaving lowland deposits in parts of Britain and USA.

marked coastlines are today's, they expanded greatly when water was held in ice sheets and sea levels were lower; floating sea ice not shown

North Pole

Maximum extent of Pleistocene ice sheets
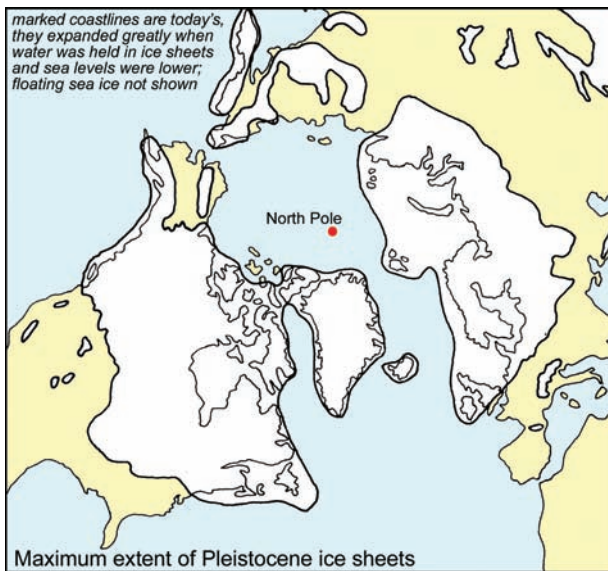
GLACIAL EROSION

Glaciers form where winter snowfall exceeds summer melt; snow layers accumulate, compressed lower zones recrystallize and these are squeezed out as flowing ice.

Erosion is largely by entrained rock debris scraped over the surface, locally leaving glacial striae (scratches).

Most glaciers move about a metre per day.

Pleistocene glaciated areas are most easily recognized by erosional landforms.

Alpine glaciation: valley glaciers in mountain areas of high relief; ice further deepens U-shape valleys between high uneroded arête ridges.

Sheet glaciation: thick ice moves over entire landscape; greater erosion of high ground reduces relief; ice can erode while moving uphill, to create irregular topography with over-deepened rock basins.

GLACIOFLUVIAL DEPOSITS

Meltwater occurs on, in, beneath and downstream of all glaciers; it erodes transports and deposits various types of glaciofluvial sediments.

Sediment is mostly sand and gravel, with moderate sorting and bedding; fines have generally been washed out; commonly non-cohesive and highly permeable, with good bearing capacity and low settlement.

Outwash: tracts of alluvial sand and gravel deposited by meltwater downstream of glacier snouts.

Kames and **eskers:** hills and ridges that were sediment fills in glacier caves; may be buried inside till.

Glaciofluvial sediments are also known as stratified till, or glacial sand and gravel.

Maximum extent of Pleistocene ice sheets over the British Isles

marked coastlines are today's, they expanded greatly when water was held in ice sheets and sea levels were lower; England was joined to France

Devensian glaciation

earlier glaciation

not glaciated (periglacial)
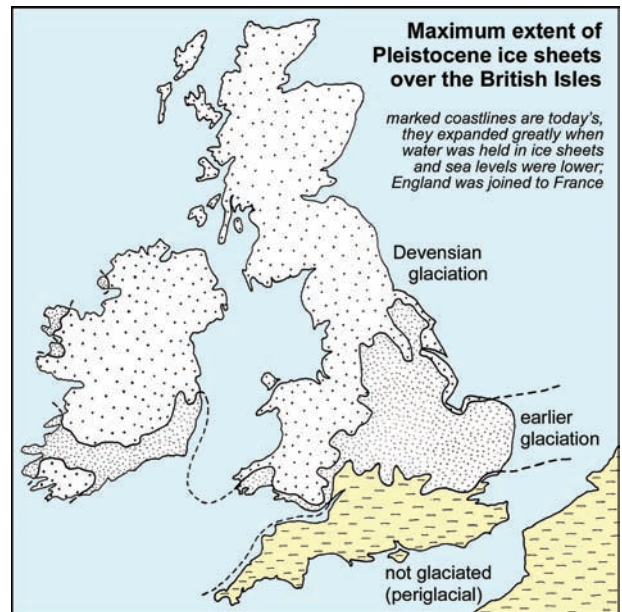
Ice Ages had other far-reaching effects.

Periglacial conditions extended over large areas, including all of southern Britain and the USA as far south as Oregon, Wyoming and Tennessee.

World sea levels fell 150 m as water was locked in ice sheets; Britain was joined to France, Alaska to Siberia. Weight of ice caused crustal sag beneath ice-sheets, followed by slow isostatic uplift after ice melted.

GLACIAL DEPOSITION

Debris of all sizes is picked up and transported by glaciers, and then dumped at glacier edges, along their bases, or mostly in terminal melt zones.

Till or **boulder clay**: general terms for glacial debris.

Moraines: morphological units of glacial till – layers, mounds, ridges or any shape of deposit that is on, or was left behind by, a glacier.

Sheet moraines: extensive till blankets of variable thickness; typically hummocky surfaces may be streamlined into drumlin landscapes.

Valley moraines: till ridges along or across glaciers or left behind in glaciated valleys:
- lateral moraines: along glacier edges, fed by debris from higher slopes;
- medial moraines: coalesced lateral moraines where glaciers converge (not so common);
- terminal, end or retreat moraines: till banks across valleys where ice melting reaches maximum at the glacier snouts; a sequence may be left up a valley by a glacier retreating irregularly.

Sediments within a glaciated valley

tributary valley

medial moraine

outwash   esker   retreat moraine

terminal moraine   post-glacial trench   lateral moraine   rock floor

post-glacial alluvium   sheet moraine   lake sediments   modern river
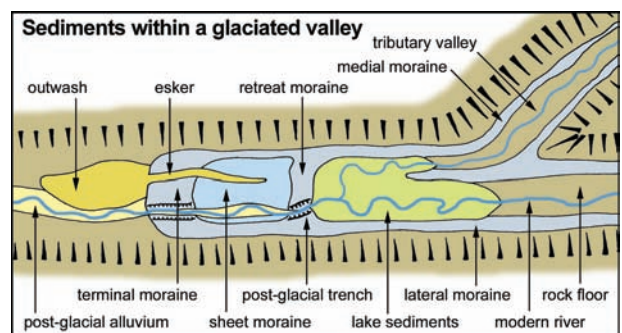
BURIED TOPOGRAPHY

Rockhead relief: features of an eroded landscape that are buried beneath drift.

Burial is consequence of deposition after erosion – common with Pleistocene climatic changes.

Topography of old buried landscape (rockhead) may not relate to modern landscape.

Depth to rockhead may be variable and irregular; greatest and least predictable under post-glacial drift in over-deepened glaciated valleys and where subglacial meltwater channels entrenched bedrock beneath ice.

Buried valleys have drift of locally greater or unknown thickness, causing added costs and potential hazard for foundations designed to bear on rockhead. May lie beneath, or be unrelated to, modern valleys. Irregular subglacial channels in rockhead commonly have very steep sides; often known as tunnel valleys.

GLACIAL TILL

Till is unsorted and unstratified glacial sediment consisting of a mixture of any or all of clay, silt, sand, gravel, cobbles and boulders.

Composition relates to the rocks which were eroded by glacier before deposition.

Also known as boulder clay, but this term can be misleading as a till with a sandy matrix may have no clay component.

- Lodgement till: carried and deposited at base of ice; generally over-consolidated by overriding glacier, and with clay content of 10–40%.
- Ablation till: deposited as ice melted from beneath it; poorly consolidated, commonly with clay content of <10%, as fines removed by meltwater.

All till may be locally variable, with lenses or zones of soft clay, running sand or large boulders. Terminal moraines may be structurally complex where glacial readvance has pushed till into ridges.

Bearing capacity may vary from 400 kPa for old, stiff lodgement till to <100 kPa for ablation till.

Compressibility is generally low except for clay-rich ablation till.

- Excavation costs on St Lawrence Seaway, on USA-Canada border, doubled when dense lodgement till was found instead of loose ablation till (which was at outcrop and wrongly expected at depth).

Temporary cut faces may be vertical in cohesive lodgement till, but need support in sandy ablation till.

Permeability is generally low but variable, related to matrix. Eigiau Dam in North Wales failed in 1925 due to piping through a sandy zone in foundation till.

Erratics: isolated large boulders; may exceed 10 m diameter; may be confused with rockhead in site investigation. Test bores for Silent Valley Reservoir, Ireland, stopped at rock at –15 m, but all had hit erratics; rockhead was –60 m. Driven piles and sheet piling cannot be used in till with erratics.

Glacial till in a Derbyshire quarry.

LÖTSCHBERG TUNNEL DISASTER, 1908

Swiss tunnel heading drove through rockhead into saturated gravels 185 m below valley floor, after false assumption of sediment depth. No allowance had been made for any reverse gradient on rock floor of glaciated valley beneath alluvial fill. In reality, prediction of rock profile was impossible without boreholes. Horizontal probes ahead of tunnel face would have given warning. Inrush of water and gravel killed 25 men; tunnel was re-routed to avoid buried valley. (The 2007 base tunnel is in sound rock 400 m below the old tunnel.)
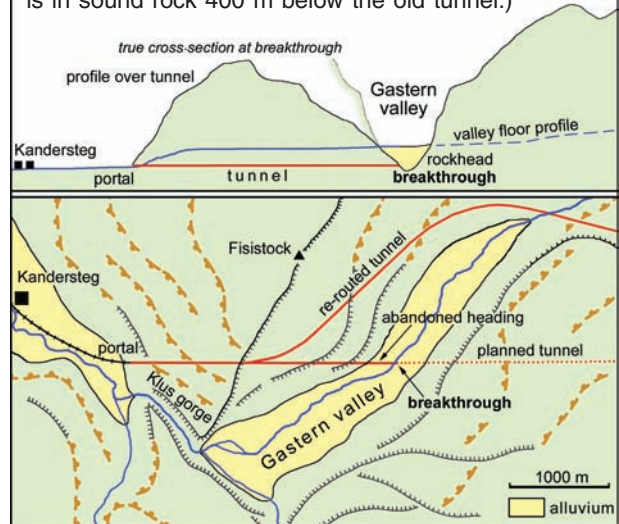
KNOCKSHINNOCH MINE DISASTER, 1950

Scottish mine heading broke through rockhead into glacial till beneath hollow filled with saturated peat on hummocky sheet moraine. Piping failure of till allowed peat inrush to mine, leaving surface sinkhole 100 m across. Flat area on ground profile indicated some sort of fill – and potentially a hazard; should have been checked before heading was advanced to rockhead.
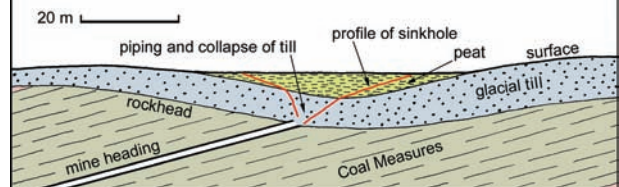
LAKE SEDIMENTS

Most lakes are created by glacial processes – damming behind terminal moraines, or post-glacial flooding of ice-scoured rock basins, over-deepened glaciated valleys and hollows on sheet moraines.

Lakes of English Lake District are in glaciated valleys with end moraines. Great Lakes of America are in ice scoured basins, partly dammed by moraines and ponded by post-glacial isostatic uplift of outlets.

Rivers destroy lakes – by sediment infill and through draining by erosional lowering of outlet. Thousands of lakes left at end of Pleistocene have since been filled and/or drained, leaving areas of lake sediments.

Lake (lacustrine) sediments are like alluvium with more silts and clays, and less gravels, so commonly have lower bearing capacity with higher settlements. Often recognize lake sediments by flat ground.

Small ponds in sheet moraine were commonly filled with mosses to form peat.

Sensitive clays were deposited in inland seas along Pleistocene ice margins in Scandinavia and eastern Canada (*section 34*).

35

16 Climatic Variants

Semi-Arid Environments

Deserts have low rainfall, less than potential evaporation; may be hot or cold. With little surface water, wind erosion and transport are effective, but periodic water erosion is still dominant process, except in rare, totally arid deserts.
Wadis, or arroyos, are desert valleys, normally dry but subject to flash floods from isolated rainstorms.
Roads across wadi floors that only rarely flood can be designed to be over-flooded; reinforced concrete or gabions are essential on downstream side, where scour and undercutting are most destructive.
Selective erosion is by slow weathering, wind transport and rare flood events; leaves residual inselberg mountains, flat-topped mesas and pillar buttes in bedded rocks, and natural arches where weathering breaches thin rock ribs.

Desert landforms: wadi, arch, mesa, butte, inselberg
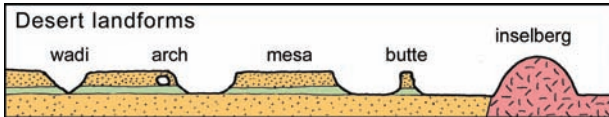
Desertification is slow loss of vegetation and expansion of desert, as in African Sahel. Due to any or all of climate change, deforestation, over-cropping, over-grazing, and soil salt increase by evaporation of irrigation water.

DESERT SEDIMENTS

Alluvial fans: banks of flood sediment and debris flows from mountain wadis. May coalesce into bajada, forming the mountain footslope with a sediment apron over a sloping bedrock pediment. Sediments are deposited rapidly, so are unsorted and poorly consolidated.
Alluvial plains: extensive lower reaches of fans; mainly sand and gravel in shallow, braided wadi channels; coarse cobble beds remain from wet Pleistocene climates.
Playas: flat floors of inland basins with fine, soft, weak silts and clays, often thixotropic. Salt and gypsum form in temporary evaporating lakes.
Sabkha: similar, but with limestones, in coastal zones.
Salt: may form thick beds in playas and sabkhas; also left by evaporation in clastic sediments. Capillary rise in fine soils may lift salt 3 m above water table, into roads and built structures. Salt crystal growth is major form of desert weathering of rocks and concrete. Impermeable dense concrete suffers less from salt breakdown.
Duricrusts: surface layers of cemented sediment, mostly sand or gravel; mineral cement deposited by evaporating groundwater. Most common duricrust is calcrete, or caliche, cemented by calcite, about 1 m thick, over unconsolidated sediment; should not be confused with rockhead as bearing capacity is low.
Loess: structureless, yellowish, calcareous silt, of grain size 0·02–0.06 mm, common in interiors of the northern continents; much was derived by wind deflation from Pleistocene glacial outwash plains. Dry or moist loess will stand in a vertical face; but it is easily gullied and piped by running water, and it disaggregates and collapses on saturation – hydrocompaction (*section 27*).

BLOWN SAND

Wind moves dry sand by sliding, rolling or bouncing (saltation). Sand abrasion undercuts rocks and structures close to ground level. Deflation removes sand, leaving desert pavements of polished pebbles.
Dunes are built by deposition in slack air, in eddies and in the lee of obstacles; they may be longitudinal (seif) or transverse to prevailing wind, irregular in shape or crescentic barchans. Active, depositional slopes of dunes have loose sand at angle of repose of 32–34°, while the flatter sides are eroded by the wind in firm dense sand.
Stabilization of migrating dunes may be achieved by trapping the sand with induced vegetation cover, or with fences and shelter belts; but impractical if sand supply is too large. Sand accumulates downwind of structures, while exposed areas are cleared by the wind; roads that slope gently down towards the prevailing wind are more exposed and therefore become self-clearing.

Corrugations (or washboarding) on dirt roads develop on dry, well-sorted sands; worst are dune sands. Damp, well-graded soils are stable; tills and glaciofluvial sands are best because clay content fills pore spaces.

Corrugated road on dune sand in Australia.
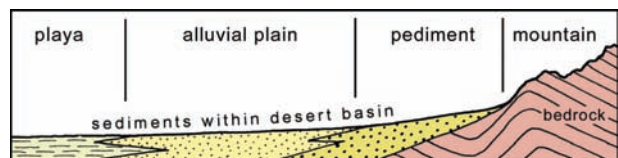
Profile through the typical zones of desert landforms.

ARID LANDFORM ZONES

	zone	slope	width	process	sediments	drainage	hazards
1	Mountain	>12°		erosion	(rock)	gorges	flash floods
2	Pediment	2–12°	1–2 km	steep fans	coarse unsorted	entrenched wadis	hydrocompaction
3	Alluvial plain	0.5–2°	1–>10 km	gentle fans	sand, gravel, fines	shallow wadis	and blown sand
4	Playa	<0.5°		basin flat	silt, mud, salt	temporary lakes	salt, blown sand

Periglacial Environments

Cold climates with limited snowfall and with no ice cover are periglacial; locally peripheral to glaciers. Winter snowfall is matched by summer melt, and vegetation is sparse, open tundra.

Today, much of Alaska, Arctic Canada and Siberia is periglacial; in Pleistocene, conditions extended over southern Britain, central Europe and central USA, south of the ice sheets, leaving periglacial structures that are found in the ground today.

Climate causes increased frost shatter and mechanical weathering, and reduced chemical weathering.

Permafrost: permanently frozen ground, to depths of 10–>200 m; deeper freezing is prevented by geothermal heat; if permafrost <50 m thick, it may be discontinuous; may include lenses of pure ice within soil and rock.

Active layer: zone of summer thawing and winter refreezing, generally 0·3–5.0 m deep; permanently frozen ground beneath prevents drainage, leaving it saturated and unstable in summer, causing widespread slope failure and subsidence.

STRUCTURES AND SEDIMENTS

Landslides and solifluction are common in active layer.
Camber folding, valley bulging increase (*section 06*).
Ice heave and collapse forms irregular cryoturbated ground, sediment-filled ice wedges, patterned ground with stone polygons; all create disturbed and vertical boundaries in soil active layer. Deeper drift-filled hollows in London Clay relate to freezing around artesian groundwater flows.
Frost shatter is extensive, commonly to 10 m deep in chalk of southern England.
Scree, or talus, is coarse, angular slope debris, with angle of repose equal to 37°, masking cliff foot profile. Many fossil Pleistocene screes are inactive in modern climate and so gain vegetation cover.
Lowland periglacial sediments include outwash gravels, alluvial and blown sand, and extensive loess.
Clay with flints is soliflucted mixture of residual soils and Tertiary clastics, widespread but generally thin on English chalk outcrops.

SOLIFLUCTION

This is the downslope movement of saturated debris – a type of wet soil creep moving about 1 metre per year. It can occur on any saturated slope, but is most common in the summer-thawed active layer of periglacial slopes which cannot drain through the deeper permafrost.

Head is unsorted, soliflucted debris; it may appear similar to glacial till, but is formed entirely of local upslope material. Head can flow by plastic deformation, but is typically well sheared, with basal, intermediate and circular slip surfaces. The shears reduce the strength to low residual values.

Head forms most easily on slopes of shale, mudstone, clay and chalk; coombe rock is chalk head. Most slopes in Britain, steeper than 5° on these rocks and outside the Devensian ice limits, can be expected to have a veneer of sheared, unstable head.

Solifluction flows, up to 1000 m long, may move on slopes as low as 2°; commonly 2–4 m thick, but may accumulate in layers to depths of >15 m on concave slopes and as valley infills.

Carsington Dam, an earth embankment in Derbyshire, failed in 1984 before the reservoir was filled. A slip surface developed through both the weak clay core (which was of an unusual shape) and a layer of head that had been left in place over the shale bedrock, beneath the dam's shale fill. The head had been wrongly interpreted as *in situ* weathered shale, and the design assumed an undisturbed angle of friction $\phi = 20°$, but shear surfaces within it reduced its strength to a residual $\phi = 12°$. This mistake, and the rebuild, cost £20M, yet periglacial head is widespread on the shale outcrops of Derbyshire and could have been expected.

PERMAFROST ENGINEERING

Subsidence, flow and heave occur on poorly drained silts and clays when ground ice is melted; sands and gravels are generally thaw-stable.
Conservation of the permafrost is generally the best means of ensuring ground stability for built structures. Any disturbance of the natural insulation (provided by the soil and vegetation) increases summer thaw, and depresses permafrost beneath buildings and roads.
Block supports for heated buildings, with clear airspace beneath, can be stable on gravel active layer over preserved permafrost.
Piles into stable frozen ground generally need to reach depths around 10 m.
Utilidors are pile-supported conduits built in streets for heated services pipelines and cables.
Trans-Alaska oil pipeline rests on piled trestles, each with internal circulating coolant and heat fins on top to dissipate stray heat into the air; it is a giant utilidor.
Gravel pads or embankments, a few metres thick, can be enough to provide insulation and let the permafrost expand into them, stabilizing the compacted old active layer. Internal cold air ducting or insulation layers of peat or wood chips further improve conservation of the permafrost and protection of the structure.

Subsided houses on permafrost in Dawson, Canada.
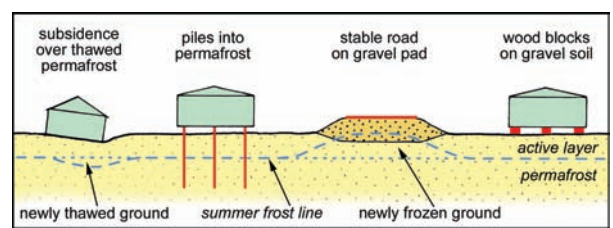
17 Coastal Processes

Wave action is the dominant mechanism in both erosion and deposition along coastlines.

Waves are powerful due to their pounding action but are also very selective in etching out rock weaknesses and controlling sediment deposition.

The largest and most powerful waves are those which have travelled furthest, i.e. have the greatest fetch.

Large storm waves are powerful and destructive.

Tidal surges cause damage when waves reach new heights; they occur on high spring tides, aided by strong onshore winds and low atmospheric pressure, as in the North Sea, 1953, and in Burma, 2008.

CLIFF EROSION

Coastal erosion is by wave action at beach level.

This creates a wave notch, which advances, leaving a wave-cut platform and undercut cliffs – which retreat by series of rock falls (or larger landslides in weak material).

Selective wave erosion of strong rock cliffs etches out faults, joints and weaknesses to form sea caves, arches and inlets that retreat between headlands and stacks.

Coastal equilibrium has slowly eroding headlands between bays in soft rocks protected by beaches.

Marine erosion is relentless; artificial control by coastal defences may be uneconomic outside urban areas, so the inevitable long-term loss of land is now being more widely accepted by government agencies.
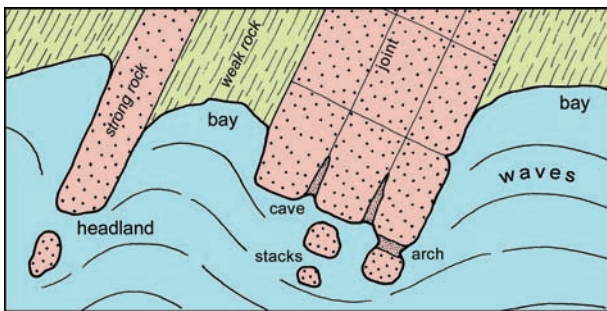
SHORELINE BUDGET

Main sources of beach sediment are eroding cliffs of soft Pleistocene material, and also river delta deposition.

On any shoreline, erosion and the production, transport and deposition of sediments are all finely balanced; any disturbance of the budget prompts renewed erosion or deposition to recover the equilibrium.

Longshore drift budget is easily disturbed by coastal engineering works, most notably where sediment is trapped or deflected into deeper water, so that beach starvation down-drift causes renewed erosion.

Similarly, any disturbance of a beach profile prompts natural processes that oppose the change in order to restore a stable form.

Coast erosion at Holderness, eastern England.

SEDIMENT TRANSPORT

Clastic sediment is mostly rolled along the seabed where it is reached by wave motion in shallow water.

Beaches are formed by sand deposition where wave upwash (swash) is greater than the backwash due to water soaking down into the porous sand.

Shingle storm beach forms higher up by larger waves.

Coastal dunes are of beach sand blown inland by wind.

Sediment washed into deeper water is deposited below wave influence, as wave-built terrace or offshore bar.

Longshore drift is due to oblique upwash of impacting waves, then backwash directly down beach slope – always away from waves arriving with greatest fetch.
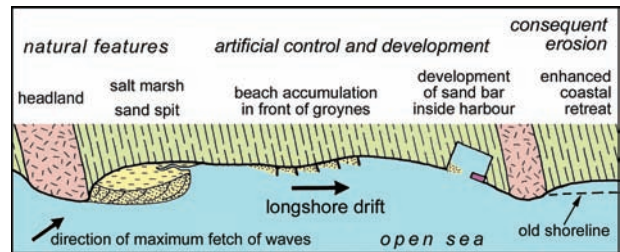
Deposition occurs in the lee of any obstacle, where sand is drifted into deep or slack water; a spit forms down-drift of a headland, and may extend into a bar across a bay or river mouth; a tombolo may form a sand link between an island and the main shore.

Salt marsh develops on mud held behind spits, storm beaches or coastal dunes.

Barrier islands, as on east coast of USA, may evolve from extended spits or emergent offshore bars.

Carbonate sediments in shallow water create varied and difficult ground conditions for coastal and off-shore structures. Strengths of shell sands and coral reefs vary greatly with type and cementation history.

Western Australia off-shore oil platforms required piles through more than 110 m of loose shell sands.

Sabkha sediments include gypsum and carbonate, both weakened by karstic solution cavities, interbedded with muds; formed in lagoons along arid coastlines.

Coastal retreat is most rapid where soft rock cliffs are eroded and longshore drift leaves no protective beach. On the east coast of England, the glacial till cliffs of Holderness retreat by about 2 m/year, by successive landslides that destroy houses, farms and roads.

Coastal Engineering

EROSION DEFENCES

A wide sand beach is the best means of preventing coastal erosion and retreat. Sea walls may prevent erosion, but wave action is relentless, and even the largest structure is only a short-term defence unless there is effective beach sediment control.

Efficient sea defence is porous to absorb wave energy; made of armour stone (blocks of >2 tonnes), concrete tetrapods, or massive wall faced with cellular concrete. Reflected waves off solid face may induce scour.

Sea walls may cost £5M/km. Economical alternative on long eroding coast (e.g. Holderness) is to create hard points – short sections of stable, fully defended shore – with intervening coast left unprotected. Down-drift of each hard point, erosion creates a shallow bay, which traps beach sediment. Eventually, a crenulated coast should become stable, but compensation is needed for short-term accelerated land loss between hard points.

BEACH CONTROL

Groynes are timber, concrete or steel barriers across beach, which prevent or reduce longshore drift by trapping sediment. Groyne spacing should be double their length to effectively stabilize beach.

Offshore breakwater, parallel to shore, absorbs wave energy and causes beach accumulation in its lee – similar to a natural tombolo.

Beach may be stabilized or expanded by pumping sea-water from a buried porous pipeline. Wave upwash adds sand to foreshore, but a drained beach absorbs and reduces backwash – so sand is not swept back out to sea. Active spits, bars and barrier islands migrate inland mainly by wave overwash. Any development, with erosion defences on the exposed outer face, causes thinning due to continued sediment loss from the inner face. The Spurn Head spit, England, and the Carolina barrier islands, USA, are now precariously thin; they should be allowed to break up and reform at a stable site further inland, as artificial defences will become increasingly expensive.

CHANNELS AND HARBOURS

Harbours, cut into the coastline or built out between breakwaters, are stable on a coast which is an erosional source area of overall sediment losses.

Harbour mouths may develop obstructing sand bars if longshore drift is strong. Jetties deflect sediment drift; they may develop spits off their ends and cause down-drift beach starvation.

Natural clearance of harbour and lagoon channels relies on tidal scour, which must exceed deposition by beach drift; larger tidal volumes and flow velocities improve scour clearance, so larger lagoons and narrow channels are better kept clear.

> **Tsunamis** are large waves generated by seabed earthquake movements; they form in series of 1–6 waves. In the open ocean they are long and low, but their fronts slow down in shallow water, and can build up to >10 m high approaching a shoreline; they reach maximum heights in tapering inlets.
>
> Best defence is warning and coastal evacuation. They take up to 24 hours to travel from the earthquake source to distant shores. Pacific Ocean has most tsunamis, so has an international warning system.
>
> There are fewer tsunamis in the Indian Ocean, so there is no warning system, but the 2004 tsunami killed 228,000 people, mostly in Sumatra and Sri Lanka.

BEACH STARVATION

Sediment input and output, by longshore drift, must be in balance to maintain a stable beach. Many artificial measures – trapping drift on a groyned beach, reducing erosion with a sea wall, deflecting sediment at a harbour mouth – reduce onward drift, and therefore cause beach starvation at down-drift sites.

This may cause beach loss or renewed erosion (as at Folkestone Warren, *section 36*) at new sites down-drift of engineered sections. Beach nourishment by artificial input of sediment is an expensive alternative to down-drift extensions of the initial control measures.

Hallsands village stood on a rock platform with a protective beach in front of it, on the Devon coast. In 1897, off-shore shingle dredging steepened the seabed sediment profile. Natural response was lowering and removal of beach within five years; so houses were exposed to waves, and destroyed in a storm in 1917.

SEA LEVEL CHANGES

Pleistocene sea levels fell by about 150 m when water was trapped in continental ice sheets, and some land areas were depressed as much as 50 m by ice weight.

Drowned valleys (rias) were flooded by sea level rise at the Ice Age end, after having been cut by rivers draining to the lower sea levels; some now form natural harbours, as at Milford Haven and Plymouth; others have sediment fills, leaving deep coastal buried valleys.

Raised beaches have abandoned cliffs, dry sea caves and fossil beach sediments; many were cut in ice-depressed coastlines at end of Ice Age after sea level had risen but before land rose with isostatic rebound; Scotland's raised beaches are due to the rapid loss of its Pleistocene ice burden. Those in California are due to tectomic uplift close to the plate boundary.

Unconsolidated raised beach sediments may be clays, sands and/or gravels, typically with lateral variation.
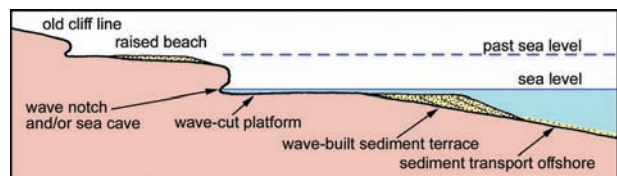
Modern sea level rise is about 2 mm per year world-wide, due to thermal expansion of seawater (and also to glacier melting); this rate may double with any increased rate of global warming (whether caused by nature or by man's activities). Local tectonic movements may greatly increase or reduce the local effect.

Rising sea levels, and/or ground subsidence, accelerate coastal erosion, cliff retreat, coastal flooding, beach losses and barrier island migration. Greatest effect is on low eastern coastlines of both Britain and the USA.

18 Groundwater

Rainfall (precipitation) is the ultimate source of all fresh water, and when it lands on the ground surface it is dispersed in three ways.
- **Evapotranspiration**: combination of evaporation from open water and transpiration by plants, both returning water to the atmosphere; in temperate climates, it may vary from 20% of the rainfall on open hills, to 70% from wooded lowland.
- **Runoff**: surface water flow into streams and rivers; increases with low rock permeability, steep slopes, intense rainfall and urbanization.
- **Infiltration**: seepage into the ground to become groundwater; important on permeable rocks, and where runoff is slow.

Groundwater is all water flowing through or stored within the ground, in both rocks and soils; it is derived from infiltration; it is lost by flow to surface springs, and by seepage out through the sea bed.

Water budget is the balance of flows for any part or the whole of a combined groundwater and surface water system; a natural budget is easily disturbed by man's activities, notably where land drainage or urbanization reduces infiltration and groundwater recharge.

PERMEABILITY OF ROCKS

Permeability is the ability of a rock to transmit water through its interconnected voids.

Aquifer: rock with significant permeability, suitable for groundwater abstraction, e.g. sandstone.

Aquiclude: impermeable rock with static water held in poorly connected voids, e.g. clay.

Aquifuge: impermeable rock with no voids, e.g. unfractured granite.

Aquitard: rock with very low permeability, unsuitable for abstraction but significant in regional water budgets, e.g. siltstone.

Permeability (= hydraulic conductivity = coefficient of permeability = K) = flow through unit area of a material in unit time with unit hydraulic head. K is expressed as a velocity, correctly as metres/second, more conveniently as metres/day (or in America as Meinzer units = gallons/day/square foot = 0·0408 m/day).

Intrinsic permeability (k), expressed in darcys, is also a function of viscosity, only significant in considering oil and gas flows through rock.

Groundwater velocities are normally much lower than the K values because natural hydraulic gradients are far less than the 1 in 1 of the coefficient definition. Typical groundwater flow rates vary from 1m/day to 1m/year, but are far higher through limestone caves.

Porosity: % volume of voids or pore spaces in a rock.

Specific yield: % volume of water that can drain freely from a rock; it must be less than the porosity, by a factor related to the permeability, and indicates the groundwater resource value of an aquifer.

Hydrological values typical for rocks

	Permeability m/day	Porosity %	Sp.Yield %
Granite	0·0001	1	0·5
Shale	0.0001	3	1
Clay	0.0002	50	3
Sandstone (fractured)	5	15	8
Sand	20	30	28
Gravel	300	25	22
Limestone (cavernous)	erratic	5	4
Chalk	20	20	4
Fracture zone	50	10	
K < 0.01 m/day = impermeable rock K > 1m/day = exploitable aquifer rock			

AQUIFER CONDITIONS

Water table (= groundwater surface) is the level in the rocks below which all voids are water-filled; it generally follows the surface topography, but with less relief, and meets the ground surface at lakes and most rivers.

Vadose water drains under gravity within an aerated aquifer above the water table.

Phreatic water flows laterally under hydrostatic pressure beneath the water table; it is the resource for all high-yield wells; there is less at greater depths and pressures, and most rocks are dry at depths >3 km.

Capillary water rises above the water table by surface tension, by very little in gravels, by up to 10 m in clays.

Hydraulic gradient is slope of the water table, created by pressure gradient required to overcome frictional resistance and drive phreatic flow through aquifer rock. Water table is steeper where permeability is low or flow is high; typical gradient is 1:100 in good aquifer. Groundwater flow is in direction of water table slope, identified in wells that are not pumped.

Rivers normally have water table sloping towards them, with groundwater flow into them. Ephemeral rivers lie above water table, and leak into the aquifer.

Perched aquifer lies above the regional water table.

Unconfined aquifer has vadose zone in upper part.

Confined aquifer has artesian water held beneath an overlying aquiclude, with a head of artesian pressure to drive the water above the aquifer, perhaps to rise to ground level; artesian water is common in sand/clay alluvial sequences, and in complex landslides.

Groundwater flow − Q = Kbwi
where K = permeability, b = aquifer thickness, w = aquifer width and i = hydraulic gradient. This is Darcy's law, easily calculated for a simple geological structure or as a rough guide for flow through a cut face; the maths is more complex for convergent flow to a well or spring where the water table steepens to compensate for the decreasing cross-sectional area of the aquifer.
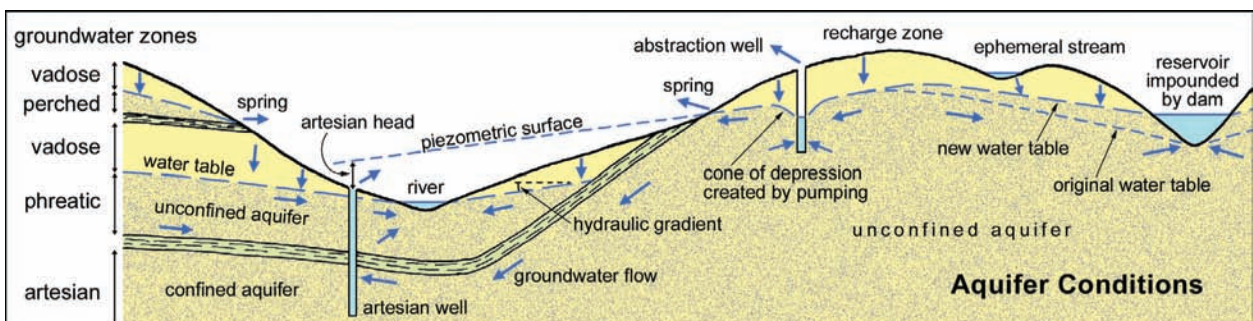
Aquifer Conditions

GROUNDWATER DEVELOPMENT

Springs are natural groundwater overflows from aquifers; many are capped or ponded for supply; a large spring yields 0·1–1·0 m³/s; smaller springs are used in rural areas; limestone caves may feed larger springs.
Qanats are ancient, horizontal adits hand-dug to a sloping water table and freely draining to the surface.
Wells are hand-dug or drilled to below the water table; hand-dug wells may have horizontal adits to intersect productive fracture zones; wells need pumping unless they are artesian; well yield depends on depth below water table, diameter and aquifer permeability; good well yields 0·1 m³/s, or about 3 litres/sec/m of depth below water table; improve yield by blasting to raise fracture permeability near well, or acid injection in limestone.
Cone of depression in water table is formed where pumped flow converging on a well creates steepening hydraulic gradient; the depth of the cone is the well drawdown, related to permeability and flow.
Reservoir impoundment raises the local water table; groundwater leaks through a ridge if water table slope is reversed in an aquifer that reaches a nearby valley.

Pump testing of a well determines its potential yield, and also the regional permeability of the aquifer.

$$K = Q.\ln(B/A)/\pi(b^2 - a^2)$$
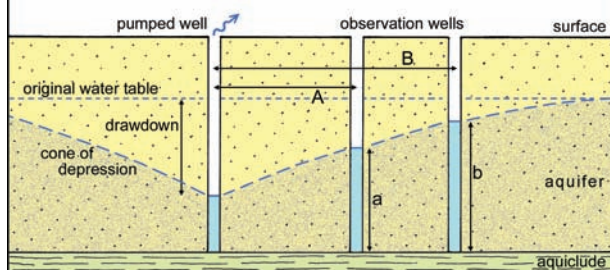
KARST GROUNDWATER

Cavernous limestones do not conform to normal groundwater rules, because their caves carry water along erratic routes in unpredictable patterns.
Karst limestones have complex water tables that are unrelated to surface topography.
Groundwater is difficult to abstract or control in karst, as wells and boreholes can just miss major conduits.
Cave streams transmit undiluted pollution to springs.
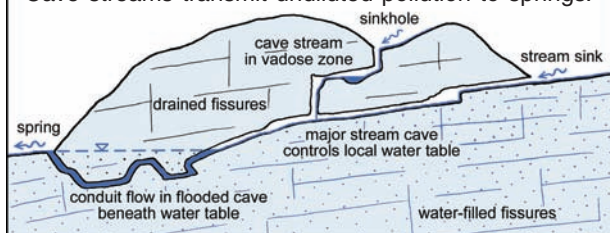
PORE WATER PRESSURE

The groundwater head provides the pore water pressure (p.w.p.) in saturated rocks and soils.
Increased p.w.p. may cause slope failure (*section 33*).
Decreased p.w.p. may permit or cause subsidence in clays (*section 28*).
In fractured rocks, joint water pressure is equivalent to p.w.p. and is critical to slope stability (*section 32*).

GROUNDWATER CONTROL

Dry excavation below the water table is possible within coalesced cones of depression created by pumping from well points round a site perimeter.
Groundwater barriers permit dry excavation without lowering the surrounding water table; barriers may be steel sheet piles, concrete diaphragm walls, grouted zones or ground freezing (in order of rising costs); grouting or freezing can also control groundwater rising from below in thick aquifers.
Slopes may be drained by ditches, adits or wells.
Capillary rise in embankments is commonly prevented by a basal gravel layer.

Packer test measures local permeability of rock and aquifer properties between two inflatable packer seals in a borehole.

$$K = Q.\ln(2L/D)/2\pi LH$$

H is measured to water table or to midpoint of test zone if this is above water table.
Falling head test is better for ground with low permeability.
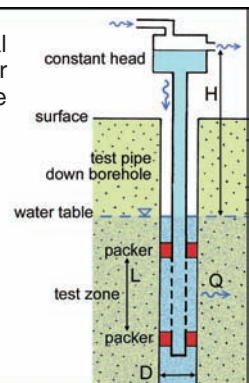
GROUNDWATER RESOURCES

Aquifer stability only ensured if abstraction < recharge.
Abstraction > recharge is groundwater mining – aquifer is depleted; water table falls, springs and wells may dry up, pumping costs increase, artesian wells may cease to flow, resource will ultimately be lost.
Aquifer recharge is possible through intake wells or the floors of leaky reservoirs.
Artesian water emerges without pumping from a flowing artesian well. Large resources may lie in synclines.
Groundwater quality is ensured by both aquifer filtration and the underground residence time in contact with absorptive clays and cleansing bacteria within soils.
Pollution is most likely in shallow alluvial gravels and cavernous limestones; major pollutants are tank leaks, and hydrocarbons from road drains in recharge zones.
Water hardness is carbonate (limestone) and sulphate.

Villa Farm disposal site, near Coventry, separated liquids in lagoons in old sand quarry 50 m across. Fluid loss of 7000 m³/year was infiltration to sand aquifer. Pollution had little radial spread, but formed a plume 600 m long in direction of hydraulic gradient.

Saltwater intrusion near a coastline is caused by over-pumping, which disturbs the saltwater interface beneath the freshwater lens fed by land infiltration. As saltwater has a density of 1·025, the freshwater lens floats on it like an iceberg and the inverted cone in the interface is 40 times higher than the matching cone of depression is deep (the Ghyben-Herzberg effect).

19 Ground Investigation

Ground investigation assesses ground conditions prior to starting a construction project.
Site investigation includes legal and environmental aspects, in addition to the ground investigation.

Objectives of a ground investigation vary with the size and nature of the proposed engineering works, but usually include one or more of:
- Suitability of the site for the proposed project;
- Site conditions and ground properties;
- Potential ground difficulties and/or instabilities;
- Ground data to permit design of the structures.

The investigation is then designed to ascertain data on three different aspects of the ground conditions:
- Drift and soil conditions, with laboratory tests and application of soil mechanics techniques;
- Rockhead, whose depth is commonly significant to both excavations and foundations;
- Bedrock, strength and structural variations, and likelihood of buried cavities are all relevant.

COSTS OF GROUND INVESTIGATION

Extent and cost of ground investigations vary greatly, depending on the nature of the project and the local complexity and/or difficulties of the ground conditions.
Expressed as percentages of project costs, guideline figures show contrasts between project types but cannot cover the variations due to differing ground conditions.

Project	% Total costs	% Foundations costs
Buildings	0.05–0.2	0.5–2.0
Roads	0.2–1.5	1–5
Dams	1–3	1–5

Typical ground investigation costs

A ground investigation must be continued until the ground conditions are known and understood well enough for the construction works to proceed safely.
This principle can and should be applied almost regardless of cost; doubling the ground investigation budget will generally add <1% to project cost; but after an inadequate investigation, unforeseen ground conditions can, and frequently do, raise project costs by 10% or more.

> You pay for a ground investigation whether you have one or not

Some recent statistics from Britain clearly demonstrate the importance of adequate ground investigation:
- 30% of construction projects delayed by ground problems.
- Unforeseen ground conditions cause most piling claims.
- 50% of over-tender costs on road projects are due to inadequate ground investigation or data interpretation.

UNFORESEEN GROUND CONDITIONS
Construction of a multi-storey car park in Plymouth was delayed by unforeseen ground conditions.
The site extended over 200 × 70 m, with a complete layer of drift and therefore no bedrock exposure.
15 boreholes found rockhead at 5–10 m deep.
Piling work then found a deep rockhead gully with steep sides, extending across nearly 10% of the site. All the boreholes had missed it; so the project was delayed, while 100 probes explored rockhead further. Bored piles were then needed over sloping rockhead.
The gully was due to dissolution of a narrow unmapped limestone band; it had been impossible to foresee.
In this case, the need for more exploration probes was only apparent with the benefit of hindsight.

STAGES OF A GROUND INVESTIGATION
Initial stage
- Desk study of available data
- Walkover survey and visual assessment
- Preliminary report and fieldwork plan

Main stage
- Fieldwork
  Geological mapping if necessary
  Geophysical survey if appropriate
  Trial pits, trenches and boreholes
- Laboratory testing, mainly of soils
- Final report

Review stage
- Monitoring during excavation and construction

These stages are in order of ascending cost, so they should form the time sequence to be cost-effective.
It is essential to start with the desk study.

Starting with boreholes is inefficient and uneconomic. Inefficient as it may be difficult to interpret borehole logs without the context of knowledge of local geology gained from a desk study. Uneconomic as the boreholes may only yield data already available and may miss ground problems that should have been identified by a desk study.

DIFFICULT GROUND CONDITIONS

An efficient ground investigation recognizes, during the initial desk study, the possibilities of any specific difficult ground conditions occurring within the project site.
It then directs the fieldwork exploration to either eliminate the considered possibilities or determine the extent of the ground difficulties.

The most common difficult ground conditions are:
- Soft and variable drift materials;
- Weathered, weak or fractured bedrock;
- Natural or artificial cavities within bedrock;
- Active or potential slope failure and landslides;
- Compressive landfill with or without soft spots;
- Flowing groundwater or methane gas.

WALKOVER SURVEY
Recognize possibly difficult ground by a site visit and the desk study, prior to cost-effective field exploration.
Check list of aspects requiring only observation:
Correlate ground features with geological map; vegetation may relate to rock type.
Local exposures: check stream banks, road cuts and quarries for geological details and soil profiles.
Land use: signs may remain of past use for mining, old tips, backfill, quarries, buildings, basements.
Interpret physical features; escarpments, moraines, terraces, floodplains, peat flats easily recognized.
Breaks of slope: all must have a reason: edge of erosion profile, geological boundary, or artificial.
Lumpy ground: created by hollows or hummocks or a combination of both. May be caused by any of a variety of conditions: sinkholes, crown holes, mine subsidence, mineshafts, waste heaps, quarry waste, moraine, landslip, solifluction. All except moraine are potential geohazards and require investigation.
Existing structures: check for distress in buildings and stability of old cut slopes.
Landslip: disturbed ground, displaced or damaged structures, deformed trees.
Groundwater: sinkholes, springs, seepages, solutional features, stream levels, flood potential.

UNDERSTANDING GROUND CONDITIONS

The outcome of a successful ground investigation is a broad understanding of the geological conditions of a site, and the implications that these may have on any planned engineering activity.

This requires an overview that may rely on geological experience – not a problem on large projects employing specialist engineering geologists, but maybe critical on small projects with a limited geotechnical team.

Ground conditions are only fully understood when different parameters are integrated into a concept:
- Nature and strength of the rocks and soils, and the difficult ground that any of these may provide;
- Fracture conditions of the rocks, with respect to the rock mass strengths that they determine;
- Geological history, and stress conditions in the ground, critical to underground engineering;
- Groundwater conditions, and slope stability with respect to pore and joint water pressures;
- Quaternary evolution, notably rock deterioration by weathering, and de-stressing by erosion;
- Man-made impacts on the ground, including any contamination of brownfield sites.

TOTAL GEOLOGICAL MODEL

This concept has been introduced to present the broad picture of ground conditions. It develops an overview, which is the normal outcome of a geologist's thinking, but is rarely foremost in an engineer's perception.

3-D drawings of ground models incorporate all the individual components of the ground conditions.

The total model matrix has three types of models.
- tectonic – that outline the background data;
- geological – to provide the broad ground picture;
- geomorphological – with the near-surface details.

Good model drawings demand some artistic ability, but even rough sketches expose deficiencies in the data on ground conditions of a site, and they focus attention on potential engineering problems.

For a small site, a model may be only a thumbnail sketch, but multiple detailed models are becoming increasingly important on large projects such as highways, pipelines and new town developments.

Outcomes of an engineering geology investigation.
- One or more conceptual ground models – which are very helpful to project managers and engineering personnel who do not have a full geological or geotechnical background.
- Identification of areas of difficult ground, and the scale of their potential geohazards.
- An engineering geology report in two parts:
  Part 1 – factual data, with all geological records;
  Part 2 – interpretation of the ground properties and conditions related to the construction project, potential problems, and the limitations of the data.

Too often, inadequate or misdirected investigations:
- rely on boreholes and trial pits that expose only a tiny fraction of the ground under a site;
- examine parameters not relevant to the problems;
- fail to discover critical ground conditions.

A total geological model for an upland site that was influenced by variations in the Quaternary climate.

Models in a ground investigation: best created after the initial stage; this should allow a more efficient main investigation with boreholes and testing; they should evolve as investigations and site works progress – in the style of an observational approach.

The models should provoke both directed and lateral thinking, and so lead to a more balanced and effective ground investigation.

Even if the models are not pursued in every detail, their concept is applicable to every engineer who has to achieve an adequate understanding of the ground conditions at his project location.

> Most cases of 'unforeseen ground conditions' are only unforeseen because nobody had looked for them.

Geomorphology is the study of the ground surface, notably the Quaternary evolution of the landscape.

The Quaternary is only a tiny fraction of geological time, but it was so recent that its processes of erosion and weathering have a disproportionate impact on the state of the ground today.

Geomorphology is often overlooked by engineers, but simple surface observations can provide data invaluable to the interpretation of sub-surface ground conditions. Primary geomorphological mapping plays a key role in highway engineering in the difficult terrains of undeveloped countries.

RECOGNITION OF GEOHAZARDS

The steps in good geotechnical risk management:
- Create a team of geotechnical experts;
- Gather all available data on ground conditions;
- Establish the likely/possible forms of construction;
- Identify the potential geotechnical hazards;
- List and rank risks for each part of the project;
- Relate risks to engineering options and to costs.

QUATERNARY PROCESSES

These accounted for a sequence of changes within the ground conditions, by mechanisms that may not be active at present:

Weathering and degradation of near-surface soils and rocks, notably related to Pleistocene periglacial zones.

Drift deposits with respect to the limits of Pleistocene glaciation, temporary lakes and river drainage patterns.

Erosional removal of cover rocks, causing stress-relief opening of fractures in rock, notably on hillsides due to valley incision (and leaving clays over-consolidated).

Slope instability in terms of past drainage states and the contrasts in slope processes in changing climates.

20 Desk Study

Every site investigation should begin with a desk study. This is an office-based exercise (therefore inexpensive) in gathering published and available information.

An initial site visit is made during the desk study; ground conditions are more readily visualized once the site has been seen, and potential ground problems can better be appreciated after a walkover survey (*section 19*).

Sources of data vary with type, size and location of site but generally fall into four groups, as below.

They also vary between countries: Britain has a greater variety of historical and recorded data than many and provides a comprehensive example of the desk study material that can be sought.

GEOLOGICAL MAPS AND RECORDS

British Geological Survey (BGS) has published and unpublished data that is readily available.

Published geological maps are normally the first desk study target; for a small investigation on uncomplicated ground they may provide all the data required.

Printed material available from the BGS includes:
• Map and book series (*tabulated opposite*).
• Reports on applied geology related to planning and development, with multiple derived maps and engineering data summaries; available for 50 urban areas, as valuable guides to difficult ground.

Digital data is now the main BGS output, over the web for licensed regular users, or to single requests.

DiGMapGB is a digitized map for the whole of Britain at scales of 1:10,000 or 1:50,000 (data always updated so better than paper copies), available on demand as digital file or print-out with appropriate descriptive text. Layers of data include geology, compressible soils, drift thickness, landslides, soluble rocks, permeability, made ground; search digital data on www.bgs.ac.uk .

Borehole records may be searched through maps, and ordered, on line at shop.bgs.ac.uk/GeoRecords .

Digital geological models, in 3-D and at various levels of detail, are increasingly available, mainly for urban areas; these provide clearer appreciation of the sub-surface geology, and may be used to generate cross-sections.

Enquiries@bgs.ac.uk or 0115 936 3143 will produce:
• Maps (including geologists' field maps), reports, borehole logs, lists of mining records, site investigation reports, and laboratory test data held by the National Geological Records Centre.
• Reports on specified areas, sites or geohazards based on interpretations by a geologist; these are produced as consultancy reports at commercial rates.

National surveys on landslides (1988), mining instability (1992) and natural cavities (1994) are available on paper; these are useful guides to potential hazards within unfamiliar areas, and all individual records are now incorporated within the BGS databases.

Mining Access Portal at www.bgs.ac.uk/nocomico lists available mine maps; it is expanding to cover all sources, including those outside the Coal Authority and BGS.

BGS libraries and borehole core stores are accessible, near Nottingham and in Edinburgh, at nominal charges.

Data Sources in USA
US Geological Survey (USGS) publishes a huge list of geological maps, reports, topographic maps, air photographs and digital data; accessible through www.usgs.gov or at the offices of State Geological Surveys (which also have their own publications).

MINING RECORDS

Coal mining has left large areas of undermined land, which are potentially unstable, in Britain and in many other countries.

Coal Authority (www.coal.gov.uk) is obliged by law to keep and provide data on all aspects of coal mining in Britain. Maps and records are open to inspection at the Mansfield office; call 01623 637233. Numbers and sizes of the plans preclude web access in foreseeable future. The same office issues permissions to enter or drill into old workings for civil engineering ground investigations.

Mining reports, for individual houses, property sales or engineering projects, provided at basic cost, notify all known past, present and future underground and opencast mining, recorded shafts and adits, and claims for subsidence damage since 1984.

Current mining: seam plans at 1:2500 are maintained by the operator, until abandonment, when all maps are handed over to the Mansfield records office.

Subsidence predictions are not provided, but advice may be gained from a consultant or the mine operator.

Past mining is incompletely recorded; records are only complete since 1947, and seam maps before then can be generalized and incomplete. As old records are unreliable, assume all workable seams (notably <100 m deep, above water table, and >0.6 m thick) have been worked, unless proved otherwise (normally by boreholes).

Abandonment plans are required by law since 1872 when a mine closes; many have been lost, but all known are with Coal Authority at Mansfield; can give useful detail, but may be difficult to relate to present locations.

Shaft register records all known shafts in coalfields, on 1:2500 maps with files noting depth, size, capping and treatment if known. Sites are noted in mining reports, and extracts of full data are available for each shaft.

Opencast mine maps at 1:2500 of all sites and backfilled areas, are held at Mansfield, but do not include data on restoration or engineering properties of backfill.

Mining other than coal has no controlling authority, so records on old stone and metal mines are extremely erratic in coverage and reliability. Primary sources are county authorities (but BGS in Scotland); some with many mines (e.g. Cornwall) have systematic records and good search facilities; others have little or no data buried in county archives, but copies of all abandonment plans are now held by Coal Authority at Mansfield.

The lost shafts of Wigan. In 1958, 500 old mine shafts were known within boundaries of Lancashire town of Wigan. In 1980, after redevelopment and site clearance, 1700 shafts were recorded in the same area. How many more shafts remain unmapped?

TOPOGRAPHIC MAPS

Old maps show features no longer visible on the ground and therefore omitted from later maps. Best are first edition ordnance surveys (6″ = 1 mile) of about 1870; mostly in local libraries for reference.

Simple comparisons with new maps may show:
• Old quarries, mines, buildings, past land use;
• Old streams, ponds, valleys lost due to landfill;
• Erosion changes in rivers, coastlines and landslips.

Various commercial companies offer comprehensive map searches. These can be an efficient route to some of the multitude of obscure sources of local information, and some also include geological data from BGS.

BRITISH GEOLOGICAL SURVEY – MAIN PUBLICATIONS

Maps 1:50,000 (or older 1:63,360)	330 sheets for England and Wales; complete digital coverage; most also as paper copies.	Separate solid and drift editions, or combined; outcrops and dips only; brief descriptions of rocks and drift, and landslide data, are better on newer editions.
Maps 1:25,000	45 areas of geological interest.	As on the 1:50,000 maps, with benefit of larger scale.
Maps 1:10,000 (or older 1:10,560)	Most of Britain is available as digital file or print-out.	Solid and drift geology in greater detail; some underground and borehole data; landslips, made ground, backfill, and some shafts.
Regional Guides	20 guides, each 100–150 pages, covering the whole of Britain.	Overviews with rock descriptions keyed to geological history; useful if 1:50,000 maps lack rock descriptions; minimal data on drift; none on engineering geology.
Sheet Explanations (or older Memoirs)	32 pages for each 1:50,000 map (Memoirs are comprehensive).	Valuable illustrated reviews to help interpretation of map data; only available for recently published maps.
Technical Reports	Descriptions are 48 or more pages, each covering an individual map.	Comprehensive reviews, masses of geological detail; later editions have useful summaries of geohazards.

PHOTOGEOLOGY

Geological interpretation of air photographs can be a valuable part of the desk study of some sites.

Interpret from vertical air photographs, scale normally about 1:10,000 on contact prints.

Photographs taken with 60% overlap along flight path, so view through stereoscope to see 3-D image with vertical exaggeration of relief.

Use in ground investigation to identify local contrasts, anomalies and relief features that are visible on photos and which relate to ground conditions.

Photos reveal little of the geology in urban areas or beneath forest cover.

Black and white photos: are widely available, and are usually the most cost-effective.

Colour photos: expensive, and sometimes less value, as colour may disguise some features.

Infra-red photos: sensitive to temperature, so may be useful to identify groundwater emerging from seepages and small springs.

Multi-spectral images: not widely available at large scale, and need specialist interpretation.

Meridian Airmaps

Interpretation of geology

Photographs show vegetation and soil; generally these relate to drift and bedrock, so contrasts on photos are interpreted as contrasts in ground conditions.

Interpretation is largely based on three factors:

Tone: generally related to water content of soil and plants; dark = wet clay; light = dry sand.
Texture: drainage channel density and patterns; rock banding and lineations; patchy or mottled ground.
Trend: single linear features or correlated anomalies, may trace geological boundaries or structures.

Geomorphological features can be directly identified, including landslips, moraines, terraces, old channels, sinkholes, breaks of slope.

Distinguish man-made features by association, e.g. ploughing patterns relate to field boundaries.

Land use may relate to rock or soil type.

Ground types on photographs

Alluvium: light sand and dark clay tones, level ground, channels, meanders.

Glacial till: irregular relief, hummocks and drumlins, patchy tones.

Landslips: arcuate head scars, concave slopes, debris hummocks, lobate toes.

Bedrock: angular jointed textures in stronger rocks; most bare rock has lighter tone, notably white limestone.

Rock permeability: relate to drainage channel density: many = clay; few = sandstone; none = limestone.

Structures: may show by linear trends, tonal zones.

Faults: straight features, may disappear under drift.

Old shafts, active or filled sinkholes: spot anomalies with dark or light tonal contrast.
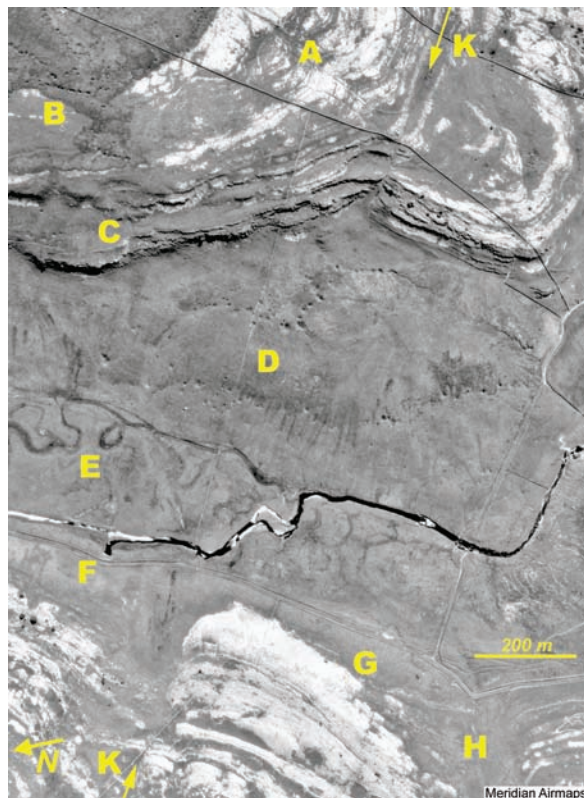
Air photograph of Kingsdale, in the Yorkshire Dales.
North is left; so shadows in morning light (from the top) give correct impression of relief across central valley.
A: bare limestone pavement with joint fissures.
B: thin till cover with many subsidence sinkholes.
C: scars along contours in horizontal limestone.
D: rounded ridge of till forming a lateral moraine.
E: valley floor of alluvium with old meandering channels.
F: river flowing from resurgence cave (Keld Head).
G: bare limestone screes and grassed lower slopes.
H: patchy till and soil over limestone in side valley.
KK: fault in limestone, unseen under valley sediments.

Black and white photos, around 1:10,000, are widely available, about £16 per print, covering 2 km square.
Source in Britain: Air Photograph Library of National Monuments Record at Swindon, call 01793 414600 or nmrinfo@english-heritage.org.uk

21 Ground Investigation Boreholes

BOREHOLE DRILLING METHODS

Holes may be drilled with a great variety of commercially available rigs; methods fall mainly into three groups, dictated by the need for soil or rock penetration and required sample or core recovery.

LIGHT PERCUSSION DRILLING

Mobile A-frame is easily towed on its own wheels by a small 4WD, simply erected, and fitted with power winch.
Steel shell is driven into the ground by a weight that is repeatedly dropped 1–2 m and then lifted by cable over the A-frame (hence 'cable and tool' rig).
Only suitable for shallow exploration of soils and soft clay rocks, though a chisel head may be fitted for some limited penetration into rock.
In cohesive clay soils, the smooth shell is driven into the ground by the weight dropped onto it, and the soil simply adheres to the inside for recovery.
In non-cohesive sand soils, the whole weighted shell may be surged and dropped, and the soil has to be retained inside by a hinged clack valve.
Can add light rotary drive for auger drill in clays (hence 'shell and auger' rig) but less suitable for most site investigations as sample is disturbed.
Widely used, as all sites require soils investigation; usually with 100 mm sampler inside 150 mm casing, capable of reaching depths of 15–40 m.
Window sampler is a small track-mounted percussion drill, which is very mobile and economical but can reach only 6–8 m deep in soils.

diamond core bit   tricone roller   drag bit

Alternative drill bits for penetration of rock.

Alternatives among drilling equipment

A traditional cable and tool rig in use in China, with its dropweight ready to fall onto the drill section.

A mobile window sampler unit set up and ready to drill through a compacted gravel surface into the soil profile of a site in England.

A diamond drill rig on a hillside in Korea, with core samples of strong limestone lifted from the split drill string and laid out in core boxes.

BOREHOLE RECORDS

All boreholes must be logged as fully and comprehensively as possible to be properly cost-effective.

Best to use conventional symbols for ease of reading by others.

Log should record at least the data on this example, on some style of conventional booking sheet that has been pre-formatted, though there is no single all-purpose design.

Description, thickness, depth, and the graphic log drawn to scale provide a basic understanding.

Tests *in situ* are used to quantify the ground properties.

Standard Penetration Test is the easiest borehole strength test for soils; N value increases with strength (*section 26*). Or use Cone Penetration Test (*section 26*).

Point Load Strength is field test on borehole core of rock (*section 24*).

Rock Quality Designation is measure of fracture density in rock (*section 25*), and core recovery is measure of weak broken zones; both values increase with quality and integrity of rock mass.

All sample points are noted.

Water table and observed inflow points should be recorded, and permeability may be determined by packer tests (*section 18*).

Nottingham Drilling	Summary Log	Number 422
Client: John Smith Construction	Location: Derwent Road Nottingham	NGR SK387284; Level 64.1 m OD
Equipment: Cable Percussion to 6.0 m, Rotary Coring to 24.0 m	Date 29-2-2008	Site co-ordinates E 67.145; N 03.350

S	K m/s	I MPa	R %	C 0%100	N blows	Depth m	Thick m	Description
D	6x10⁻⁵				6	1.4	1.4	Mixed rubble and fill
U					18		3.2	Firm glacial till with cobbles and pebbles in grey sandy clay matrix
U (−5)					22	4.6	2.3	Dense grey yellow sands (weathered bedrock in situ)
					34	6.9		
					>50			
54 mm core	2x10⁻⁵	0.7	25				3.5	Hard buff sandstone, occasional pebbles, thick bedded
			50					
−10		1.2	10			10.4 / 11.0	0.6	Weak, poorly sorted pebble bed
		1.9	80				1.4	Hard, massive, buff sandstone
	7x10⁻⁸	1.1	40			12.4	2.9	Strong, dark grey mudstone, sandy to 13.8, ironstone nodules below 14.0
		0.9	25			15.3		
−15			50			16.6	1.3	Cross bedded, yellow sandstone
			0			17.2	0.6	Void
						18.0	0.8	Debris with timber traces
			20			18.5	0.5	Friable coal with dirt bands
							2.1	Very stiff, pale grey clay with coal traces
−20	8x10⁻⁵		30			20.6	0.8	Strong, black, fissured limestone
		0.2	15			21.4	1.1	Medium hard, blocky shale
			50			22.5	1.5	Strong, buff sandstone
		1.8	80			24.0	end	

D Disturbed sample   S Sampling   I Point Load Strength   R Rock Quality Designation
U Undisturbed sample   K Permeability   N Standard Penetration Test   C Core recovery

ROTARY CORING

Truck-mounted rig with full rotary drive, which can be applied with downward force.

Air, water or bentonite mud flush, pumped down inside drill string, and washes chippings back up outside.

Tip of cylindrical drill bit is tungsten carbide or with diamond inserts (hence 'diamond drilling'). Normally double tube barrel holds full core in inner non-rotating barrel about 1–3 m long.

Can penetrate any soil or rock to >100 m deep.

Commonly use N size, providing 54 mm diameter core from cased hole of 89 mm diameter.

Larger diameters are better in weaker rocks as they give better core recovery of soft or friable rocks.

Continuous flight hollow-stem auger can be used in clays; not common in exploration.

ROCK PROBING

Rotary percussion rig, with or without a hammer action, capable of rock penetration.

Tricone roller or drag bits with air or water flush to remove chippings (hence 'open hole drilling').

Truck-mounted to provide rotation and downward force; large rigs can reach >100 m deep.

No core recovery (hence 'destructive drilling'), but much cheaper than diamond drilling because there is no need to repeatedly withdraw the drill string to extract core.

Penetration rate indicates strength of rock, soil or voids; flushed chippings can be examined; flush loss also indicates cavities.

Wash boring uses water flushing in driven shell to probe soils (common in USA, but rare in Britain).

Hand-held pneumatic drill can reach 8 m into uniform rock. Used mainly to locate shallow cavities in rock and to locate rockhead beneath thin soils.

HOW MANY BOREHOLES, HOW DEEP?

These can only be very rough guidelines.

Spacing: buildings   10–30 m apart;
road lines   30–300 m apart;
landslides   at least 5 in line for profile.
Depth: 1.5 × foundation width, below founding depth, plus at least one deeper control hole to 10 m below foundation unless rockhead found; 3–5 m below rockhead to prove sound rock; probes to 3–10 m to locate rock cavities.

Spacing and depth may be varied considerably in light of local conditions and appropriate to size of structure. Cavernous rock may need probes at each column base. Old mine working may need proving to depths of 30 m, and location of old shafts may need probes on 1 m grid.

BOREHOLE COSTS

Drilling costs may be estimated as accumulation of:
• Cost to supply rig onto site;
• Cost of set-up on each new hole;
• Cost per metre of hole drilled.

Table shows approximate relative costs (2008 figures in £).

	on site + *per hole* + *per m*		
Window sampler, soil <8 m deep	400	25	7
Light percussion, soil >8 m deep	700	50	22
Probing in rock or soil	700	50	7
Rotary coring in rock	800	60	75
Trial pits, 4 m deep, backfilled	750 for 8 pits		

Costs vary with number of *in situ* tests required.
Probes are cheaper on close-spaced grid and in uniform rocks that do not require casing of hole.

22 Geophysical Surveys

The techniques of geophysical exploration involve the remote sensing of some physical property of the ground using instruments, which in most cases remain on the ground surface; therefore non-intrusive investigation.

Passive methods accurately measure ground properties and search for minute anomalies (local distortions within the overall pattern). These include gravity and magnetic surveys (and radioactivity, which is limited in applications for ground investigation).

Induction methods send a signal into the ground and pick it up again nearby. These include seismic, electrical and electromagnetic surveys; latter include GPR (radar), NMR (nuclear magnetic resonance) and others.

USES IN GROUND INVESTIGATION

Geophysics is low cost compared to multiple boreholes. It can be cost-effective in ground investigations within certain terrains – where any one, or more, individual types of geophysical survey may be appropriate; there is no single geophysical system applicable to all problems. It is essential to select the best method for any given situation, so it is often beneficial to take advice from a consultant who is independent of commercial operators of the individual methods.

Geophysical surveys have three main applications in ground investigations:
• Reconnaissance assessments;
• Filling in detail between boreholes;
• Searching a large area for anomalies before drilling.
Modern geophysical techniques produce increasingly successful data that have been applied effectively to various specific problems in ground investigation.
• Search for unknown cavities: GPR if depth <10 m, or gravity survey if cover depth < the expected diameter.
• Search for suspected mine shafts: magnetic survey.
• Trace lateral contrasts, notably between sand and clay, in shallow drift: GPR, electromagnetic survey.
• Rockhead profiling between boreholes: refraction seismic survey.
• Estimate rock fracturing ahead of new tunnel drive; seismic tomography is optimum if site conditions allow.

Interpretation of geophysical data invariably requires boreholes, to calibrate profiles or to test-drill anomalies. Magnetic searches for buried mineshafts are simple enough for operation and interpretation by untrained personnel with low-cost rented equipment.
All other geophysical surveys require operation and data interpretation (only possible by computer inversion of the raw data) by specialists who are working as part of a ground investigation team.

GEOPHYSICAL SURVEY COSTS

Comparisons of costs are tenuous because each method is best applied to only certain ground problems.
Unit costs decline on larger surveys because set-up costs are applicable only on the first day.
Very rough guide is given by the coverage achievable within a day at a cost of about £2000 at 2008 prices:

Microgravity survey	0.25 ha on 5 m grid
Magnetic survey	1.5 ha on 1 m line spacing
Electromagnetic survey	2.0 ha on 2 m line spacing
Ground probing radar	1.0 ha on 1 m grid
Seismic refraction	8 spreads along 1 km
Seismic tomography	2-D profile to 40 m depth (between available boreholes)
Borehole	1 cored hole 20 m deep

ELECTROMAGNETIC SURVEYS

Non-contacting terrain conductivity meter creates an electromagnetic field in the ground and measures field distortion some metres away; low-cost equipment, simple to use, similar in principle to large metal detector.
Measures mean conductivity in a hemisphere of ground reaching to depths of 6–30 m.
Can be continuous reading, two-man operation.
High conductivity of clay, basalt and water, contrasts low conductivity of sand and limestone.
Can use to map shallow lateral changes: clay-filled fissure zones, filled sinkholes, rockhead steps, alluvial channel fills, highly-permeability fracture zones.
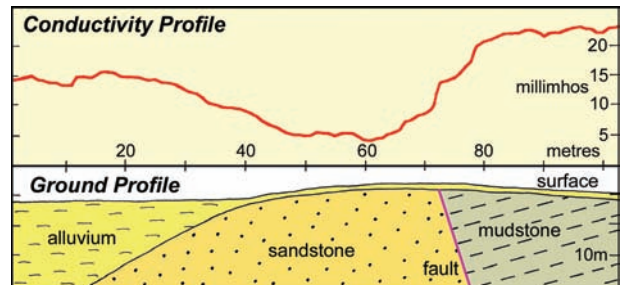
Electromagnetic traverse over faulted mudstone and sandstone with variable alluvium cover.

GROUND PROBING RADAR (GPR)

Trolley-mounted transmitter and receiver record the microwave electromagnetic radar signals reflected from ground contrasts.
Ground cross-section is produced as computer output; outputs are complicated by reflection interference, but some can be realistic displays. Calibrate depth and materials with borehole.
Limited depth penetration is main restriction: 10–20 m in dry sand, only a metre or so in wet clay.
Can tow behind car at 5 km/h for continuous profile.
Can use to map shallow drift profiles, filled sinkholes, shallow voids.
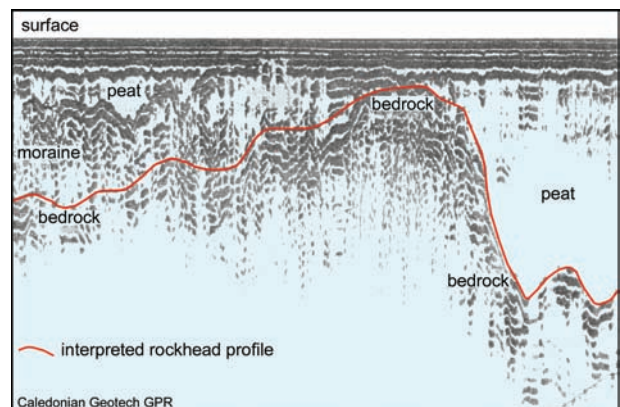
Ground radar profile of drift and rockhead for a road project in Scotland. Profile is 200 m long and 3 m deep.

ELECTRICAL SURVEYS

Numerous methods, both contacting and inductive, are applied successfully to mineral exploration, and are also used widely in ground investigations.
Resistivity or conductivity surveys, generally with arrays of four ground electrodes, can be used to map lateral and vertical changes in ground conditions.
Require specialist interpretation with computer inversion.

MAGNETIC SURVEYS

Record distortions of Earth's magnetic field.
Proton magnetometer measures total field; low cost, robust equipment. Measures to 1 nanotesla ($1nT = 1\gamma =$ about 1/50,000 Earth's field).
Simple to use, 10 seconds per station, one-man operation.
Dipole anomalies (+ve next to –ve), easily recognized, lie over vertical linear features, e.g. buried mine shafts.
Unlined shafts with fill of wall rock may go undetected.
Fences, drains, power lines, iron-rich fill prohibit use.

Proton magnetometer in use, and map of a magnetic survey on a site in the Derbyshire coalfield. Stations are on grid of 3 m; contours are at 100 nT intervals above base of 48,000 nT. Dipole anomalies lie over one known shaft and indicate the location of two more shafts.

GRAVITY SURVEYS

Record minute variations in Earth's gravitational force.
Gravimeter measures the length of an internal weighted spring; high-cost, very delicate instrument. Measures to 0·01 gravitational unit (1 gu = 10^{-6} ms^{-2} = 0·1 mgal).
Ten minutes per station, one-man operation.
Negative anomalies are created by underground voids (caves or mines) or low density soil or rock (in buried valleys or sinkholes); both significant to engineering.
The limit is set by background noise, but microgravity surveys with computer analysis of closely spaced data points can trace small mines to depths of 20 m, and larger limestone features to much deeper.
Depth and size of void may be interpreted from shape of anomaly, but normally drill all negative anomalies.
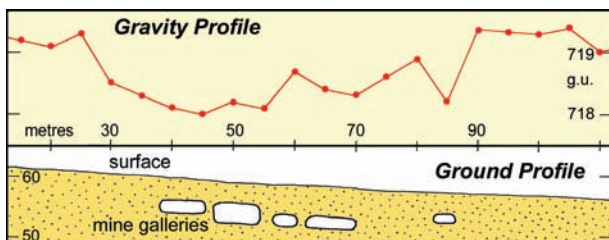
Gravity surveys over sand mines in Nottingham.

SEISMIC SURVEYS

Shock waves, produced by hammer blows or explosions, are reflected or refracted at geological boundaries.

Reflection Seismic
Seismic waves reflected from deep strata boundaries.
Successfully used for all oil exploration.
Some applications in shallow ground investigation.

Refraction Seismic
Seismic waves refracted at shallow geological boundaries and returned to surface.
Drop-hammer or 3 kg sledge hammer adequate for 20 m penetration; deeper with explosive shock source; small geophones detect wave arrivals; low cost equipment and two-man operation.
Refraction relies on faster layer at depth: rockhead is ideal boundary to detect, with slow soil over fast rock. Graphical plot of first wave arrivals reveals depths to boundaries and velocities (hence strength properties).

Surface Wave Seismic
Vertical Rayleigh waves are used to assess variations in ground stiffness at successive depths to about 50 m.

Seismic velocity (speed of shock wave through rock) increases with strength of rock, and decreases with more fracturing – related to RQD (*section 25*).

Rock or soil	Seismic velocity (P wave)
Drift and soil	500–1500 (m/s)
Shale and sandstone	1500–4000
Limestone	3000–5000
Granite	4500–5500
Fractured rock	V (unfractured) $\times$ RQD/100

GROUND TOMOGRAPHY

Transmitters and detectors in adjacent boreholes acquire data for intervening ground. With signals to and from all combinations of depth positions integrated by computer, a tomographic image of the ground properties is generated, in 2-D profile between two boreholes, or in 3-D model between multiple boreholes.
Mainly used with seismic signals or electrical resistivity, and can produce spectacular results that identify voids or anomalies within unseen ground.
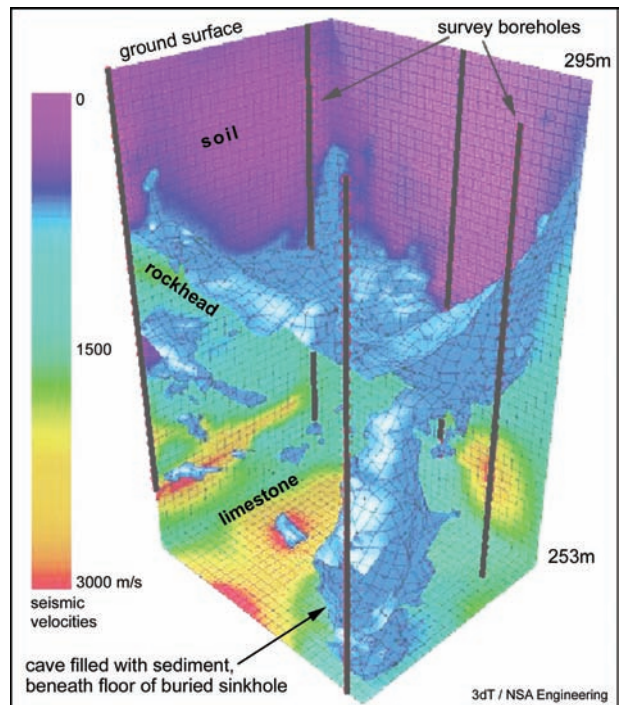
3-D image from seismic tomography between five boreholes, of a buried sinkhole beneath a road in Pennsylvania.

23 Assessment of Difficult Ground

Each ground investigation must be tailored to the local potential problems

Overview of possible hazards recognizes the geological conditions that determine the scale of each: for any one site, many potential hazards can be eliminated in the desk study phase, while others demand specific investigation techniques.

GROUND SUBSIDENCE

Beyond the acceptable limits of structural settlement on soils, this can only occur on certain rock types.

Limestone with solution cavities provides the most variable and difficult ground (*section 29*).

Subsidence can also occur on clay, peat, loess, chalk, salt, gypsum, basalt (*sections 27, 28*).

Mined ground creates a major potential hazard.

SOFT GROUND

Mostly provided by alluvial clays, lake sediments, organic soils, young clays and artificial made ground.

Laboratory testing of soils needed to determine the safe bearing capacity with acceptable settlement.

CAVITY SEARCH

Natural and artificial cavities in rock are all notoriously unpredictable in their locations.

Local building codes may require probes for 5 m at each column base, with central vertical hole and holes splayed out at 30° on each corner.

ROCKHEAD RELIEF

May influence foundations and tunnelling.

Buried valleys are most likely in areas of Pleistocene glaciation and meltwater erosion; larger features may be traced by seismic surveys.

Solution features and pinnacles dissect limestone rockhead; may need many boreholes or soil stripping.

Tunnelling up through rockhead is always a major hazard; must rely on boreholes from the surface and/or probing in advance of heading. Latter would have averted the Lötschberg tunnel disaster (*section 15*).

SINKHOLES

Notable hazard in soil or drift cover on cavernous or fissured limestone (*section 27*).

May need grid of probes to rockhead; case wash borings to prevent flushing and sinkhole inducement.

Dynamic probing rig hammers a cone into the ground to provide a continuous record of SPT (*section 26*) in any soil type, and low values indicate incipient collapse of soils into an enlarging void beneath:

N = 5–10 for normal soils;
N = 0–2 for soils in tension and about to fail.

SLOPE FAILURE

Potential threat of landslides depends on ground slope, rock type and inclinations of rock structures; limit angle for stable slopes may be around 10° in clays, 30–40° in well fractured rocks, and up to vertical in strong, massive rocks (*section 37*).

Local data (with water conditions) allows hazard zoning. Trenches are useful to assess shallow slide geometry, and are the most reliable method for recognizing solifluction shears – they were not used prior to the Carsington Dam failure (*section 16*).

Monitor potentially active slides through a wet season.

EARTHQUAKES

Destruction can be minimized by appropriate design.

Active fault zones may be recognized by displacement of recent sediments; geological mapping permits some authorities to restrict new buildings within 15 m of known faults (35 m for larger structures), with an extra 15 m setback on faults not accurately traced.

Geological mapping can construct four zones of ground with respect to vibration amplification in sediments: recent muds (most unstable); thick drift cover; thin drift cover; bedrock outcrop (relatively stable).

Liquefaction hazard mapping records well-graded, low-density soils with high water table – the least stable.

Full earthquake hazard mapping also includes landslide potential, tsunami threat and dangers from dam failures.

ROCKHEAD PROFILE UNDER MOTORWAY

Site investigation for motorways round Birmingham. Pre-construction boreholes were spaced 30–150 m along line of proposed road, 5–40 m deep to sample soils and to prove rockhead.

Found deep buried valley, offset 300 m from modern river course, filled with silts, sands and soft clays.

Photograph of the viaduct and profile of the ground, both where the M5 motorway crosses the buried valley revealed by boreholes beneath the River Tame.
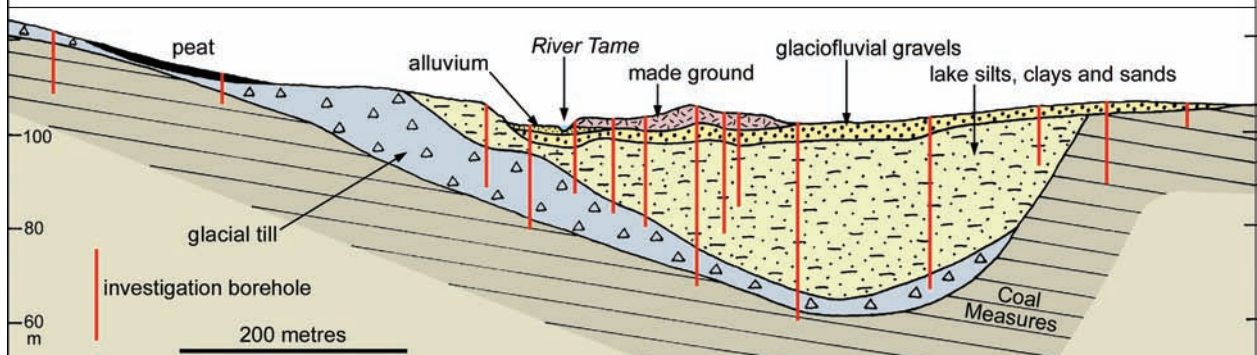
CAVITIES UNDER REMOUCHAMPS VIADUCT

Motorway viaduct in Belgium built on folded limestone, shale and sandstone.
Desk study showed cavernous limestone.
Microgravity survey gave indefinite results.
4–8 cored boreholes on each of 13 pier sites; found strong sandstone, soft weathered shale, and irregular rockhead over solid limestone.
Footings on shale were redesigned for low loading.

Excavation found caves beneath two of the five footings on limestone; had been missed by all the boreholes.
Grid pattern of new probes on all limestone footing sites; 300 holes found no more caves.
First borehole programme was inadequate; second was excessively cautious.
Caves were filled with concrete; one pier was relocated by 15 m to avoid largest cave.
Ground conditions increased contract cost by 15%, including delay costs when caves were found.

Remouchamps Viaduct
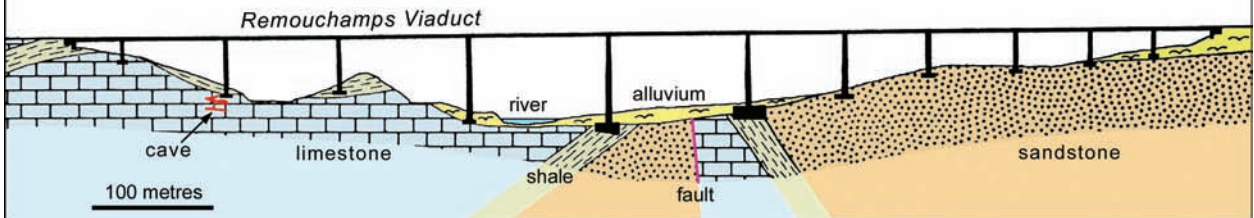
REDEVELOPMENT SITE IN COALFIELD

Site for housing within old Derbyshire coalfield.
Staged ground investigation revealed difficult ground.
Desk study: indicated coal outcrop, old brick pit, shallow old mines, approximate locations of five shafts.
Site visit: confirmed recent fill on whole site, one sinkhole probably over old shaft.
Boreholes: four light percussion holes showed 4–12 m soft fill over weathered shale. Two trial holes found edge of fill. Methane tests gave low values.
Magnetic survey: found five dipole anomalies, three of them within 5 m of recorded shafts.
Probing: needed on 1 m grid on all shaft locations and magnetic anomalies until shafts are positively located; deep cover of fill made costs prohibitive for the value of the site, so the project was abandoned.

MINED GROUND

Best guide to potential hazard is historical data obtained during desk study (*section 20*).
Coal Measures are the most extensively mined rocks; granites and limestones have the most mineral veins.

The 30 m guideline: mines <30 m deep are more likely to collapse and endanger the surface; mines >30 m deep are generally, but not always, stable.
Backfill in opencast mines is usually prone to high compaction; highly variable and best load tested *in situ.*
Redevelopment of second-hand ground nearly always finds 'unforeseen ground conditions'; areas of mining and fill provide worst case.
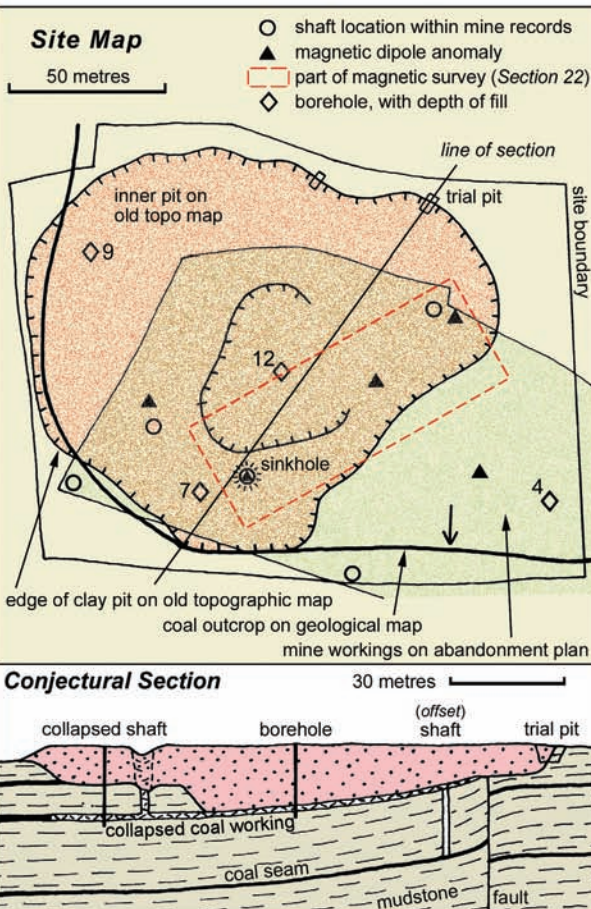
HAZARD ZONING OVER OLD COAL MINES

Coal outcrop positions, dip directions and dip amounts are enough to identify, on geological map, zones where shallow mining could occur and requires checking.
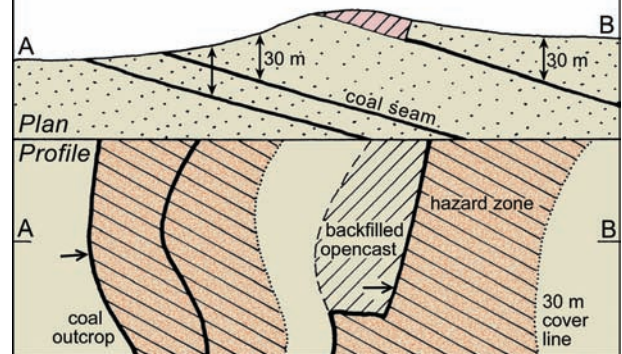
BURIED SHAFT SEARCH

Must check every suspected site before construction.
Shaft register of Coal Authority has many records that were compiled only from best fit of old maps; these can only be relied on to give locations within about 10 m.
Check for any disturbance of ground or drainage.
Check old maps and air photos; ask local residents.
If soil cover < 2 m, trench or strip with backhoe.
If cover is thicker, geophysics may be useful; magnetic survey is generally best and cheapest (*section 22*).
Last resort is expensive probing to rockhead: start at 'best-guess' location, then spiral out on a grid; probe spacing must be 0·5 m less than the suspected shaft diameter, so 1·0–1·5 m for small old shafts, and 2–4 m for larger, more recent shafts.
Many searches have needed more than 50 probes.

24 Rock Strength

Strength of intact rock depends on component mineral strengths and the way they are bound together – by interlocking or cementation.
Rock mass strength applies to a mass of fractured rock within the ground, and largely relates to the spacing and types of the fracture weaknesses.
Hardness is not directly related to strength; normally only relevant to ease of drilling.
Rock failure is normally in shear; uniaxial compression in laboratory tests produces oblique failure shears.
Compressive strength of most rocks is greater than applied engineering stresses; exceptions are weak clay, and any heavily weathered or densely fractured rock.
(UCS concrete = 40 N/mm^2 = 40 MPa)

Strength and failure relationships on Mohr diagram
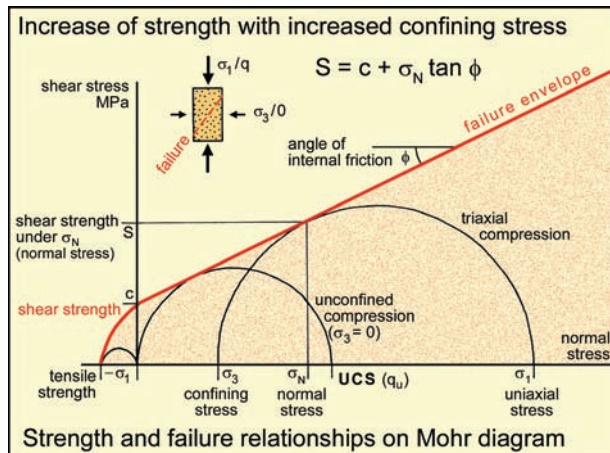
Tensile Strength (T_o, S_t)

Rarely measured or applied directly.
Generally about UCS/20 to UCS/8 for rocks.
Flexural strength relates to tensile strength on the outer surface, and is not easily measured or defined.
Elastic mica plates give slate high flexural strength.

Unconfined Compressive Strength (q_u, UCS)

Strength under uniaxial load in unconfined state.
UCS of dry rock is standard for defining rock strength.
Broadly relates to porosity, therefore to dry density.
Most igneous rocks have porosity <1%, UCS >200 MPa.
Sedimentary rocks with density <2.3 t/m^3 generally have UCS <70 MPa.
UCS increases with age in most sedimentary rocks due to increased lithification and reduced porosity.

Modulus of Elasticity (E)

Stress increment per strain increment, therefore directly related to strength. Known as Young's modulus.
Ductile failure starts where confining stress > UCS.
Modulus ratio is E/UCS. Around 300 for most rocks; >500 for some strong, stiff limestones; <100 for deformable rocks, clays, some shales.

Strength Properties of Rocks

rock type	density dry t/m^3	porosity %	dry UCS range MPa	dry UCS mean MPa	UCS saturated MPa	modulus of elasticity GPa	tensile strength MPa	shear strength MPa	friction angle $\phi°$
Granite	2·7	1	50–350	200		75	15	35	55
Basalt	2·9	2	100–350	250		90	15	40	50
Greywacke	2·6	3	100–200	180	160	60	15	30	45
Sandstone – Carboniferous	2·2	12	30–100	70	50	30	5	15	45
Sandstone – Triassic	1·9	25	5–40	20	10	4	1	4	40
Limestone – Carboniferous	2·6	3	50–150	100	90	60	10	30	35
Limestone – Jurassic	2·3	15	15–70	25	15	15	2	5	35
Chalk	1·8	30	5–30	15	5	6	0·3	3	25
Mudstone – Carboniferous	2·3	10	10–50	40	20	10	1		30
Shale – Carboniferous	2·3	15	5–30	20	5	2	0·5		25
Clay – Cretaceous	1·8	30	1–4	2		0·2	0·2	0.7	20
Coal	1·4	10	2–100	30		10	2		
Gypsum	2·2	5	20–30	25		20	1		30
Salt	2·1	5	5–20	12		5			
Hornfels	2·7	1	200–350	250		80			40
Marble	2·6	1	60–200	100		60	10	32	35
Gneiss	2·7	1	50–200	150		45	10	30	30
Schist	2·7	3	20–100	60		20	2		25
Slate	2·7	1	20–250	90		30	10		25

These are mean or typical values, which can only be taken as approximate guidelines.
All values refer to intact rock which has not been weakened by weathering. Unquoted values indicate extreme variation related to orientation etc., or lack of adequate data.

Sedimentary rocks become stronger with age and tectonic stress; these values are typical for Britain and eastern USA; most rocks of similar ages are stronger in areas of plate boundary activity such as Alpine Europe and western America. Values of ϕ are for intact rock, ignoring fractures.

SHER STRENGTH OF ROCKS

SHEAR STRENGTH OF ROCKS

May be regarded as having two components:
• cohesion (and tensile strength) due to interlocking;
• internal friction, increasing under confining load.

Confined Triaxial Strength

Rock strength greatly increases where confined in the ground, to values generally beyond significance to engineering loading.
Triaxial testing relates shear strength to normal stress.
Rarely measured in rocks (but important for soils).

Angle of Internal Friction ϕ

Relates confined shear strength to applied normal load, by the Coulomb equation: $s = c + \sigma_n \tan \phi$, meaning:
• shear strength = cohesion + normal stress $\times \tan \phi$

Shear Strength (S_i, S_s)

Resistance to direct shear when unconfined.
General relationship applies: $UCS = 2S_s \tan (45 + \phi/2)$.
S_s varies $UCS/6$ in strong rock, to $UCS/2$ in soft clay.
Peak strength on initial shearing declines to residual strength along the sheared surface; there is no accepted measure of rock brittleness (post-peak strength decline).
Shear strength equates with cohesion (c) of soils.

EFFECTS OF WATER

The presence of water and any increased pore water pressure significantly reduce rock strength.
Water interrupts the bonding between minerals, and allows the break-up of clay cements in some sedimentary rocks.
Pore water pressure acts in opposition to confining stress; this reduces effective normal stress in triaxial situation, and therefore reduces confined shear strength. Important in clays and soils.
Saturation slightly reduces ϕ, and greatly reduces apparent cohesion.
Water greatly reduces strength of weak, porous sedimentary rocks, but has minimal effect on strong rocks with low porosity.

Strength Recognition and Description

Rock/soil description	UCS (MPa)	Field properties
Very strong rock	>100	firm hammering to break
Strong rock	50–100	break by hammer in hand
Moderately strong rock	12·5–50	dent with hammer pick
Moderately weak rock	5·0–12·5	cannot cut by hand
Weak rock	1·5–5·0	crumbles under pick blows
Very weak rock	0·6–1·5	break by hand
Very stiff soil	0·3–0·6	indent by fingernail
Stiff soil	0·15–0·3	cannot mould in fingers
Firm soil	0·08–0·15	mould by fingers
Soft soil	0·04–0·08	mould easily in fingers
Very soft soil	<0·04	exudes between fingers

STRENGTH TESTING

Laboratory tests of rock strength suffer because of rock variation (notably in weaker sedimentary rocks), so all values recognize error of $\pm$ 20%.
Also, tests of intact rock ignore the fractures that dominate the level of rock mass strength.
In practice, it is therefore often adequate to identify the rock and read strength values from tables.

Unconfined Compressive Test
Cube or cylinder of rock with flat, cut, parallel faces is loaded uniaxially between flat steel platens; sample diameter = 54 mm.
Most common and easiest test of rock strength.

Triaxial Test
Cylinder of rock is loaded axially (σ_1) with equal confining stresses on radial axes due to fluid bath pressure (σ_3).
Plot on Mohr diagram to determine ϕ and c.

Ring Shear Test
Transverse shear on two surfaces across rock cylinder.
One of a number of shear tests, which can also be applied with confining pressure to determine ϕ.
Generally restricted to soils and weak rocks.

Brazilian Test
Cylinder of rock is loaded across its diameter between two flat steel platens.
Easier than direct tensile test.

Point Load Test
Cylinder of rock is loaded across its diameter between two 60° steel points with tip radius of 5 mm.
Standard portable apparatus ideal for rapid, direct field testing of borehole cores.
Can also apply multiple tests on irregular rock lumps with dimensions close to 1:1:2.
Use 54 mm core (or apply correction factor on larger core that gives lower values), and ignore any low results due to fracture failures.
Point Load Strength (I_s) is then close to $UCS/20$.

Schmidt Hammer
Hand-held, spring-loaded hammer measures rebound from rock surface; rebound values correlate with UCS, and decline significantly in fractured rock.

Schmidt hardness	20	30	40	50	60
UCS (MPa)	12	25	50	100	200

Very rapid field test on exposed rock faces may identify weaker or weathered rock, or loose fracture blocks.

UCS	Point Load	Brazilian	Ring Shear	Triaxial	
compression	tensile	tensile	shear	confined shear	
$q_u = \dfrac{4P}{\pi d^2}$	$I_s = \dfrac{P}{d^2}$	$T_o = \dfrac{2P}{\pi d L}$	$S_s = \dfrac{2P}{\pi d^2}$	$\sigma_1 = \dfrac{4P}{\pi d^2}$	

Mohr's circle

Draw Mohr's circles with diameters from the minor to major principal stress values along normal stress axis.
Envelope is then tangential to test circles.
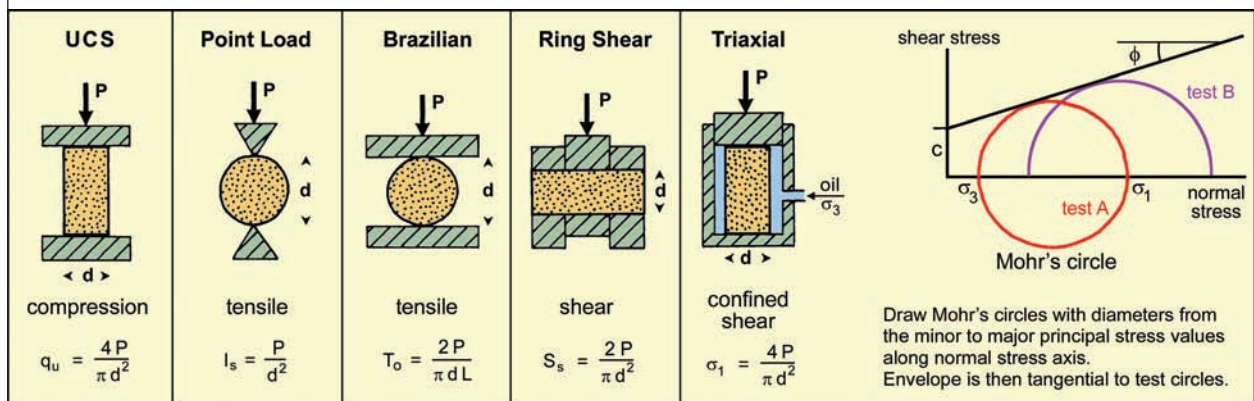
25 Rock Mass Strength

Strength of a rock mass largely depends on the density, nature and extent of the fractures within it.
Rock mass strength also relates to rock strength, weathering and water conditions.

FRACTURE DENSITIES

Rock fractures include microfissures (spacing mostly 1 mm –1 cm), joints (1 cm –1 m) and faults (>1 m).
Fractures include bedding, cleavage, schistosity.
Fractures allow inelastic deformation and reduce rock mass strength to 1/5 to 1/10 of the intact rock strength. This fraction may be known as the Rock Mass Factor.
Assessing fracture density is subjective, except by RQD.

Rock Quality Designation (RQD) is a quantification of fractures in borehole core >50 mm in diameter; lengths of individual core pieces are measured as they come from the drill barrel, and:
• RQD = Σ(core lengths >10 cm) × 100/borehole length.
Values of RQD >70 generally indicate sound rock.

FRACTURE ORIENTATION

Influence of orientation is only assessed subjectively in terms of favourability with respect to potential failure by sliding or rotation at a particular site or part of a site.
Importance of orientation is shown by UCS variation in blocks of slate with well-defined cleavage.

Significance of rock fractures on opposite sides of a road cutting

Strength of a Slate Related to Cleavage
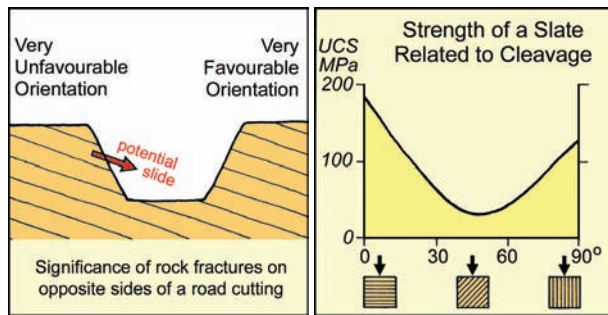
FRACTURE TYPES

Fracture roughness influences its shear strength.
Shear of very rough fractures requires dilation of rock mass as irregularities override each other.
Roughness is difficult to assess and quantify.
Fracture infills include clay gouge, slickensided gouge, clay from weathering, and fault breccias.
Typical friction angles (ϕ): clean rock   20–50°
                                  clay fill   10–20°
                                  breccia   25–40°
Cohesion across fractures varies 0–500 kPa.

ROCK MASS CLASSIFICATION

Assessment of rock mass strength recognizes cumulative effect of different geological features.
Classification is therefore an accumulation of weighted values given to selected parameters.
Two most widely used systems are the Geomechanics RMR system which adds rating values, and the Norwegian Q system which multiplies rating values.
Both systems are dominated by fracture properties.
Applications to specific engineering problems where rock mass class gives approximate guideline values of ground parameters, as in the lower table.

Geomechanics System of Rock Mass Rating (RMR) uses parameters and point scoring, as in table below.

Norwegian Q System successfully multiplies rating values to determine the rock mass quality (Q) as:
$$Q = (RQD/Jn) \times (Jr/Ja) \times (Jw/SRF)$$
Factors with rating ranges from good to bad are:
RQD = Rock quality designation   100–10
Jn   = Joint set number   1–20
Jr   = Joint roughness factor   4–1
Ja   = Joint alteration and clay fillings   1–20
Jw   = Joint water inflow or pressure   1–0.1
SRF = Stress reduction factor due to
         excavation   0.5–400
Q values range from <0.01 to >100.
System is tabulated in the appendix (*section 40*).

Geomechanics System of Rock Mass Rating

Parameter	Assessment of values and rating				
Intact rock UCS, MPa Rating	>250 15	100–250 12	50–100 7	25–50 4	1–25 1
RQD % Rating	>90 20	75–90 17	50–75 13	25–50 8	<25 3
Mean fracture spacing Rating	>2 m 20	0·6–2 m 15	200–600 mm 10	60–200 mm 8	<60 mm 5
Fracture conditions Rating	rough tight 30	open <1 mm 25	weathered 20	gouge <5 mm 10	gouge >5 mm 0
Groundwater state Rating	dry 15	damp 10	wet 7	dripping 4	flowing 0
Fracture orientation Rating	v. favourable 0	favourable −2	fair −7	unfavourable −15	v. unfavourable −25
Rock mass rating (RMR) is sum of the six ratings				Note that orientation ratings are negative	

Guideline Properties of Rock Mass Classes

Class	I	II	III	IV	V
Description	very good rock	good rock	fair rock	poor rock	very poor rock
RMR	80–100	60–80	40–60	20–40	<20
Q Value	>40	10–40	4–10	1–4	<1
Friction angle ϕ (°)	>45	35–45	25–35	15–25	<15
Cohesion (kPa)	>400	300–400	200–300	100–200	<100
SBP (MPa)	10	4–6	1–2	0.5	<0.2
Safe cut slope (°)	>70	65	55	45	<40
Tunnel support	none	spot bolts	pattern bolts	bolts + shotcrete	steel ribs
Stand up time for span	20 yr for 15 m	1 yr for 10 m	1 wk for 5 m	12 h for 2 m	30 min for 1 m

Foundations on Rock

SAFE BEARING PRESSURES

Guideline values for maximum loads that may safely be imposed on undisturbed ground.

May be estimated in many ways, all based on past experience and incorporating ample safety factors to allow for variable ground conditions.

Values are useful preliminary design guides, as it is normally uneconomic to complete meaningful field tests on fractured rock masses.

May be based on rock type:

Safe Bearing Pressure – typical values		
Rock types	Unweathered and massive	Heavily fractured or thinly bedded
Strong igneous rock, gneisses	10 MPa	6 MPa
Strong limestones and sandstones	4 MPa	3 MPa
Schists and slates	3 MPa	2 MPa
Strong mudstones, soft sandstones	2 MPa	1 MPa
Shale, sound chalk, soft mudstone	750 kPa	400 kPa

Or based on rock strength and fracturing:

Safe Bearing Pressure – *guidance values*

UCS (MPa)				
100	4	8	12	SBP (MPa)
25	1	3	5	
10	0.2	1	2	
RQD	25	70	90	
Fracture spacing	60	200	600 mm	

Improved estimates of SBP can take account of the rock modulus ratio (E/UCS); less deformable rocks with high modulus ratios, such as limestone or granite, can be ascribed higher SBP than softer rocks, such as shale, for the same values of UCS and RQD.

SBP values are also adjusted by conventional factors with respect to foundation shape; reductions for large, shallow or cyclically loaded foundations, are generally of little direct significance due to the high bearing capacities of rock (as opposed to soil).

Settlements on rock are generally small, and are rarely constraining influences once bearing capacity criteria have been satisfied. (They are normally the limiting factor for foundations on clay soils.)

UBP = Ultimate Bearing Pressure = load at failure.
SBP = Safe Bearing Pressure = UBP / Safety Factor, usually 3; similar to Presumed Bearing Value quoted for soils.
ABP = Acceptable Bearing Pressure = SBP that is further reduced to satisfy specific structural requirements, notably settlement; reduction factor may be significant on soils, but is usually close to 1 for rocks.

Foundations for Toronto CN Tower

World's tallest free-standing structure is 550 m high, weighing 110,000 tonnes.

Founded on shale, UCS = 10–25 MPa, E = 3.7 GPa, RQD = 50–80, with some thin weak bands that were mapped and avoided.

Slab foundation 7 m below rockhead, beneath 10 m drift. Mean load on shale is 580 kPa, with peak stress in high wind of 2.89 MPa; compared to design SBP for deep caissons of 7.2 MPa in the same rock.

Settlement was 6 mm, after 6 mm heave in excavations.

FAILURE OF ROCK

Sound rock is capable of bearing most normal engineering loads; the same cannot be said for soils. Normal variations in rock properties are covered by generous factors of safety in engineering design.

Major zones of significant weakness, including underground voids, can cause failures; these should be avoided by adequate site investigation.

There are four possible modes of failures:
• Shear failure and upward displacement of the rock, due to imposed loading > rock strength;
• Compaction of porous rocks (causing extreme settlement), also due to loading > rock strength;
• Rock failure into underground cavity, where rock roof fails in shear or flexural tension;
• Landsliding and lateral displacement, where slope profiles are too steep.

shear failure *weak rocks* / compaction *clay, peat, fill* / cavity *caves, mines* / landslide *steep slope*
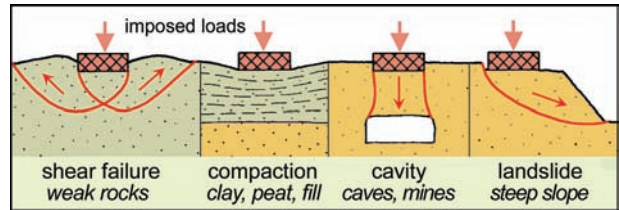
INFLUENCE OF BURIED VOIDS

Plug or beam failures of rock under structural loading over underground cavities depend on the rock strength and fracturing, the cavity size and depth, and the applied loads and stresses.

Natural and mined cavities can vary greatly in size, shape and stability, and each one requires individual assessment where it is relevant to engineering works.

Risk of ground failure increases if any one of the following guideline criteria is met:
• Cavity width > 0.7 times thickness of rock cover;
• Rock cover thickness underneath end-bearing piles is < 5 times pile diameter;
• Loading to SBP above <3 m of strong rock;
• Cover of weak rock or soil (with progressive failure and cavity migration) is < 10 times cavity height.

plug failure / beam failure / migration failure / pile failure
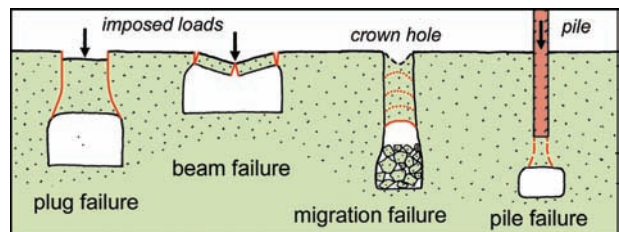
GROUND IMPROVEMENT

Treatment of fresh rock is rarely necessary or economic for structural foundations.

Weathered and weak rock near the surface is better removed, or piled through.

Injection of cement grout to fill rock pores and increase strength is limited by low permeability of intact rock.

Grouting can double mass strength of fissured rocks. Underground cavities can be filled with grout injected through 100 mm boreholes; may need 3–4 m grid of holes if cavities are partially blocked; use fluid mixture of 1:10 ratio of cement : PFA or fines; need stiff grout with sand or gravel to form perimeter barrier to avoid high losses away from site.

Alternatives to cement grout are foamed concrete or uncemented rock paste, if need is only to prevent progressive roof falls.

26 Soil Strength

Properties of a soil depend on the grain size, mineralogy and water content, all of which are interrelated.
Clay minerals can hold a high water content; for fine grained soils, the critical concept is consistency when it is related to water content.

SOIL CONSISTENCY

With varying water content, a soil may be solid, plastic or liquid. Most natural clays are plastic.
Water content (w) = weight of water as % of dry weight.
Consistency limits (Atterberg limits) are defined as:
Plastic limit (**PL**) = minimum moisture content where a soil can be rolled into a cylinder 3 mm in diameter.
Disturbed soil at PL has shear strength around 100 kPa.
Liquid limit (**LL**) = minimum moisture content at which soil flows under its own weight.
Disturbed soil at LL has shear strength around 1 kPa.
Plasticity index (**PI**) = LL–PL. This refers to the soil itself and is the change in water content required to increase its strength 100 times; it is the range of water content in which the soil is plastic or sticky.
High PI soils are less stable, with large swelling potential.
Liquidity index (**LI**) = (w–PL)/PI. This is a measure of soil consistency and strength at a given water content.

Clay Mineral	Activity	PI	ϕ
Kaolinite	0·4	30	15
Illite	0·9	70	10
Smectite	>2	400	5
PI values are for soil with 75% clay fraction			

SOIL CLASSIFICATION

Soils are classified on grain size and consistency limits.
A-line distinguishes visually similar clays and silts.
More subdivisions exist in a full soil classification.

CLAY MINERALS

Plasticity and properties of clay soils depend on amount and type of clay minerals.
Soils with <25% clay minerals are generally stronger, with low PI, and $\phi < 20\%$.
Activity of clay = PI / % fines (<0·002 mm diameter).
Soils with high clay fraction and high activity can retain high water content, giving them low strength; and these also have low permeability.
Activity is mainly due to clay mineral type; smectite (montmorillonite) clays are the most unstable.

SHEAR STRENGTH

All soils fail in shear.
Shear strength is a combination of cohesion and internal friction; expressed by Coulomb failure envelope.
Cohesion (c) derives from interparticle bonds; it is significant in clays, but zero in pure sands.
Angle of internal friction (ϕ) is due to structural roughness; higher in sand than in clay.
Shear strength = cohesion + normal stress × tan ϕ
Normal stress is critical to shear strength but pore water pressure (pwp) carries part of overburden load on soil, thereby reducing normal stress.
Effective stress (σ') = normal stress (σ) – pwp
Shear strength is correctly defined in terms of effective stress, so that:
Shear strength (τ) = c' + σ' tan ϕ'

Soil Classification		grain size	typical values		
type	class	mm	LL	PI	ϕ
Gravel	G	2–60			>32
Sand	S	0·06–2			>32
Silt	ML	0·002–0·006	30	5	32
Clayey silt	MH	0·002–0·006	70	30	25
Clay	CL	<0·002	35	20	28
Plastic clay	CH	<0·002	70	45	19
Organic	O	–			<10
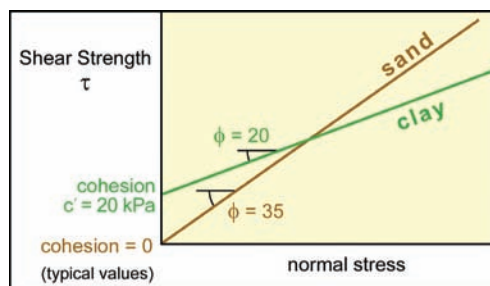
Properties of Cohesive Clay Soils							
material	state	LI	SPT, N	CPT, MPa	c, kPa	m_v, m²/MN	ABP, kPa
Alluvial clays	soft	>0·5	2–4	0·3–0·5	20–40	>1·0	<75
	firm	0·2–0·5	4–8	0·5–1	40–75	0·3–1·0	75–150
Tills and	stiff	−0·1–0·2	8–15	1–2	75–150	0·1–0·3	150–300
	very stiff	−0·4–−0·1	15–30	2–4	150–300	0·05–0·1	300–600
Tertiary clays	hard	<−0·4	>30	>4	>300	<0·005	>600

Cohesion (c) is equivalent to short-term shear strength.

STRENGTH DECLINE IN CLAYS

Drainage progress of a loaded clay is critical, as any increase of pore water pressure may lead to failure; significant in new excavations and embankments.

Peak strength declines to residual strength due to restructuring, notably alignment of mineral plates, during dislocation along a plane. Change is due to almost total loss of cohesion and also reduction in friction angle. Significant in all clays, notably those with higher PI.
Brittleness = % decline from peak strength
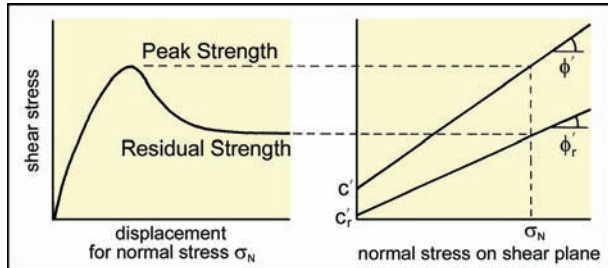
Sensitive clays lose great proportion of their strength on restructuring of entire mass; they have high LI and small grain size, so cannot drain rapidly and load is taken by pwp; shear strength approaches zero.
Sensitivity = ratio of undisturbed : disturbed strengths, and relates to undrained brittleness.

CONSOLIDATION

This is decrease of volume, under stress.
Primary consolidation is large and fast; due to expulsion of water, until excess pwp is zero.
Secondary consolidation is small and slow; due to restructuring and lateral movement; it is the same as drained creep.
Normally consolidated clays are those that have been compacted by their present overburden of sediments.
Over-consolidated clays are those more compacted in the past by overburden soils subsequently removed by erosion (or by glacier ice); they can bear loading up to their previous overburden stress with only minimal compression and settlement.
Compression coefficient = m_V = reduction of thickness with increase of stress; correlates closely with LL.

CONE PENETRATION TEST (CPT)

In a site investigation borehole, a 60° cone (diameter of 36 mm) is driven into soil at 15–25 mm/second, followed by a concentric outer sheath.
End resistance and sheath resistance are measured.
Friction ratio = (side friction / end friction) x 100 %; ratios on standard electrical systems differ on less commonly used mechanical systems.
Values relate to soil types and packing state, and give indication of Acceptable Bearing Pressure.
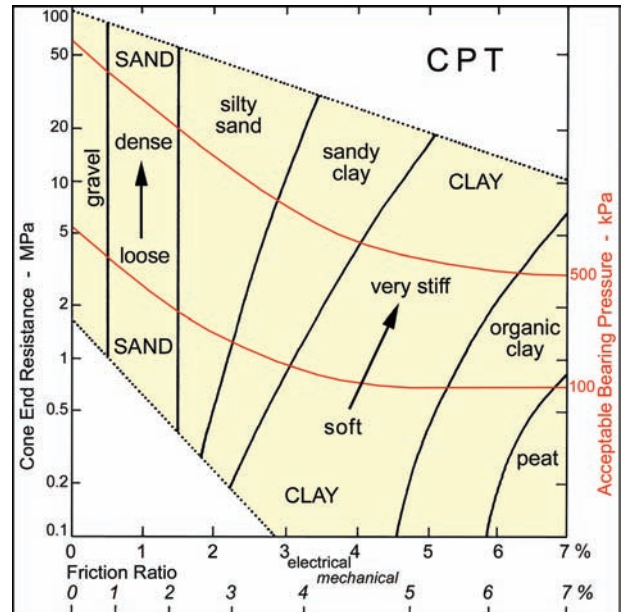
ACCEPTABLE BEARING PRESSURE

Values relate largely to the soil water content and the consolidation history.
Depend on SBP and acceptable settlement.
Settlement = m_V × thickness × imposed stress
Rate of settlement depends on permeability; slow in clay soils that cannot drain rapidly.
Settlements on clay may be large: they are then referred to as subsidence, caused by various processes that affect clays (*section 28*).

Non-cohesive Soils

Sand soils, and gravels have no cohesion, except that derived from any clay matrix and water suction.
Sand stands in steep slopes when wet due to negative pore pressure (critical in building sand castles), but will not stand when dry or saturated.
Strength, slope stability and bearing capacity all derive from internal friction; φ for granular soils (sands and gravels) ranges 30–45°; increases due to grading, packing density and grain angularity.
Settlement is small and rapid; not usually considered, except on very loose sands and artificial fills.
Properties are best assessed *in situ* by SPT; N values are a function of packing density and grading.
Bearing capacity of sandy soils may be improved by dynamic consolidation (with a 20 tonne weight repeatedly dropped from a crane) or by vibro-compaction.

Properties of Sands					
Packing	*RD*	*SPT*	*CPT*	φ	*SBP*
v. loose	<0·2	< 5	<2	<30	<30
loose	0·2–0·4	5–10	2–4	30–32	30–80
m. dense	0·4–0·6	11–30	4–12	32–36	80–300
dense	0·6–0·8	31–50	12–20	36–40	300–500
v. dense	>0·8	>50	≥20	≥40	≥500

STANDARD PENETRATION TEST (SPT)

In a site investigation borehole, a 51 mm split-tube sampler is driven for 150 mm.
Using 64 kg hammer dropped 760 mm, number of blows (N) is counted to drive the tube the next 300 mm.
A simple, effective test; N values closely relate to sand properties; should be used with care in clay soils.
(At shallow depth N may be multiplied by empirical correction factor, F, to allow for low stress:
F = 350 / (25D + 70), where D = depth in m.)

Relative Density (RD) is a measure of grain packing on a scale from loosest to densest possible states of compaction.
SPT refers to corrected N values.
CPT values are end resistances (MPa), for fine sand; values are lower in silts and higher in gravels.
Friction angles (φ) are for average sand; add 2° for angular grains; subtract 3° for rounded grains; add 5° for gravels.
SBP values, in kPa, are for foundations 3 m wide with settlement <25 mm; multiply by 1·4 for strip foundations 1 m wide; values are halved for sand stressed below water table.

Geohazards

Collapse of old mine shaft forgotten beneath restored site, Walsall.

Vaiont landslide, Italy, with rock scar above tree-covered debris.

Moving houses threatened by erosion and beach loss, Alabama.

Sinkhole collapse in soil and rock over buried gypsum, Ripon.

Road across scree and debris of large landslide, Indian Himalaya.

Ground anchors supporting landslide at Hoar Edge, Pennines.

Rotational landslide in thick soil on deforested hillside, China.

Flooding in Venice due to subsidence on deltaic sands and clays.

Old pillar-and-stall mine with thin pillars of strong limestone, Dorset.

Earthquake-proof in San Francisco.

Driven piles in alluvial sand, England.

Fly rock from blast of unsafe buttress, Cheddar Gorge.

Anchored panel wall retaining poor rock at tunnel portal, Wales.

Rock fall from glacially over-steepened valley side, Switzerland.

Earthquake damage to temple built on alluvial sand, Burma.

Failure of steep hillside after unusually heavy rain, Jordan.

Subsidence sinkhole near deep limestone quarry, Pennsylvania.

Lined tunnel, too close to hillside, destroyed by landslide, Taiwan.

27 Ground Subsidence

Subsidence is only possible where the ground material can be displaced into some sort of underground voids, which can only occur in certain rock types.

Macrovoids, large cavities: solution caves in limestones (*section 29*); much rarer natural cavities in other rocks, including salt and basalt; mined cavities in any rocks of economic value (*sections 30, 31*).

Microvoids in very porous, deformable rocks: most important in clay (*section 28*); in peat, some silts and some sands; in made ground and backfill (*section 30*).

Subsidence cannot occur on solid, unmined rock, except by shear failure and rotation to the surface under excess load, or by landslides within slopes (*section 32*).

SALT SUBSIDENCE

Rock salt may occur as extensive beds in sedimentary sequences. It dissolves in circulating groundwater rapidly enough to cause slow natural subsidence.

Most solution takes place at the rockhead beneath permeable drift; thus creates a residual breccia of the collapsed mudstone that was originally interbedded with the salt; cavities collapse before they become large.

Linear subsidences are localized over 'brine streams' – zones of concentrated groundwater flow along rockhead, many along buried outcrops of the salt bands; typical subsidences are 5 m deep, 100 m wide, 5 km long.

imposed loads

microvoids
clays, peat, fills
macrovoids
mines, caves

ground subsidence

permeable drift — zone of active subsidence where salt meets rockhead — stable ground over dry salt

wild brining — bastard brining — flooded old mine — modern deep mine dry and stable — controlled brinefield

residual breccia

linear subsidence movement accelerated due to wild brining

"brine stream"

flash subsidence collapse of old mine after bastard brining

alternating sequence of mudstone and salt beds

mudstone

stable brine-filled chambers created by controlled brining

mudstone

based on the Cheshire saltfield

Geohazard of potential subsidence can therefore be recognized largely by rock type on geological maps.

All rocks do compact under load. Weak mudstone or sandstone can compact enough to cause settlement of structures, but normally well inside acceptable limits.

COLLAPSIBLE SOIL HYDROCOMPACTION

Some fine soils collapse due to restructuring when saturated for the first time; this hydrocompaction may cause subsidence by 15% of the soil thickness. The collapse is due to total loss of cohesion, after disruption of fragile clay bonds or solution of a soluble cement.

Loess collapses most easily where it contains about 20% clay; with more or less clay, it is less unstable.

Alluvial silts deposited by flood events in semi-arid basins (notably in California), some tropical soils and some artificial fills may all exhibit collapse on saturation.

Collapse potential is highest in soils with dry density of <1.5 t/m^3, liquid limit <30, and moisture content $<15\%$ in dry climate zones. Recognize potential by consolidation test with saturation part way through the loading cycle.

Consolidation curves for a low density loess

Collapse potential

↓ dry density t/m^3

natural moisture

wetted

pre-wetted

collapsible

stable

stress kPa

liquid limit
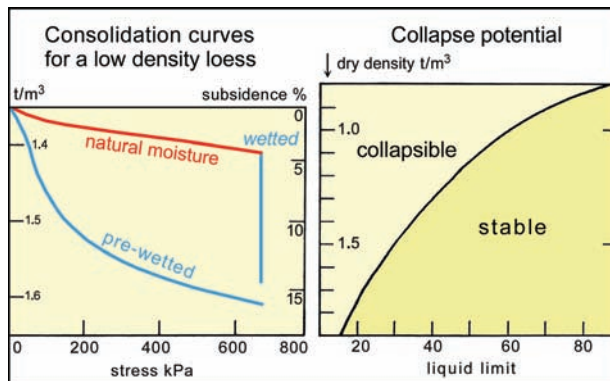
Some collapsing soils only hydrocompact with loading. Subsidence hazard is highest in irrigated arid areas.

Soil collapse may be induced prior to construction by pre-wetting through flooding; thin soils respond to dynamic consolidation or vibro-flotation.

Wild brining is uncontrolled pumping from the brine streams; it greatly accelerates formation of the linear subsidences, which may then form in tens of years.

Deep solution mining (controlled brining) and modern deep mines in dry salt are both stable: no subsidence.

Pumping brine from old shallow mines (bastard brining) causes serious collapses; now illegal in Britain.

Cheshire has the worst salt subsidence in Britain; houses and structures in Northwich all have timber or steel frames or concrete rafts that can be jacked up. Now that wild brining has almost ended, subsidence due to natural solution is very slow – but does continue.

Surface movements are small and slow; engineering precautions are as for longwall mining (*section 31*).

GYPSUM SOLUTION

Gypsum may be dissolved and removed naturally. Solution is slower than of salt, faster than of limestone – rock can dissolve within the lifetime of a built structure.

Rockhead pinnacles may be dissolved by groundwater, so may not be safe for foundations in the long term.

Caves are smaller and less common than in the strong limestones, but may create a significant hazard where weak roof rock collapses easily to create sinkholes.

Plugging or filling cavities in gypsum requires care, as diverted groundwater may rapidly create new caves.

NATURAL CAVES

Common in limestone (*section 29*) and gypsum; basalt has lava tubes on shield volcanoes; rare in other rocks.

Open fissures beneath soil cover may develop around heads of landslides and as gulls on camber folds.

Soil pipes, sea caves and rock arches are all of limited extent; latter are conspicuous as surface features.

TECTONIC SUBSIDENCE

Crustal sag can cause very slow subsidence; combines with sea level rise to cause coastal flooding; London subsides 1–2 mm/year; hence Thames Barrier. Large deltas have crustal sag and sediment compaction, causing subsidence up to 8 mm/year in Mississippi delta.

SUBSIDENCE ON PEAT

Peat may contain ten times its own weight of water; it can shrink by 10–75% under load.

When loaded to exceed its very low shear strength, peat also creeps and spreads; so very high settlements are normal; coefficient of compressibility, $m_V > 1.5$ m²/MN.

Drainage of peat causes subsidence of up to 60% of the groundwater head decline; less on later redrainage.
Was major cause of New Orleans suburbs lying below sea level, and therefore flooded so widely in 2005.

Wastage, by oxidation of biomass above watertable, continues at low rate dependant on climate; causes surface lowering, and major loss of agricultural land; reduced by maintaining high water table.

Strength of undrained peat is negligible, drained peat may be UCS = 20–30 kPa, and E = 100–140 kPa.
Peat consolidated by structural load gains strength; may reach SBP = 50–70 kPa. Primary consolidation takes place in days; secondary stage may last years.
Laboratory testing and consolidation prediction are hindered by peat's variability and difficulties of sampling; full scale field tests are often worthwhile for major projects.

CONSTRUCTION ON PEAT

Removal is economical if peat is less than about 3 m thick. Displacement of thicker peat is possible by end-tipped sand, purely by gravity, or aided by jetting to 6 m deep, or peat-blasting to 9 m deep.

Piles through peat are often economic, and are required by state law in some parts of the USA; house foundations may be left above ground if drained wastage continues.

Pre-loading is successful with surcharge of 1–3 m of sand or fill for 1–12 months; rebound is about 5%.

Sand drains are of limited use as peat permeability is already high; wick drains have been used to accelerate consolidation in English Fenlands.

Embankments on peat may cause more settlement than their height. So lightweight fill is used; polystyrene blocks are best; sawdust, brushwood and peat bales have been used in Canada and Ireland, and are stable when depressed below water table.

Rafts can be used for light, centrally loaded buildings, with under-rim to reduce peat spreading; houses on rafts in northern England settled 800 mm on 2.5 m of peat with imposed load of only 15 kPa.
Basements to give nil net loading rarely economic in houses.

Pumped drainage and ground subsidence recorded over 150 years against the Holme Post in the peat of the English Fenlands.
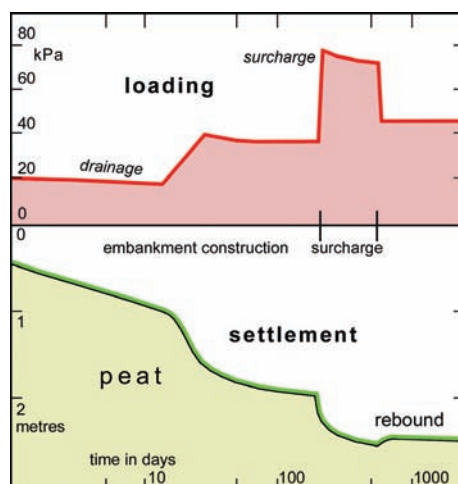
Loading and settlement of an embankment for a road over peat in Canada.

EARTHQUAKE LIQUEFACTION

Sand may liquefy due to a temporary loss of effective stress during period of earthquake vibration, if it is:
 • uniformly graded, with grain size <0.7 mm;
 • poorly packed with low relative density;
 • below the water table at shallow depth.

Hazard zones may be defined by SPT, notably where N values < 20 at 10 m depth.
Liquefaction causes total loss of strength during the period of vibration, as in the 1964 earthquake at Niigata, Japan, when intact, earthquake-proof buildings subsided rapidly into saturated alluvial sands.
Stabilize sand and reduce the hazard by dynamic consolidation, drainage and water table decline, or by surcharge to raise internal stress.
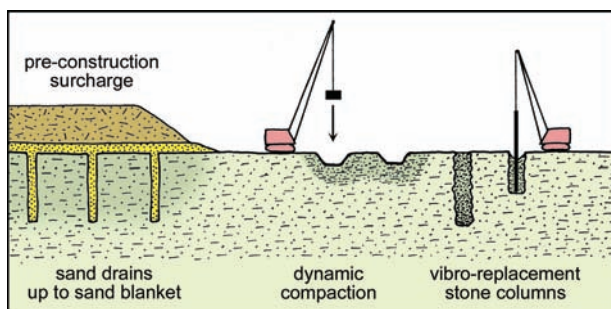
GROUND IMPROVEMENT

Surcharge: consolidation accelerates under a few metres of placed fill, and almost stops when surcharge is removed, after 6–12 months, prior to construction.

Drainage: accelerates water expulsion, and therefore accelerates consolidation; may allow settlement beneath embankment to be completed during construction time. Sand or fibre drains spaced at 1–3 m are most effective at depths < 15 m.

Grouting: cannot penetrate clays; 10% cement mixed into clays of LL <45 increases strength.

Liming: adding 5% lime creates stronger soil; reduces plasticity and shrinkage; stabilizes montmorillonite by replacing sodium with calcium.

Vibro-compaction: densify sandy, non-cohesive soils with a crane-supported vibrating poker.

Vibro-replacement; feed crushed stone beside poker to create stable stone columns in cohesive soil or fill.

Dynamic consolidation: drop 15 t block, 3–5 times, 20 m from crane, at all points on 5–10 m grid, to densify sandy soil; this may also fissure thin clay layers, and thereby accelerate drainage consolidation.

Ground freezing: expensive temporary stabilization of excavation, mainly of tunnels.

Geotextiles: increase shear strength, notably with coarser geogrids, but can only be installed in placed soils, not in undisturbed ground.

28 Subsidence on Clays

Clays have high porosity with deformable grains of clay mineral; so they have high potential compaction.
• Compaction = volume decrease = consolidation •
This is due to water expulsion (primary consolidation), followed by restructuring (secondary consolidation).
Consolidation of clay, subsidence of surface and the settlement of structures all increase with imposed load or with drained water loss.
Subsidence is greatest on thick clay, with high smectite content, low silt content and of young age with minimal history of over-consolidation.
Bearing capacity of clays ranges 50–750 kPa, largely related to water content; generally limited by settlements that exceed acceptability long before threat of failure.
Older clay, shales and mudstones are stronger and less compressible; strong mudstone may have SBP = 2000 kPa; hard shales deteriorate by slaking.

SETTLEMENT

Clay is consolidated by imposed structural load.
All clays cause some degree of settlement.
Water is squeezed out by applied stress.
Subsidence of ground, and settlement of structures, depend on initial water content of clay and stress applied; laboratory assessment is by consolidation test.
Remedy is to avoid loading the clay, or to wait for settlement to stop (or reduce to acceptable rate).
Modest settlement beneath buildings may fracture brittle drains; subsequent leakage may remove mineral soil in piping failure; this also causes subsidence but involves a different process (*see opposite*).
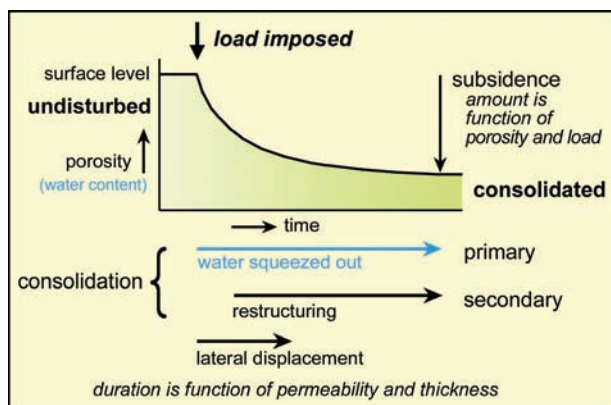
SHRINKAGE

Consolidation of clay is accelerated by water loss.
All clays exhibit some degree of shrinkage.
Water is drained out, causing volume decrease of drained soil; also loss of pore water pressure support.
Tree roots cause shrinkage in top 2 m of clay soil, but reached 6 m in London Clay in recent dry summers.
Britain's insurance claims for damage to houses on shrinkable clays are over £500M/year.
Pumped drainage of site may cause shrinkage nearby.
Remedy is control and stabilization of pore water pressure in clay.
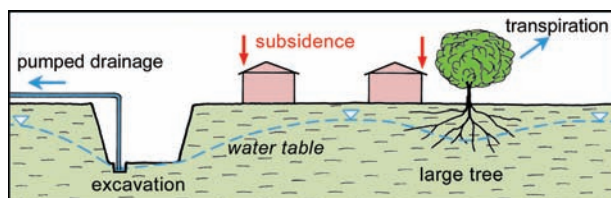
DIFFERENTIAL SETTLEMENT

Settlement of a structure most serious when differential. Commonly due to uneven loading, lateral change of silt content in soil, rockhead slope or uncontrolled drainage. Tilting of a tall structure creates differential loading, and that then accelerates differential settlement.
Transcona grain elevator, Canada, tilted 27° in a day in 1912; clays under raft base compacted unevenly over sloping rockhead, then sheared and displaced laterally.

LEANING TOWER OF PISA

Cathedral bell tower is 58 m high, 4 m out of vertical; it weighs 14,000 t, and imposed stress of 500 kPa on clay with ABP ~50 kPa.
Main settlement is due to compaction and deformation of a bed of soft clay at depth of 11–22 m. Differential movement probably started due to clay variation within the overlying silt layer; subsequently, the main tilting was due to eccentric loading.

Stabilization in 1993–2001 was by inducing controlled subsidence of the north side. Temporary counterweight, of 600 t of lead blocks, tilted the tower back 15 mm, to remove immediate threat of instability. This was followed by creep closure of 41 uncased boreholes, each 225 mm in diameter, with repeat drilling to remove a total of 35 m³ of soil. This tilted the tower back by another 425 mm; so it is now in no danger of collapse.
With the differential loading, subsidence and tilting will continue, and drilling will be repeated in the future.
Cable bracing was just for security during drilling.
Temporary tendons confined masonry to reduce risk of bursting failure until load was reduced by tilt reduction.
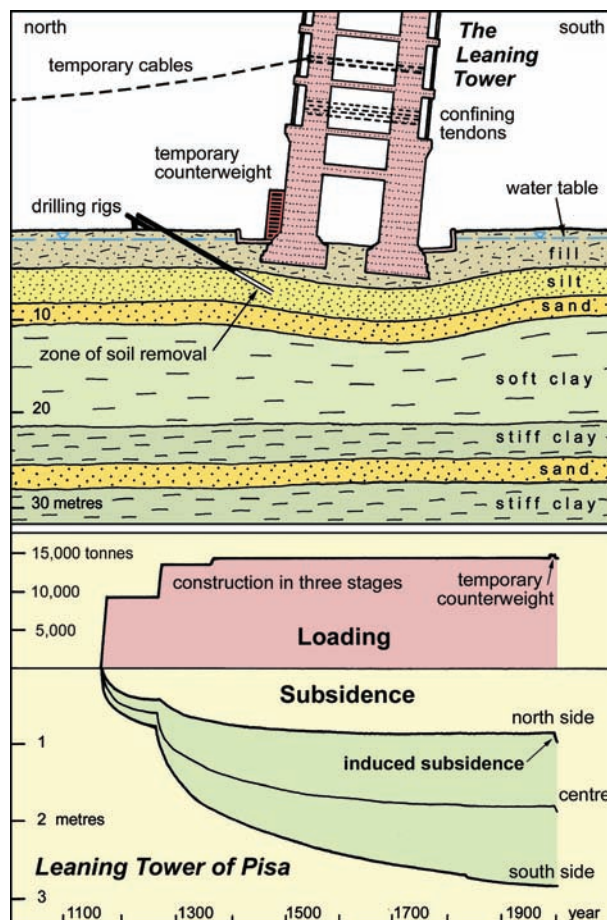
SEVERE SETTLEMENT: MEXICO CITY

City is built on drained lake bed in basin ringed by mountains of volcanic rock.

Young, porous, highly compressible clays are largely montmorillonite (smectite); water content around 300%.

All buildings on shallow foundations settle severely.

Palace of Fine Arts was built on a massive concrete raft; imposed load of 110 kPa caused 3 m settlement.

Heavy rafts create their own subsidence bowls and damage adjacent buildings.

Stable foundations are piled to sand.

Latino Americana Tower has buoyant foundations with basements to reduce imposed load, and piles to upper sand. Designed so that settlement (of 0·25 m) due to compaction of lower clay equals the ground subsidence due to pumped head decline in the upper clay.
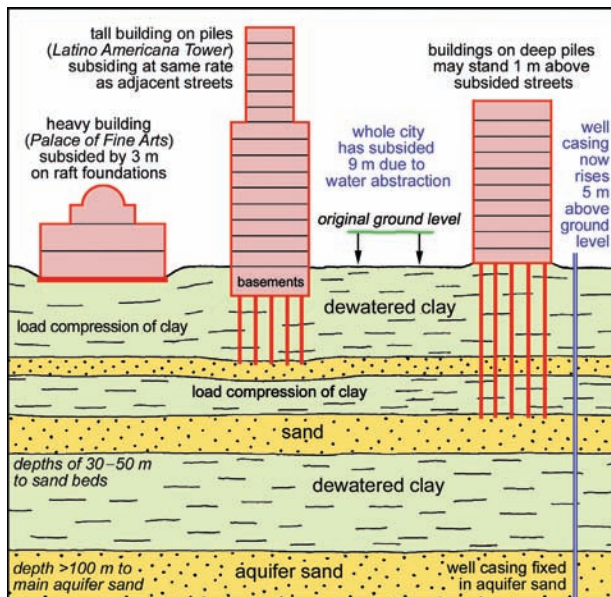
REGIONAL SUBSIDENCE

Groundwater abstraction which exceeds natural recharge causes decline of water table.

Loss of pore water pressure within clays causes widespread subsidence; significant where overpumping is from sand aquifers interbedded with clay aquitards.

Pumping from sand causes small, instantaneous, elastic, recoverable compaction of the sand.

Repressuring of aquifers has caused elastic rebound of sand – but < 10% of original subsidence.

Compaction of clay is greater and inelastic, and is non-recoverable; it occurs as groundwater pressures equalize between sand and clay, with a time delay due to the low permeability of clay.

Ratio of subsidence to head loss varies with clay type:
  • 1 : 6 on young Mexico City montmorillonite,
  • 1 : 250 on old consolidated London Clay illite.

Subsidence stops if water tables recover.

Venice has subsided on clay; large areas flood on a very high tide (known as an *aqua alta*), while St Mark's Square now floods on about 100 tides per year. Induced subsidence has stopped since pumping of groundwater was controlled, but continuing natural subsidence, along with rising sea levels, demand tidal barriers (now under construction) on the three entrances to the lagoon.

Mexico City has 9 m of subsidence on montmorillonite clays interbedded with overpumped sands; well casings, founded in the sands, now protrude in the streets.

Bangkok is now fastest subsiding city, at >10 cm/year.

Santa Clara Valley, California, was the first site where it was recognized that water table decline correlated with ground subsidence, which reached 4 m, before it was stopped by restrictions on groundwater abstraction.

EXPANSIVE SOILS

Clay soils that exhibit major free swelling on hydration and similar contraction on desiccation.

Montmorillonite is the cause – unstable clay mineral that associates with water, causing crystal expansion with force of 600 kPa, then loses water by drainage or desiccation. Sodium variety is most unstable, with liquid limit up to 500, and activity >5; calcium variety is more stable.

Smectite = unstable clay mineral group
Montmorillonite = main member of smectite group
Bentonite = clay soil with high smectite content

Montmorillonite clays form primarily by weathering of volcanic rocks in warm climates, so minor in Britain; annual costs of uplift damage on expansive soils in USA exceed combined costs of earthquakes and flooding.

Highest swelling is in any soils which are rich in montmorillonite, fine grained, dense and consolidated, dry, remoulded, lightly loaded, with high plasticity index.

Field recognition of expansive soils: sticky when wet; polished glaze on cut dry surfaces; dry lump dropped in water expands so fast that it breaks up explosively.

Remedies for expansive soils: liming to form stable calcium variety; control of groundwater, as soils are stable if they stay wet, or are kept dry under buildings.

SOIL PIPING

A through-flow of water washes out the finest soil particles, thereby increases the porosity, then washes out progressively larger particles to create a pipe.

Cavity may reach metres in diameter before collapse.

Commonly form where seepage water carries soil into broken drain; or naturally through terraces in silty soils.
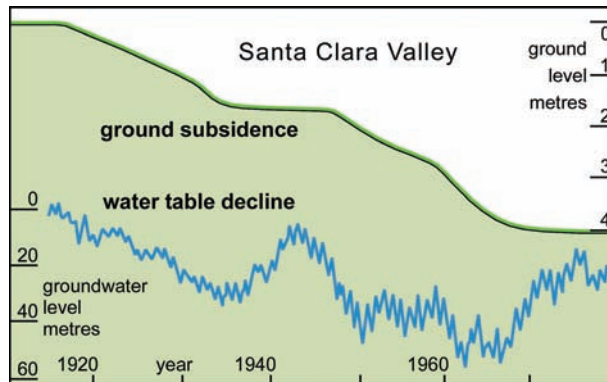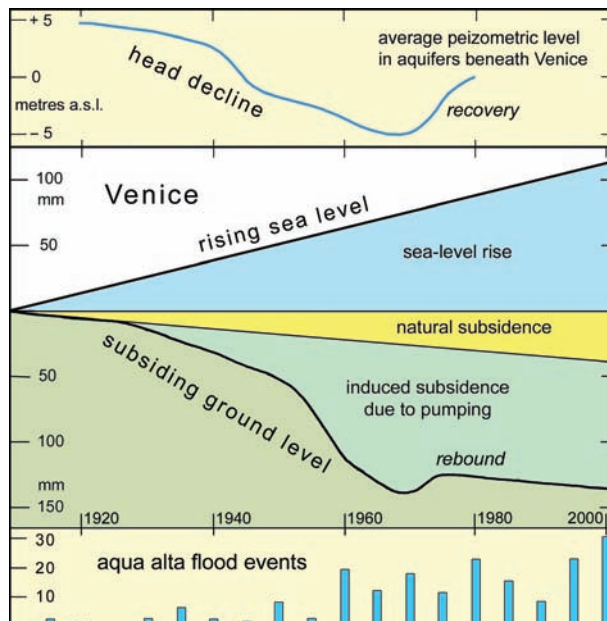
29 Subsidence on Limestone

Limestone is the only common rock that is soluble in water. It dissolves in rainwater enriched by carbon dioxide derived from organic soils, so the processes and results are on a larger scale in areas of warm, wet climate.

Karst features are erosional forms produced by solution on bare rock surfaces, beneath the soil at rockhead, and within the rock.

Dissolution is highly selective, so that most joints are etched out to create fissures, gullies and caves; they may be full of air, water or soil, between remnant blades of strong, unweathered rock. This creates the highly variable ground conditions that typify limestone areas.

Pinnacled rockhead is a highly fissured limestone surface beneath a soil cover. Tall, narrow, unstable or loose pinnacles may be supported only by the soil, and fissures may extend far below into caves. Rockhead relief in tropical areas may be > 20 m.

SINKHOLES

These are all forms of closed surface depression with drainage sinking underground; also known as dolines, and ubiquitous in karst terrains. Different types have different implications for engineering activity.

Solution sinkholes develop slowly like blind valleys; slow rates of formation create no subsidence threat.

Collapse sinkholes are not common, and events of rock failure are rare. Collapse processes contribute to forming many sinkholes; over geological time, they can create zones of broken unstable ground in limestone.

Buried sinkholes provide potential differential settlement over compacting fill. Conical, cylindrical or irregular; isolated or clustered; 1–50 m deep, 1–200 m wide. Effectively represent an extreme form of rockhead relief with short buried valleys.
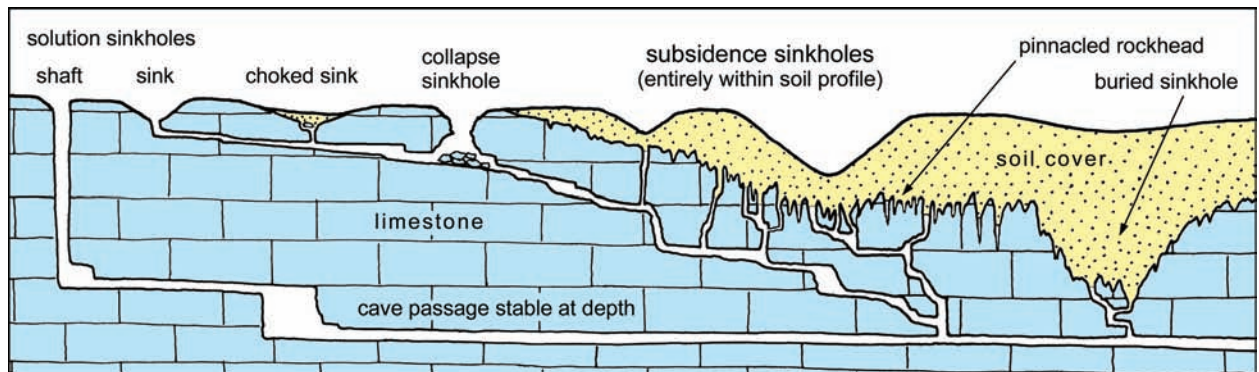
GROUND INVESTIGATION ON LIMESTONE

Many boreholes are needed to map pinnacled rockhead and buried sinkholes, and many rock probes are required to prove solid rock without caves, as at Remouchamps Viaduct (*section 23*).

Local and site history is the best guide to cave and sinkhole hazard. Shale boundaries and fault lines may have concentrations of sinkholes and caves.

Deep probes should prove bedrock to depths at least 0·7 times likely cave width; may need splayed borings to prove that pinnacles are sound.

Subsidence sinkholes account for 99% of ground collapses on limestone. They form in soil cover, above cavernous rock, due to down-washing of soil (also known as suffosion or ravelling) into bedrock fissures. Sinkholes may be 1–100 m across. Locations are totally unpredictable; most common in soils 2–15 m thick.

In non-cohesive **sandy soils** surface slowly subsides.

In cohesive **clay soils** cavity forms first at rockhead, then grows in size until the soil arch fails, to cause sudden dropout collapse of surface.

Induced subsidence sinkholes are much more common than natural failures; caused when and where drainage through rockhead increases, so washing away more soil; most events are triggered by rainfall.

Water table decline effectively induces sinkholes, mostly when it declines past rockhead; large areas are affected by over-pumping for supply, as in Florida, and smaller areas by quarry, mine or site de-watering.

Uncontrolled drainage diversions on construction projects cause many new sinkholes; also structural loading, excavation, de-vegetation, irrigation and leaking pipelines. Unlined drainage ditches and soakaway drains (unless sealed down to rockhead) must be avoided on limestone, especially in alluviated valley floors.

Boreholes on a site in Kuala Lumpur, Malaysia, with an interpreted geological profile reflecting a complex pattern of dissolution along fissures in the massive limestone.

FOUNDATIONS ON LIMESTONE

Driven piles may lose integrity where they bear on rock over a cave, are bent due to meeting a pinnacled rockhead, or are founded on loose blocks ('floaters') or unstable pinnacles within the soil.

Concrete ground beams may be aligned or extended to bear on rock pinnacles that have been proven as sound; aggregate pad, stiffened with geogrid, may act in same way and avoid loading the intervening soil.

Can inject stiff compaction grout to stiffen soil over limestone and prevent its suffosion into fissures (and lift a structure), but injection of a fluid grout can incur large losses into adjacent caves before sealing karstic fissures.

Strip or raft foundations can be designed to span any small failures that may develop subsequently.

Most important single measure is to control drainage, over or into soils above limestone, during and after construction, to stop new subsidence sinkholes forming.
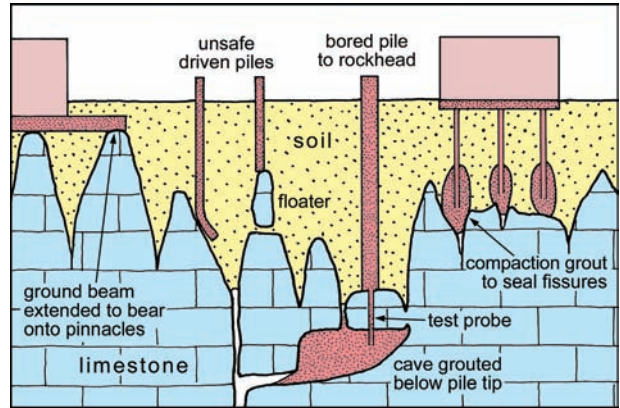
Sinkhole repair must prevent soil entering the bedrock fissure, while allowing drainage without diversion of water into another unprotected fissure. Coarse rock fill with filters and reinforced soil above is generally effective. Uncontrolled filling always leads to subsequent renewed failure.
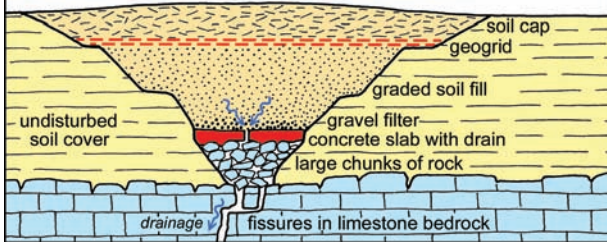
CAVES IN LIMESTONE

Fissures are opened by dissolution, until they take all available drainage underground; they evolve into an infinite diversity of cave passages and chambers. In many limestones, most caves are <10 m across, but some tropical areas have cave chambers >100 m wide. Bedding planes and fractures influence the shape of most cave passages.

Cave locations within limestone are unpredictable; they commonly have no surface indication; though isolated cavities cannot exist, entrances may lie hidden beneath soil or may be only small tortuous fissures.

Cave roof collapse is only likely under structural loading where the solid cover thickness is less than 0·7 times the cave width. But small individual cavities can permit punching failure and can threaten the integrity of individual piles or column bases.

Statistically, most caves are deep enough to have no direct influence on surface engineering.

FOUNDATIONS ON CHALK

Chalk is weak, friable, pure limestone; when fresh, UCS = 5–27 MPa; but porosity is 30–50%, so UCS reduces to 50–70% when saturated.

It may have solution features, caves and sinkholes, but these are generally on a smaller scale than in strong limestones.

Weathering of chalk by frost action is severe, to produce weak rubbly debris. This commonly reaches depth of 10 m in Britain due to periglacial weathering during the Ice Ages.

Putty chalk and fine-grained rubble chalk are thixotropic when saturated, and turn into slurry when disturbed. Should not be excavated or handled in wet winter months, but can be used as fill when dry.

Pile driving in chalk creates slurry at tip; this stabilizes when left undisturbed, so piles may carry higher working load if left for a time after driving. Settlements in chalk are often lower than expected, as rock strength increases under steady load.

Driven concrete piles have ultimate end resistance of N/4 MPa, where N = SPT. Risk of solution cavities below pile tip means that load is best attained by skin resistance, with ultimate values of about 30 kPa on displacement piles and 150 kPa on cast-in-place piles.
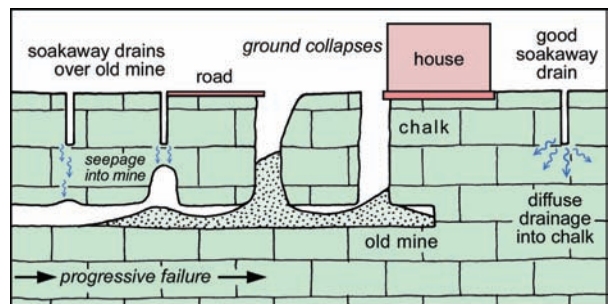
Failures beneath roads in Bury St Edmunds, due to chalk liquefaction between soakaway drains and old mines.

Liquefaction failure of putty chalk occurs where it is saturated along route of concentrated drainage flow and can then fail into a cavity beneath, which is usually a mine, gull or cave.

Ground collapses at Norwich and Bury St Edmunds (in East Anglia) and at Reading are mostly related to old mines below soakaways or drain failures; some are collapses of clay-filled pipes within the chalk.

Good surface drainage and ban on soakaways are necessary in chalk areas, especially where voids may exist, in areas with a history of mining or with known caves, or along cambered escarpments with gulls.

Chalk properties relate to the grade of weathering. Tabulated values are typical of those for the Middle Chalk. Most of the Upper Chalk within Britain is more porous, so is weaker.

Weathering grade	Description	Creep at 400 kPa	SPT N	SBP kPa
V	structureless putty	significant	<15	50–125
IV	friable rubble	significant	15–20	125–250
III	blocky rubble	small	20–25	250–500
II	medium hard	negligible	25–35	500–1000
I	hard and brittle	negligible	>35	>1000

30 Subsidence over Old Mines

Ground stability ultimately depends on the style of mining utilized, which is generally dictated by the shape, size, depth and value of the ore or extractable rock.

STOPING. Conventional deep mining, of mineral vein or any shape of orebody, creates large open underground voids known as stopes. Subsidence threat is localized, but may totally sterilize narrow strips of ground directly over the mines; a wider potential hazard is failure of hanging walls left above inclined stopes.

PILLAR AND STALL. Deep mining of thin low-dip beds by partial extraction; utilized for most coal working before 1940. Between 10% and 40% of the mineral ore (or the coal) is left in place to form pillars that support the roof; these are in random plan or in systematic rooms, stalls or bords in old hand-worked mines, or in regular grid in modern machine-operated mines. Many of the older mines were over-extracted, and therefore create a long-term subsidence threat, but modern mines with better control have no surface effect.

LONGWALL. Total extraction of coal in modern mines, causing surface subsidence that is normally automatic, immediate and unstoppable (*section 31*).

SOLUTION. Wild brining pumps natural brines from salt beds at shallow depth, and greatly accelerates linear subsidences above natural brine flows (*section 27*). Controlled brining pumps fresh water into, and brine out of, salt at depth, and should be totally stable.

OPEN PIT or **QUARRY.** Total extraction of bulk rock (quarry) or mineral ore (open pit) together with any waste rock needed to ensure pit wall stability. Backfill is rarely possible or economic in large workings, except for some waste rock fill in worked out areas. Small old quarries are far more numerous; many of these contain unstable and compressible fills of domestic refuse, where both settlement and methane hinder redevelopment.

OPENCAST or **STRIP MINE.** Continuous operation of surface excavation, ore removal and backfilling with displaced overburden. Dragline may cast overburden over the site of ore removal, but earthscrapers are now used more commonly to take the overburden around the extraction site. Approximate ground level is restored with uncompacted fill, which is graded to desired profile and re-covered with topsoil; bulking of broken fill roughly compensates for removal of ore or coal. Commonly used for modern coal working; multiple seam extraction may leave benched rockhead profile beneath fill.
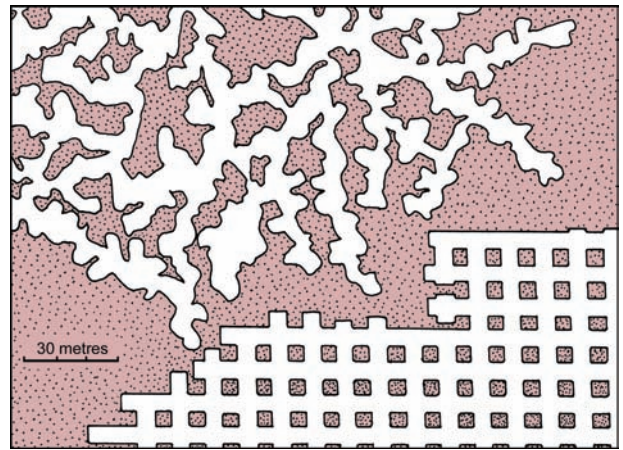
Pillar and stall mining of gypsum bed 2 m thick.
Above: plan of old irregular and modern regular workings.
Below: stable mudstone roof in the modern workings.
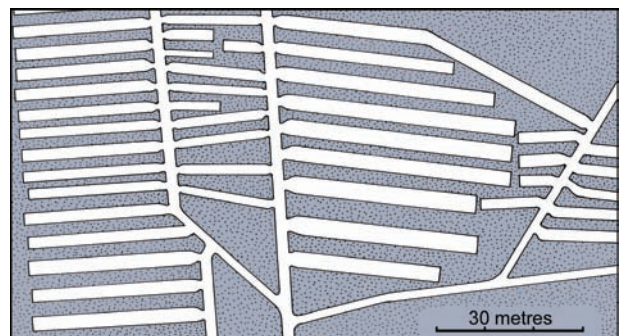
Bord and pillar working of a coal seam 1 m thick.

Opencast Mining

nearby stockpiles of topsoil (for restoration), and of overburden from first cut (to go into last cut)

topsoil over original rockhead
original coal outcrop
restored graded surface
dumped piles of backfill prior to grading
final ground profile
overburden being dumped
stripped bench exposing coal
overburden stripping
topsoil removal
high wall
final rockhead
opencast mine
Coal Measures
new rockhead
uncompacted backfill
coal removed by excavator
walking dragline casts overburden across site
coal to be extracted
final coal outcrop

MINE PILLAR FAILURE

Mine pillars fail where they are left too slim, are subsequently overloaded or are subject to weathering and erosion. Multiple failures, domino-style, may affect large areas and were common in the past due to over-extraction and pillar-robbing. Pillars can sink into soft clay floor in flooded mines, to cause slow subsidence.

Collapse of old mines may be delayed 100 years or more. Modern threat of ground failure is minimal in mines >50 m deep, where any imposed load is small compared to overburden load and pillar weathering is slight.

ROOF FAILURE AND CROWN HOLES

Roof span failure and progressive breakdown of beds causes upward stoping (migration of cavities), especially in thinly bedded Coal Measure rocks.

This may reach the surface to create a crown hole by sudden collapse; or the stoping may be stopped by beam action of a strong bed, by formation of a stable arch in thinner beds, or by bulked breakdown debris meeting and supporting the roof.

Crown holes are rare from mines at depths greater than about 30 m or 10 times extracted seam thickness.

FAILURE OF OLD SHAFTS

Thousands of old mine shafts are a widespread hazard. Small old mines had more shafts than large modern mines; shaft records are incomplete, so ground investigation must pursue any documented or physical indication.

Shafts are mostly 1–5 m diameter, 10–300 m deep; may be lined with brick, concrete or dry stone or may be unlined in rock; may have loose or compacted fill to bottom of shaft or above unstable stopping, or may be empty; may be covered with timber, vegetation, steel or concrete, or may be well sealed and capped.

Shaft cap should be reinforced concrete slab of diameter 2·6 times that of shaft, founded on sound rock. Coal measure shafts usually require filling, or grout injection of old fill, for development within 20 m; remedial costs may exceed £20,000.
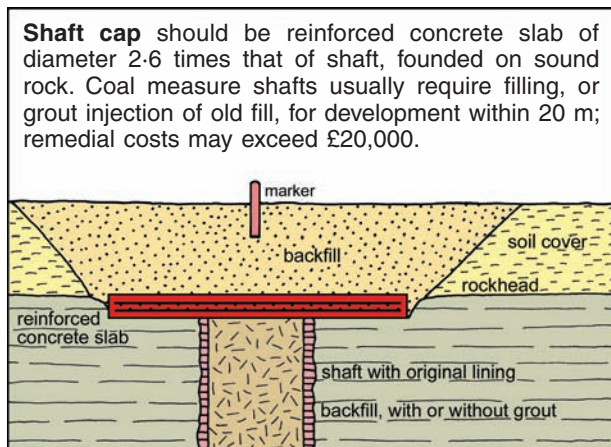
SAFE COVER FOR OLD MINES

Guideline figure is 30 m for old coal mines, so this is also the minimum depth for borehole investigation.

At >30 m depth, the broader pillars designed to carry higher overburden load rarely collapse, and roof stoping cannot normally reach the surface to form crown hole.

Even within Coal Measures, local conditions may vary, with strong sandstone roof or old weak pillars eroded by water; some mines 10 m down are stable for houses; others have needed filling at 50 m depth.

Safe depths are different for rocks other than Coal Measures; buildings are safe 3–5 m above old mines in Nottingham sandstone; pillar failure in limestone mines 145 m down near Walsall caused surface subsidence after stoping collapse of mainly shale cover.

TREATMENT OF OLD MINES

Excavation and backfill is normally only feasible and economic to <5 m depth.

Piling is normally limited to 30 m depth, and only through drift or shale, as boring through sandstone is uneconomic; cannot be used where dip is steep, where there is any risk of sliding, or where subsidence deformation due to deep mining is active or anticipated.

Grouting may need 100 mm bored holes on 3–6 m grid to ensure complete filling. Must include marginal zone of width that is 0·7 times depth to encompass zone of influence. Perimeter is sealed first; grout stiffened with pea gravel forms cones around holes bored on 1·5 m centres, which coalesce to create a wall within the mine. Can fill with low-strength foamed concrete or lean rock paste to prevent roof collapse between sound pillars.

Founding on rafts or reinforced strip footings may be good for low-rise buildings over mines of marginal depth.

Remedial costs may reach £100,000 per hectare, but should not exceed 5% of project costs to be realistic.
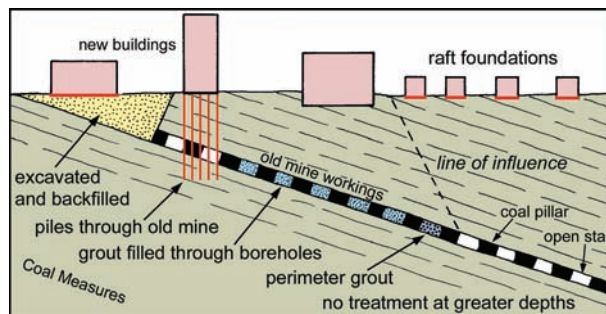
Bell pits are shafts generally <10 m deep to old coal workings that reach only a few metres from the shaft and are not interconnected. Most are in dense groups, and must be filled or excavated prior to development.
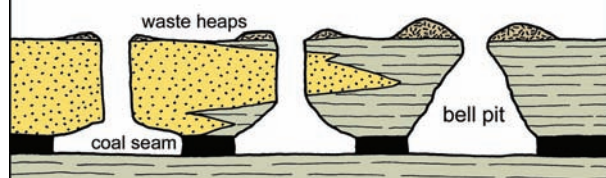
31 Mining Subsidence

Total extraction mining removes all of the mineral from a bed, allowing the unsupported roof to fail and cause inevitable and predictable surface subsidence. It is used world-wide in most modern underground coal mines.

Longwall mining is the method used in Britain. Extraction is by a machine coal cutter moving back and forth along a single migrating coal face up to 400 m long. After a slice of coal about 1 m thick has been cut from the whole length of the face, the hydraulic roof supports are advanced, the roof behind is allowed to fail, and the process is repeated. A panel of coal is removed, about 300 m wide and maybe over 2000 m long, with no support beyond the working face and access roadways.

Alternative method is a version of pillar and stall mining followed by pillar removal on the retreat. Surface subsidence effect is same as for longwall.
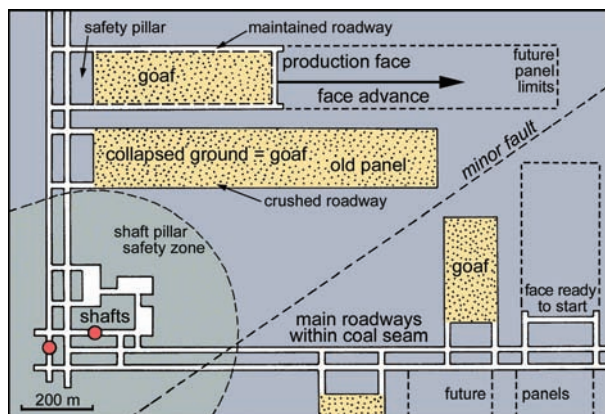
SURFACE SUBSIDENCE

The ground surface is deformed above a working coal face by a subsidence wave that migrates at the same rate as the face advance – usually 10–20 m per week. This subsidence wave has a number of effects.

Subsidence must be less than seam thickness, so usually about 1 m; may accumulate to >15 m by multiple seam working over time; causes little structural damage but has impact on drainage and piped services.

Ground strain develops first as extension (on convex part of the wave), then a return to neutral, followed by compression (on concave part of the wave). This causes most of the structural damage in mining subsidence.

Total strain is the sum of extension and compression, and is typically 1–10 mm/m or 0·001–0·01.

Angular movement is tilt on the subsidence wave; mainly significant to tall chimneys and sensitive machines.

Micro-earthquakes may occur due to movements in strong, massively jointed rocks under stress.
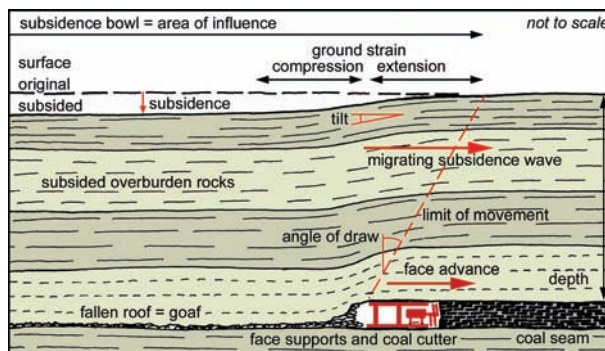
PATTERNS OF SUBSIDENCE

Mining subsidence follows well defined pattern.

Depth and lateral extents of the subsidence bowls and strain profiles, can be predicted on the basis of many past measurements (*section 40*), and the empirical data conforms closely to theoretical calculations.

Critical parameters that determine subsidence movements are the depth of working (h), the panel width (w), and the extracted thickness of coal (t).

Above an extracted panel, the ground moves downwards and also inwards, so that an area of ground larger than the panel is affected. The angle of draw is normally 30–35°, increasing slightly in weaker rocks.

Area of influence extends 0·7h outside the panel; edge is not clearly defined as it tapers to nothing.

Subsidence wave has a length of about 1·4h, with a midpoint of maximum tilt and neutral strain almost over the coal face. Surface wave migrates with the advancing face and develops similar profiles over the panel sides.

At any one point on the surface, movement occurs over time taken for wave to pass, 38 weeks for wave 560 m long over a 400 m deep face advancing at 15 m/week; so surface movement completed within a year.

Urban areas, where compensation costs may exceed 20% of coal's value, are not now undermined in Britain.

> **After mining** in a region ceases, drainage pumps are switched off; groundwater rebound then raises joint water pressures and reactivates over-stressed faults; may cause new phase of localized ground movement.

Layout of panels in a typical modern coal mine.

Strain profiles show outer zone of extension and inner zone of compression. Maximum strains are close to panel edge. Residual compression falls to zero over centre of panel where w/h > 1·4.

Subsidence and strain are most severe over shallow, wide panels in thick seams; they are also complicated by multiple workings and areas of complex geology.

Geological factors (faults, strong rocks) account for 25% of movements with damage being more or less than predictions. Steep dips displace the subsidence bowl in downdip direction and significantly distort strain profiles.

CONSTRUCTION IN SUBSIDENCE AREAS

Concrete rafts are simplest and cheapest foundations for buildings; smooth based, formed on polythene over a bed of 150 mm granular sand to absorb horizontal strain; reinforced both top and base, maximum 20 m long or with stiffening beams on top.

Structural units should be small or articulated to tolerate strain. Deformable structures with sliding panels and spring bracing can be designed. Most structural damage is by tensile strain, so tie-bars can protect old buildings. Piles need care as tilting can diminish integrity.

Pipelines need flexible joints, and gravity-flow drains need slope greater than predicted tilt. Can be exposed and placed on sliding chocks during undermining.

Bridge decks may be on three-point roller or spherical bearings, with bitumen or comb expansion joints; may need temporary support, or deck removal, while being undermined. Jacking points for bridges, machines or buildings are cheaper built-in than added later.

Geological factors may distort subsidence patterns. **Fractures** (joints and gulls), in strong, competent rock at outcrop, localize movement into zones of high strain between stable areas where rock blocks act as natural rafts. Strong sandstones, and the Magnesian Limestone of northern England, develop open fissures in tension, with subsidence sinkholes in soil cover.

Faults localize movement with zones of high strain and ground steps due to displacement.
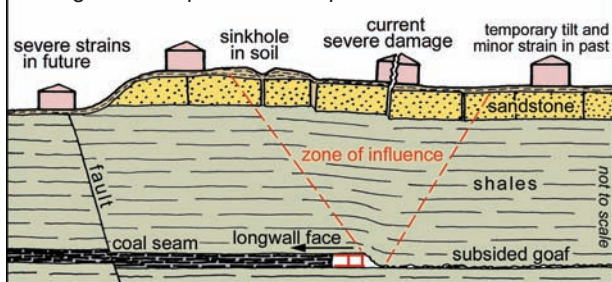
Brownfield Sites

Increasing demand for building land, and a shortage of greenfield sites, creates a need to re-use 'brownfield' sites – derelict land, or 'made ground' that includes old opencast mines, backfilled quarries, old industrial sites and disused waste dumps.

Of these sites, about 65% are contaminated with toxic metals, chemicals, organics and/or hydrocarbons.

On clean made ground, settlement is main problem.

SITE INVESTIGATION

On brownfield sites, this is more than a normal ground investigation, as many legal, historical and environmental factors have to be considered; it is a specialist field, where the concept of a total geological model (*section 20*) may be particularly appropriate.

Staged investigation is best on an unknown site; with pits and trenches to sample solids, hollow probes to test gases, and boreholes to monitor leachate flow.

CONTAMINATED LAND

This includes any site where buried substances may become accessible and so present a health hazard.

Each site is different, and may respond differently to disturbance, notably by migration of leachates or gas; remediation is only needed where the risk is unacceptable, but limits are not easily defined.

Harmful materials may have to be removed to a safe site, may be buried on site (except oils) under clean soil cover, or may be isolated by grout cut-off and deep burial. Total clean-up may be cost-prohibitive.

Organics may be reduced by on-site bioremediation.

SETTLEMENT OF FILL

Uncontrolled fill may have high potential compaction. For loading of 100 kPa (house strip footings), Young's modulus E may vary from >10 MPa for dense rockfill to <1 MPa for domestic waste. Creep can last for years. Easy field test of settlement is a sand-filled skip left on site for a month; most movement is very rapid.

Normal to use raft foundations for houses on soft fill. Main hazard is long-term differential settlement (tilt) over variable fill. Buried opencast high walls and quarry faces must be traced and avoided; tilt could be excessive and could break a raft.

Inundation collapse is loss of volume when fill is first saturated, by changed drainage or rising water table after mine-pumping stops. Loss of thickness may be 1% on compacted rock debris, over 7% on non-engineered mine waste, and higher on some refuse.

TREATMENT OF MADE GROUND

Various methods of ground improvement (*section 27*) can reduce long-term settlements.

Pre-loading effectively compacts the ground to a depth that is about 1·25 times the depth of surcharge.

Dynamic consolidation is effective to depths of 9 m in sand and rockfill, or 6 m in clay or mixed refuse.

Vibro-replacement stone columns can improve any fill. Pre-inundation may treat dry fill prone to collapse.

Methane, derived from buried domestic waste or from coal-bearing rocks, should be drained to the air, or may be tapped and burned for power production.
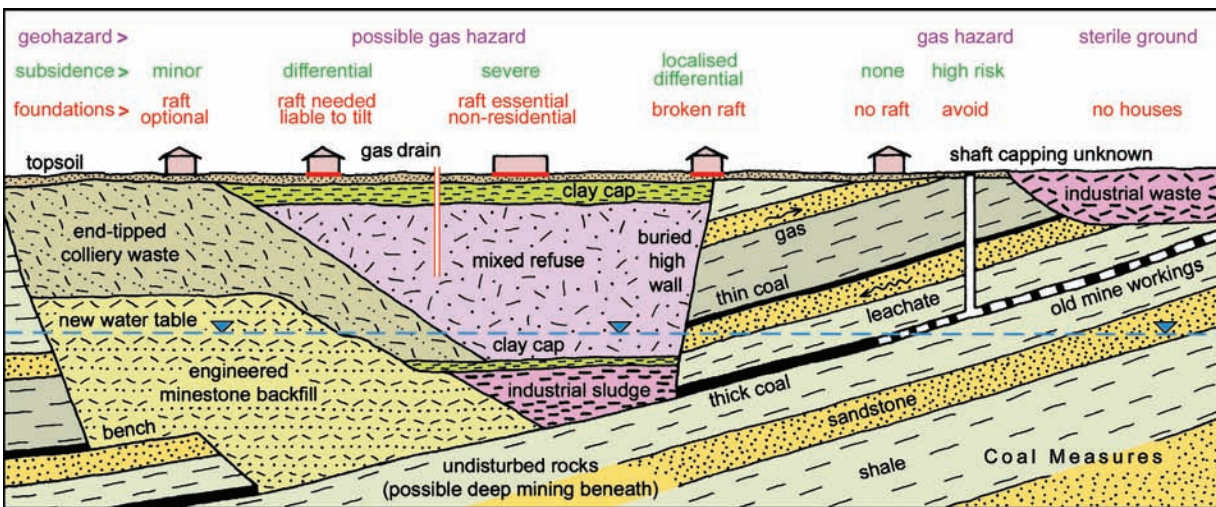
32 Slope Failure and Landslides
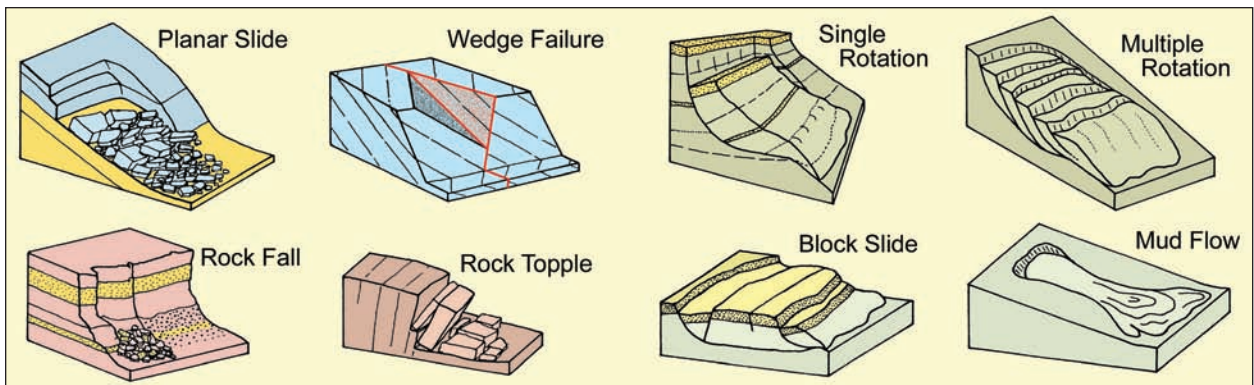
Nearly all slopes ultimately degrade by the natural processes of weathering and down-slope transport.
On most slopes this is a continuous, very slow process. Landslides occur where a slope remains static for a long period and then fails in a single dramatic event.
The result in both cases is the same; landslides are one end of a spectrum of natural processes.
Landslides may occur in any rock type.
They commonly occur where some geological structure, planar weakness or local contrast interrupts the process and pattern of slow degradation.
Potential landslide sites are commonly recognizable by their geological structure.
Even at a potential site, each landslide is normally triggered by an individual event or process.
Landslides are only understood by assessment of both the initial structure and the trigger process.

UNSTABLE SLOPES

Each rock material has its own equilibrium slope angle.
Clays are generally unstable at $>10°$, roughly $\phi/2$.
Most rocks of moderate or greater strength can be stable in vertical walls 100 m high if they are massive with only vertical and horizontal fractures. Granite forms a vertical wall 700 m high on Half Dome California, and the vertical cliffs 150 m high at Beachy Head, Sussex, are formed in much weaker chalk. Minor stone fall is always a hazard on these high faces.
Planar weaknesses – bedding planes, joints, etc. – inclined towards the slope create potential slip surfaces in any rock; slopes degrade back to any major fractures with dip $> \phi$ (may be $<20°$ for clay infilling; cohesion and water pressure are also significant).
Densely fractured or thin bedded rocks weather back to slopes of 20–40°.
Potential failure can be assessed on any of the above criteria in context of local data. Rock slides are mostly related to existing planar weaknesses (bedding, joints, faults, cleavage or schistosity) that daylight within a surface slope (i.e. they have unfavourable orientations and are exposed at outcrop at their lower ends).

TYPES OF FAILURE

Large rock failures are mostly planar or wedge slides on one or more plane surfaces.
Small rock failures are commonly falls or topples.
Clay failures are mainly single or multiple rotational slides, ideally on circular slip surfaces.
Mud slides, mud flows and debris flows develop from weak clays or in failed and broken rock material after initial displacement.
Complex failures are common and involve multiple processes; block slides generally have planar slip surface except for circular head scars.

Head scar of a rotational slide breaks a road in Yorkshire.

SPEED OF FAILURE

Slow: more common in soft clays and ductile materials, notably reactivated old landslides. Thistle Slide, Utah, 1983, moved <1 m/h for two weeks.
Rapid: typical of brittle rock failures as rock is greatly weakened by initial shearing or fracturing. Velocities of >100 km/h are common, as at Madison Canyon.
Cyclic: failure creates a stable slope as the debris becomes toe weight, but erosion of the debris then permits repeat failures, as at the frequent landslides along the boulder clay cliffs of the Humberside coast. Alternatively, due to annual changes of groundwater levels; Mam Tor Slide (*section 35*) moves every winter but is stable in summer.

MADISON CANYON LANDSLIDE, Montana, 1959

Geology and slope angle varies along canyon wall.
West part: 45° slope in strong dolomite – stable.
East part: 30° slope in weak schist – stable.
Mid part: dolomite buttress below schist slope – unstable.
Increased stress in earthquake broke dolomite buttress; unsupported schist slope then failed: 20M m³ landslide.
Failure of this part of the slope was inevitable, whenever dolomite buttress was adequately eroded or weakened; vibration from earthquake was just the trigger process.
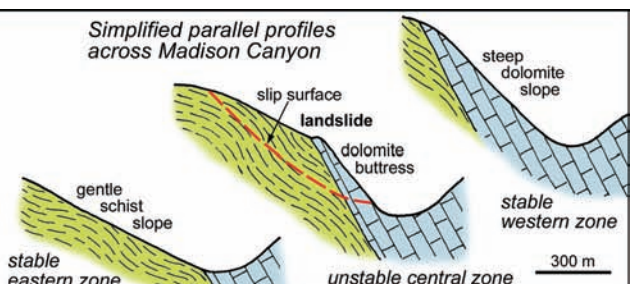
GROS VENTRE SLIDE, Wyoming, 1925

Strong sandstone above weak clay, dip 18° into valley. River eroded toe of slope, removing sandstone support, until 38M m³ moved in bedding plane slide. Similar to prehistoric slides on same side of valley; opposite steeper slope is stable with dips into hillside. Slide debris blocked the valley, creating new lake; when first overtopping by the river, rapid erosion of debris dam caused destructive downstream flood.
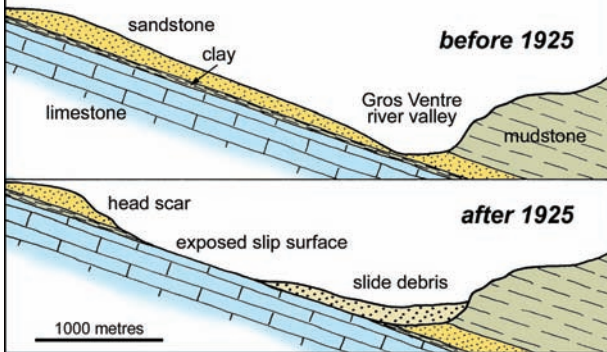
LANDSLIDE TRIGGER PROCESSES

Each landslide event can be ascribed to a process that triggered the failure of a potentially unstable rock mass.
Cause of failure is therefore a combination of unstable structure and one or more trigger events.
Water: rise in groundwater pressure (due to rainfall event or changed drainage) is by far the most important single trigger factor behind landslides (*section 33*).
Toe removal: removing toe of a slope reduces resistance to movement.
Natural toe removal: erosion by river undercutting (Gros Ventre, *above*); erosion by wave action, causing numerous coastal slides (Folkestone Warren, *section 36*); glacial erosion, leaving oversteepened hillsides (Mam Tor, *section 35*).
Artificial toe removal: by quarrying or mining (Frank), excavation for building site (Hong Kong), or road widening (Catak) (*all in section 33*).
Head loading: adding material above neutral line of a slide increases its driving force. Portugese Bend slide, Los Angeles, 1956, was activated by fill placed for a new road that added 3% to slide mass in zone above a slip surface dipping 22° in weak clays. Folkestone slide, 1915, was activated by rock falls from head scar (*section 36*).
Natural head loading causes slope instability on many active volcanoes.
Strength reduction: weathering ultimately weakens all slope materials; slow creep causes restructuring of clays that are stressed within slopes (*section 34*); slow processes eventually reach critical points.
Vibration: cyclic and temporarily increased stresses may cause soil restructuring or rock fracturing.
Artificial vibration, as from heavy road traffic (contributory at many small road failures) or from pile driving (which caused a clay slide destroying Swedish village of Surte in 1950).
Earthquake vibration has caused numerous slides, including Madison Canyon. A 1970 earthquake in Peru started a rock fall on Mt Huascaran, that developed into a giant debris flow moving fast enough to rise 150 m over ridge and bury 20,000 people in the town of Yungay.

Many slides have complex origins, where and when a number of contributory factors coincide; common that rainfall is the final trigger after toe removal (natural or man-made) has destabilised the slope.

STABILITY OF A SLIDE MASS

Basic forces on a slide block are:
W = weight of block, with two components, D and N.
D = driving force = W sin α.
N = normal stress on slip plane = W cos α − u.
u = uplift force due to pore water pressure.
c and F = resistances in reaction to D.
c = cohesion across slip plane.
F = frictional resistance on slip plane = N tan ϕ.
R = resistance to shear = c + (W cos α − u) tan ϕ.
Safety factor = R/D = resistance / driving force.
c and ϕ are properties of the rock material.
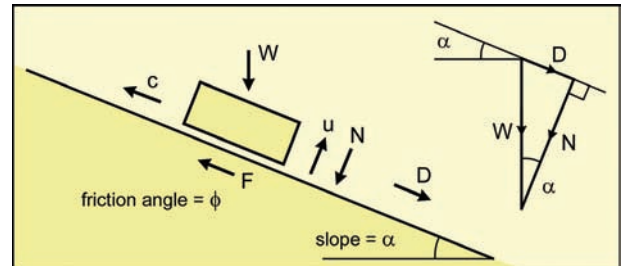
Neutral line: a curved slip surface beneath a slide mass has a neutral line boundary (NL) between a steep section where D > R and a flatter section where R > D.
Tension joints and open fissures at head of slide may contain water that exerts a horizontal joint water pressure (J) additional to the driving force.
Deformation within the slide mass must occur as it moves over a slip surface which is other than plane or cylindrical; resistance to this deformation, by cohesion and friction along multiple internal slip surfaces, adds to the resisting force.

Forces acting on a complex landslide with some engineered features. Notation as above.
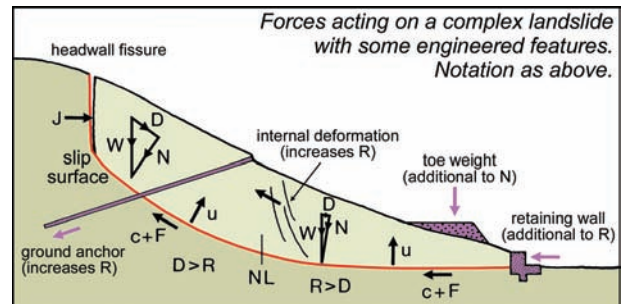
Stability analysis of a landslide may be by assessment of forces in two dimensions in individual slices of the mass; these vary across the slide and may include artificial constraints.
Full landslide stability analysis is more complex due to:
• breaking slide into small units;
• reaction forces between these units;
• variable water pressures;
• estimated values of c and ϕ;
• reactions in three dimensions.

Force diagrams, drawn to scale, quantitatively represent components in a two-dimensional stability analysis. Slice is stable while F+Ac > sliding force, but this is only one slice out of a larger slide mass.

slice width = 1 metre   units = kN

71
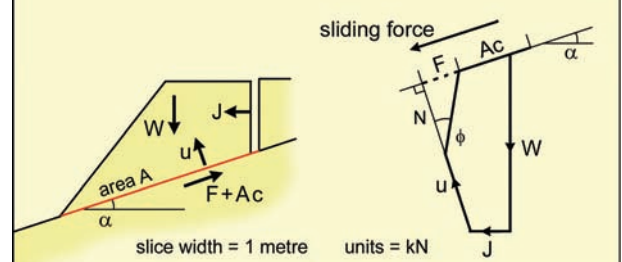
33 Water in Landslides

Groundwater is the most important single factor in triggering landslide events.

Rising water tables and rising water pressures, are contributory to most slope failures; the majority of landslides occur during rainstorms.

Effective stress is reduced by any increase in water pressure and there is a consequent reduction in resistance to shear (*sections 26 and 32*).

Joint water pressure in rocks and pore water pressure in soils are equally important.

Drainage is therefore critical to slope stabilization (*section 36*).

Water input to a slide mass also has the long-term effect of internal weathering. Loading by water in a slide mass may increase the driving force.

Water does not act as a lubricant. The only material approaching the properties of a lubricant in a slide is clay softened by increased water content.

SCARBOROUGH LANDSLIDE, 1993

Single rotational slide formed in clay slope 30 m high, then retrogressive failure of head scar destroyed hotel. Full causes were not investigated; may have included changes to land drainage. Then long period of drought had weakened the dried clay with shrinkage cracks, prior to heavy rainfall that raised pore water pressure.

FRANK SLIDE, Canada, 1903

Glacially over-steepened slope in Rockies cut in dipping limestone of marginal stability.

Rock fissures opened due to creep movement initiated by crushing of inadequate mine pillars left in vertical coal seam across toe of slope.

Failure occurred after first day of spring thaw.

Rockfall of 37M m³ buried the mining town of Frank.

Cause was a combination of the dipping limestone, the mined toe and the input of snowmelt water.
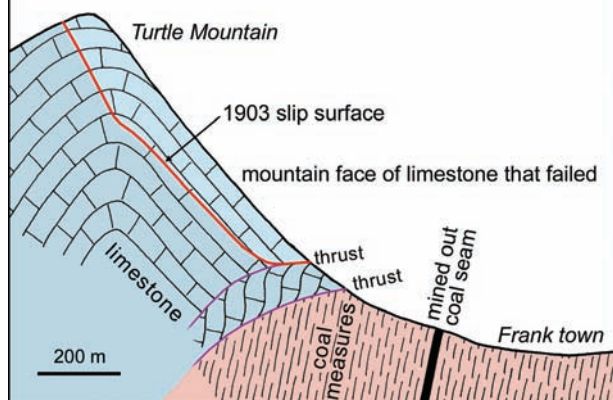
SOURCES OF INPUT WATER

Rainstorms: High rainfalls from individual storms cause numerous shallow slides where high water pressures can rapidly reach slip surfaces.

Hundreds of slides in Jordan, in early 1992, due to rare heavy snowfall and rapid melt in a normally semi-desert terrain; soils, rocks and fills all equally affected.

Destructive 1988 slide at Catak, Turkey, failed during the first period of high rainfall since road widening had steepened the slope four years previously.

Shallow earth slides and debris flows are annual events during rainstorms on steep slopes of the shanty town favellas in Rio de Janeiro.

Rainfall seasons: Deep-seated slides are more affected by annual fluctuations of water table.

Winter groundwater maxima create a landslide season lasting from November to March in Britain.

Monsoons trigger most of the landslides in SE Asia.

Spring snowmelt is the main factor in alpine regions, after slopes have been stable during winter freeze.

Numerous sets of data show correlation between rainfall and slide movement; mostly on small scale with rapid response, or on large scale with response delayed 1–10 weeks; Portuguese Bend and Vaiont are examples.

Artificial inputs: Impounding water in a reservoir raises regional water tables, as at Vaiont.

De-vegetation of a slope allows increased infiltration.

Irrigation of farmland or gardens has caused many terrace edge failures in dry regions such as California.

Secondary effects: Opening of tension fissures in head zone, as slide starts to move, captures runoff and increases infiltration.

PORTUGUESE BEND SLIDE, Los Angeles

Coastal slide of 100 ha of weathered shale, on 6° slope. Slow creeping movement has totalled 40 m since 1956, destroying 127 houses and damaging the coast road. Complex, relatively shallow, slide responds to both individual rainstorms and seasonal weather patterns.
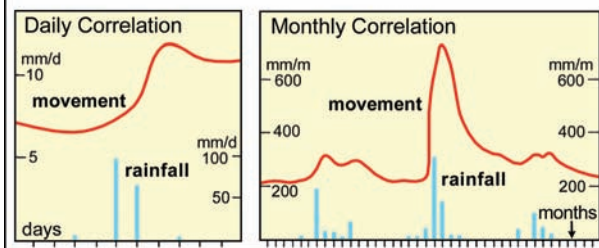
EARTH SLIDES IN HONG KONG

Frequent shallow slides on steep slopes in urban area.

Slides form in soil layers and decomposed granite and volcanic bedrock (weathering grade IV and V).

Soils drain quickly on steep slopes, but are saturated by periodic heavy rainfalls.

Weathering yields sand and clay soils from bedrock; slope movement creates layered soils.

Sand soils over clay soils drain freely; are recognized as low-hazard zones.

Clay soils over sand soils, with lateral variations and lenticular beds, can create inclined artesian aquifers; these may have high water pressures on underside of clay caps where slip planes can develop; they are now designated as hazard zones on steep slopes.

Clay layers can be more important as impermeable seals than as easily sheared planes.

VAIONT RESERVOIR SLIDE, Italy, 1963

The Vaiont slide involved a magnificent dam, an awful reservoir site, and the world's worst disaster caused by civil engineering – leaving 2043 people dead.

Vaiont Dam: in Alps north of Venice; cupola (double arch) dam 266 m high, of concrete 4–23 m thick.

Landslide on 9 October 1963; 270M m^3 of rock, forming a slab 200 m thick, moved 400 m at 20–30 m/s. Landed in reservoir and created huge waves.

Wave 100 m high overtopped dam (which survived), but then destroyed Longarone and other villages.

Limestones, strong and impure, form slide mass; thin bedded with many clay horizons in lower part; interbed horizons are 5–100 mm thick, of plastic clay, PI = 30–60, ϕ = 8–10°; below slide is pure limestone.

Dip = 30–45° N (downslope) at slide head, easing to 10–15° (and more towards east) near valley floor.

Slide mass was massive wedge on bedding plane slip surfaces and along faults on eastern edge. It moved as a single slab. It was a preglacial landslide mass, reactivated because new movement was possible into post-glacial Vaiont river gorge through old slide toe (this was only fully recognized after the event).

Groundwater pressures were raised by impounding the reservoir; also rose due to rainfall; high pressures beneath slide's basal clays, in limestone fed by karst sinkholes high to south. Heavy rain just before failure.

Movement of hillside was monitored since dam completed 1960; slip of 0–35 mm/day correlated with discontinuous reservoir filling; also correlated with rainfall in previous 60 days. Small part of slide failed in 1960.

Slip surface largely followed the preglacial slip plane in the clay beds; also broke across some limestone beds. Resistance to shear mainly on eastern side of the wedge, where ϕ = 36° along fractures.
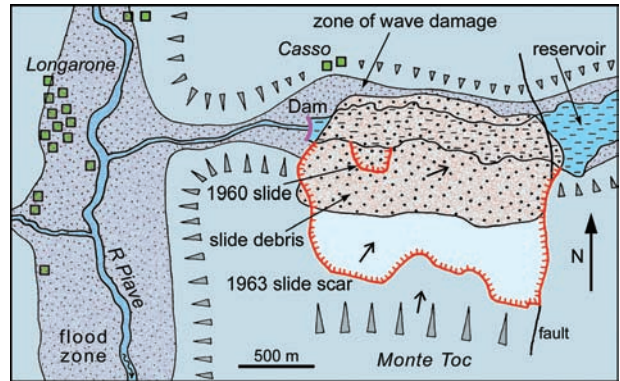
Stability analysis, completed after the event and in the knowledge of the preglacial landslide slip surface, suggests factors of safety (FS) for different states.
Reservoir was designed to fill to 722 m; it failed at 701 m during a wet period; but it would have failed anyway when filled to 722 m, even in dry weather.

Reservoir level = none	Rainfall = low	FS = 1.21
none	high	1.12
710 m	low	1.10
710 m	high	1.00
722 m	low	1.00

Cause: unstable dipping limestone forming old slide.
Triggers: high rainfall and reservoir impoundment.
Rapid failure: due to brittle rupture of some key limestone beds and rock units, after years of creep had reduced mass strength; borehole monitoring data suggests lack of movement and stress accumulation in toe of slide while surface was creeping.
Fatal error was to assume slide-mass would creep until it stabilized on the flatter toe. Potential instability was recognizable; a reservoir was therefore inappropriate.
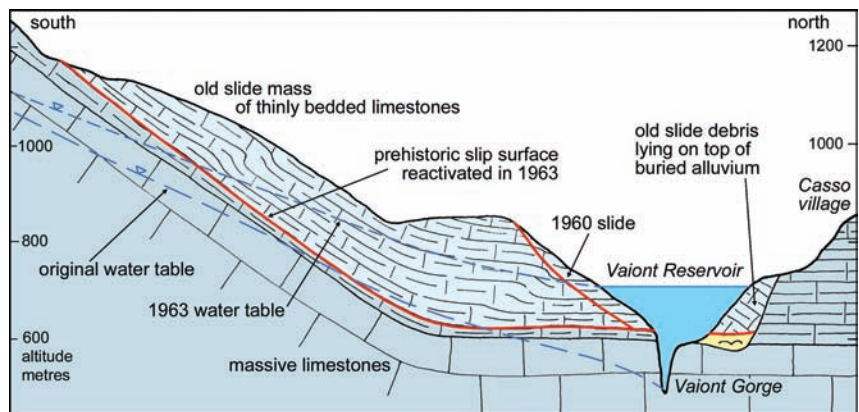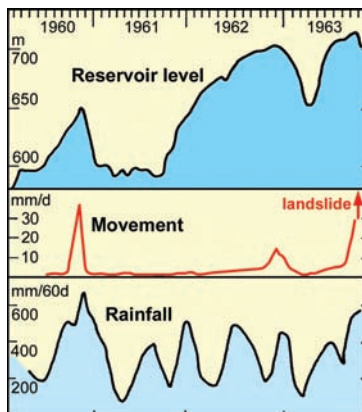
PO SHAN ROAD SLIDE, 1972

Largest slide on Hong Kong island, killed 67 people.
Natural slope at 36°, with soil 15 m thick.
Existing buildings were on 20 m piles to sound rock.
Cause: steep soil slope + high rainfall + cut face.
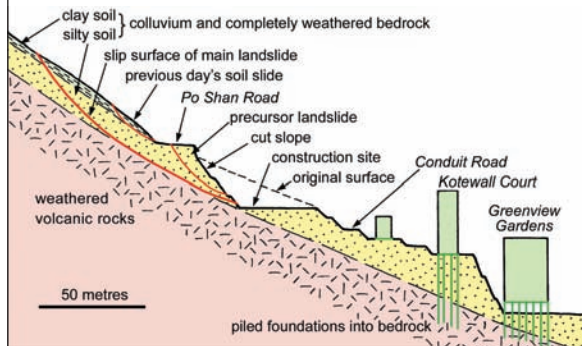
Sequence of events is significant:

1. Construction site left cut slope unsupported for 7 years; exposed soil softened in bare slope at 75°.
2. Small falls, groundwater seepages, and head cracks in Po Shan Road, were observed for a year before event.
3. Rainfall of 700 mm in 3 days prior to slide was highest on record; caused small adjacent slides.
4. The day before main slide, a slip produced 5 m head scar in Po Shan Road and debris flows on the building site.
5. Four hours before main slide, most of the cut face failed, and debris flows crossed Conduit Road 2 m deep.
6. Immediately before main slide, a small slip from higher on the hill landed on Po Shan Road.
7. Main slide carried 25,000 m^3 of rock and soil debris, and moved 280 m, in less than a minute.
8. Kotewall Court, a 13-storey block of flats, was pushed off its foundations, tilted over and collapsed, destroying (in passing) the upper floors of Greenview Gardens, the next block of flats downslope beside the main slide.

73

34 Soil Failures and Flowslides

CLAY SLOPES

Clays are the weakest, most unstable, slope material.

Undisturbed clays can stand in steep temporary slopes rendered stable by cohesion, pore water suction and peak frictional strength.

Disturbed clays, and those that have been restructured through creep over time, commonly have internal realignment of the clay particles so that they are roughly parallel. This reduces their internal friction and also eliminates cohesion; at the same time drainage equilibrates and eliminates suction.

Natural slopes, with long-term stability, depend on internal friction only. Saturated clay soils have nearly half their weight carried by pore water pressure; so slope is generally stable at angle close to $\phi_r/2$, with residual value of ϕ_r (*section 26*).

London Clay has $\phi_r = 20°$; slopes are stable at <10°, and do not exist at >12°.

Old slides are at residual strength; they are reactivated mainly by head loading or toe removal.

Failure surface in homogeneous soil is a slip circle.

Critical slip circle, of lowest safety factor, is found by tedious calculation of all possible circles, summing data on slices and using iterative methods; this is now always done by computer.

Back analysis obtains soil strength parameters by stability analysis of failed slopes when safety factor = 1.

PROGRESSIVE FAILURES

Clays are brittle and lose strength as they fail.

Brittleness = % loss of shear strength, in decline from peak to residual.

Clay soil is locally over-stressed in slopes that are too steep or too high; deforms and loses strength, passing load to adjacent soil; shear zones grow and coalesce; overall strength declines to ultimate failure of slope.

Scale of progressive movement and partial failure depends on brittleness.

At intermediate stages, some of the soil is loaded at peak strength, while some is losing its strength in the post-peak deformation.

Mean strength during failure is close to ϕ for peak strength, with cohesion close to 0.

Progressive failure may take years. Many railway cuttings in London Clay have failed after 50–100 years, before reaching residual strength.

Coastal landslide on the Isle of Wight; a soft clay has failed between vertical beds of sand, developing into a mudflow with typical arcuate pressure ridges.

FLOWSLIDES

Soil, clay or rock debris may fail as flowslide where the material behaves as a liquid, when water content is above the liquid limit. Usually due to decrease in strength, not to increase in water.

Liquefaction: total loss of strength due to undrained restructuring. Disturbance, by shearing or vibration, destroys soil skeleton; with loss of grain contract and decrease of porosity, soil load transfers pore water; water pressure > normal stress, so effective stress = 0 and soil therefore acts as a liquid. Subsequently, drainage reduces pore water pressure, allows grain contact, and there is therefore thixotropic recovery of strength.
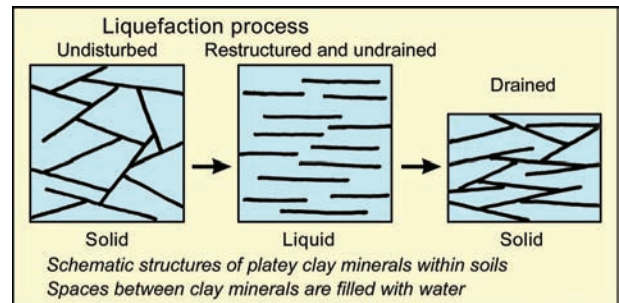
Fluidization: develops in moving materials, notably in large rock falls and pyroclastic flows. Grains continually bounce off each other with no permanent grain contact or strength. Pore fluid may be water or air. May also involve hovercraft effect on cushion of trapped air. Stops when movement reduces to critical point.

Flowslides are extremely mobile, so can move over low gradients. Most develop from smaller initial slides, notably slope failures in sensitive clays, slides in non-cohesive tip debris, rock falls in mountain regions. Also triggered by earthquake vibration.

Fluidized rock falls include those at Frank and Yungay (*section 32*) and Saidmarreh; also many large slides that block deep valleys in Himalayas. Most violent are known as *sturzstroms* in Alpine terrains.

SAIDMARREH ROCKSLIDE, Iran

Prehistoric slide, perhaps largest in world.
Limestone slab, 20,000M m³, slipped on dip of 20°.
Fluidized debris travelled 16 km across valley floor, at >300 km/h, and up over ridge 450 m high.
Slide debris was first thought to be glacial till.

SOLIFLUCTION

Downslope movement of saturated debris.

Periglacial conditions (*section 16*) in Pleistocene caused numerous slope failures in Britain.

Solifluction of active layer was widespread on slopes as gentle as 4°, notably in clays, mudstones and chalk.

Head is name used in Britain for soliflucted soils.

Postglacial thaw of permafrost permitted drainage and thereby marginal stabilization, leaving shear surfaces in the head with residual strength of $\phi_r = 8$–15°.

Many slides reactivated since recent deforestation.

Any slope >5° in clay, which was in the periglacial zone during the Pleistocene, is likely to have head debris that is prone to reactivation and slope failure.

Sevenoaks Bypass, in Kent, had to be relocated across soliflucted slope; Pleistocene flows on slopes of 2–7° consisted of head few metres thick overlying clay; upslope cutting sides were impractical to stabilize.

QUICK CLAY SLIDES

Sensitivity, or extreme undrained brittleness, is loss of strength when sheared.

Sensitivity is defined as ratio of compressive strengths, undisturbed: disturbed.

Sensitive clays have sensitivity >4.

Quick clays have sensitivity >16.

Highest sensitivity in clays or silty clays, due to realignment of clay plates (mainly illite) and silt grains.

Fine grain and low permeability hinder drainage and allow liquefaction to develop fully.

Leda Clay of Eastern Canada is the classic example of quick clay, along with similar clays in Norway and southern Sweden.

These were in marine clays formed around margins of Pleistocene ice sheets; were then uplifted by glacial unloading; they now form low valley-floor terraces with steep edges where cut into by postglacial rivers.

Clay particles were originally flocculated into clumps due to bonding in saline porewater.

Leaching by modern rainfall removes the salt and the inter-particle bonding, leaving a metastable structure.

Liquefaction is caused by small slope movements in terrace edges when porewater has <1 ppm salt.

Flowslides develop and rapidly expand headwards.

Stabilization may be possible by brine injection.

NICOLET FLOWSLIDE, Canada, 1955

Typical failure of terrace in sensitive Leda Clay.
Rapid headward growth carried away buildings, and left large arcuate scar 10 m deep.
Debris from the flowslide spread 250 m into river.

TURNAGAIN HEIGHTS SLIDE, Alaska, 1964

Clay terrace 25 m high with 8 m gravel cap.
Clay has 40–53% with <2μ diameter; sensitivity 10–40.
Major earthquake had local intensity VIII, with strong motion for >4 minutes (an unusually long duration).
After 90 seconds of vibration, clay liquefied.
Major translation slide; movement in lower 8 m of clay.
Slide area extended to 50 ha; 75 houses were wrecked, some moved 150 m.
Ground stable again after earthquake vibration ended.
Clay sensitivity known from laboratory tests in 1959.
The hazard had been recognized, but had been ignored as it would only materialize in an earthquake; but this was almost inevitable in southern Alaska.

ABERFAN TIP FAILURE, Wales, 1966

Best known of many similar colliery tip failures because it struck the village school and killed 112 children.

Failed material was artificial, but causes lay partly within the geology of the natural ground beneath.

Multiple event, with rotational slip followed by flowslide and mudflow.

Location of Tip 7 (which failed) was very unsuitable.
- Tip overlay natural spring from sandstone.
- Springline along base of Brithdir Sandstone well known as site of many previous tip failures in Welsh Valleys.
- Tip extended over sheared debris of the 1944 slide from Tip 4, higher on the hill.

Rotational slip was created by head loading of slope – common event on tips built from the top.

Large scale of the slip was due to saturation of its debris by the spring beneath; three previous failures at Aberfan were over springs, there were no failures of dry tips.

Slow movement; 6 m headscar developed within a few hours before formation of the flowslide.

Mining subsidence ground strain produced local extension zone; this increased rock fracture permeability and spring flow, raising water pressure within tip.

Flowslide formed in saturated debris that restructured in the rotational slip, with reduction of porosity and strength decline to residual.

Liquefaction as debris could not drain; low permeability due to high content of fines from mine washing plant.

Flow of 110,000 m³ debris, moved 610 m on 13° slope.

Rapid consolidation occurred when the flow stopped.

Mudflow formed in some of debris with water released from sandstone when main slide stripped off glacial till.

Cause: essentially the saturation of the undrained tip debris, which was placed over a spring – due to a total lack of ground investigation prior to tipping.

Other factors then increased the scale of the disaster.

Profile through tip # 7
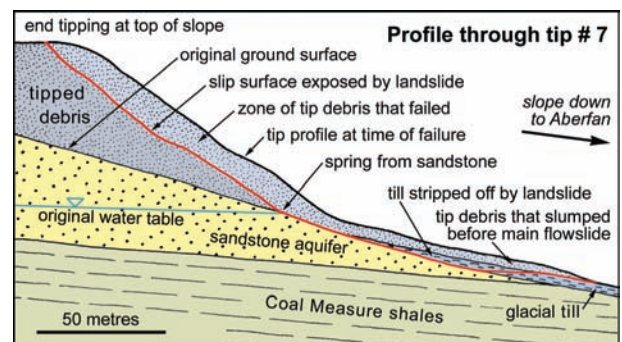
35 Landslide Hazards

POTENTIAL SLOPE FAILURES

Most failures of rock slopes are related to planar weaknesses with unfavourable orientations.

Wedge failures are most likely where line of intersection of two fracture planes dips $< \phi$ and daylights in steeper slope; best interpreted graphically by stereo-projection.

Hazard zones. A failure potential can be recognized, but incomplete data on any buried rock structure means that stability analysis can only be estimated, and risk assessment is therefore subjective, as it is dependent on strengths and structures assumed.

Time of failure cannot normally be predicted except that it will probably be during or just after a rainstorm.

Size and speed of future event is rarely predictable.

Small unsafe slopes may be economically stabilized.

Large unstable slopes are best avoided if possible.

LANDSLIDE HAZARD MAPPING

Can be effective for route planning and land use zoning.

Assessment parameters include:

- rock type, structure and strength;
- soil type and plasticity;
- slope angle and shape;
- drainage state and level of water table;
- history of previous landslides;
- land use, including vegetation type and change.

Local data is the basis for any hazard evaluation, notably the slope angles known to fail in each rock and soil type, and any particular rock structures.

Key factor is recognition of old, inactive slides.

OLD LANDSLIDES

Low stability because shear surface has reduced to residual strength with little or no cohesion. Reactivated with no peak strength to overcome.

Stable slopes are therefore close to $\phi_r / 2$ in saturated soils and debris; slightly steeper in rocks and where water table cannot rise to surface.

Recognize old slides by surface features:

- irregular hummocky ground on slipped material;
- lobate plan of debris and solifluction flows;
- unsorted slide debris, which may resemble glacial till;
- concave upper slope and/or convex lower slope;
- head scars, rounded in soils, angular in rock;
- back dips in slipped blocks due to rotation.

Shear zones: in rock, may have parallel shear slices and fragmented rock; in soils, are mostly remoulded, soft to medium stiff, wet, silty clay, 1–50 mm thick.

Slip surfaces, in rock and soil, may be clean breaks with or without polished surfaces and/or slickensides.

Identification of slip surfaces may be difficult in boreholes due to core loss in the shear zone, or by confusion with simple fractures.

Investigation of shallow slides is best with trenches or trial pits; trench wall cut smooth with knife normally shows slip planes in clays (especially after they have opened due to shrinkage on drying); can be important in recognition of solifluded head.

ACTIVE SLOPE MOVEMENT

Surface signs include: fresh scarps or terraces; new ponds, undrained hollows or pressure ridges; fresh sharp rock fractures; distorted tree growth.

May be able to locate depth to slip surface by offset of a borehole that is left unlined or cased with flexible plastic, or by acoustic emission profiling.

SLOPE HEIGHT

Cohesion allows slopes to stand at angles $> \phi$ (angle of internal friction of the rock or soil).

Frictional resistance, effective stress and driving force are all functions of mass, increasing with slope height; cohesion is a function of area, independent of height, so it has less proportional effect in high slopes.

Low slopes can therefore stand at steeper angles than high slopes in same material.

Intact rock (horizontally bedded) will stand in vertical cliffs of height limited only by UCS; coastal cliffs in weak chalk stand 150 m high.

Height and slope of natural and cut faces is limited by fractures – mainly their orientation, also density, roughness and shear resistance.

High slopes in dry materials all have stable angles that approach the lesser of ϕ or the dip of significant structural weaknesses that daylight in the slope.
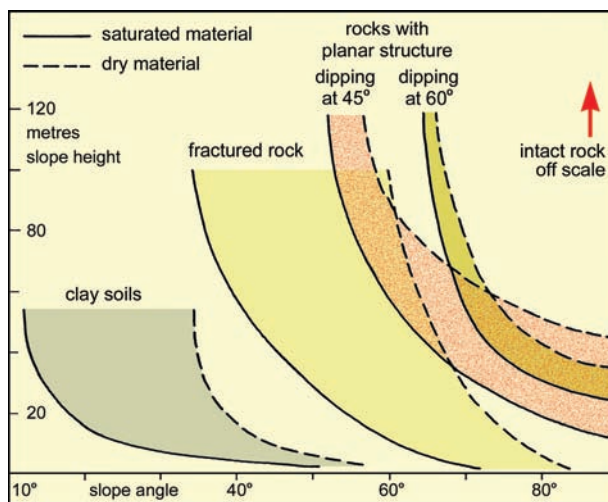
Influence of natural slope height on stable slope angle.

All stable slope angles are reduced by saturation (roughly halving the tangent of the angle); saturated values apply to long-term stability in natural slopes.

Shallow surface slides and isolated rock falls are independent of slope height.

Karakoram Highway crosses over 500 km of mountains between Pakistan and China, with steep slopes in the geologically active terrain; some part of the road is closed on average one day in two by rock falls, debris flows and mudslides landing on road; most blockages are cleared within a few days, and repeat failures are inevitable; stabilization of high slopes above the road is impractical and uneconomic; but the roadbed is well engineered, so it rarely fails except on a very small scale.

MAM TOR LANDSLIDE

Glacially over-steepened slope on shale and sandstone in English Pennines.

Landslide is 300 m wide, 1000 m long, >3000 years old.
Upper part is multiple rotational landslide of bedrock slices, with road stepped over minor head scarps.
Lower part is debris flow, creating wavy road profile.
Road across the slide has been closed since 1977.

Stability analysis considers slices extending down to slip surface, each 1 m wide, and each broken into sections of uniform properties.

Factor of safety = FS = shear resistance/driving force

$$FS = \frac{\Sigma c' L + \Sigma (W \cos\alpha - uL) \tan\phi'_r}{\Sigma W \sin\alpha / (1 + d/b)}$$

c' = apparent cohesion,
      taken as 0 on reactivated slip surfaces.
L = length of slip surface in vertical sided section.
W = mass of slice; unit weight = 20 kN/m³.
α = inclination of slip surface.
u = pore water pressure
      = height of water table above slip surface.
ϕ'_r = angle of frictional shear resistance,
      taken as residual value of 14°,
      from tests and back analysis of nearby slides.
d/b = slide depth/slide width,
      for edge drag due to lateral earth pressure.

Calculated values of FS for whole slide are close to 1·0; these are correct, as slide is in critical state, just moving; so assumed values of c and φ are good.

- Upper slide: analysis of typical slice section:
  where d = 20, u = 10, α = 13°; then FS = 0·86;
  if water table is lowered, u = 5; then FS = 1·01.
- Lower slide: analysis of typical slice section:
  where d = 15, u = 12, α = 7·5°; then FS = 1·19;
  if water table rises to surface, u = 15; then FS = 0·99.
- Whole slide: FS reduces by 0·05 for every 1 m rise of water table.

Movements of around 0·7 m occur one winter in every four, when threshold groundwater levels are exceeded – by a winter month with rainfall 60% over average following a year of above-average rainfall.

Drainage with deep sub-horizontal boreholes or adits (*section 36*) would stabilize the slide effectively.

Earth shift from head to toe would have minimal effect as debris could flow round any toe weight (or anchor).
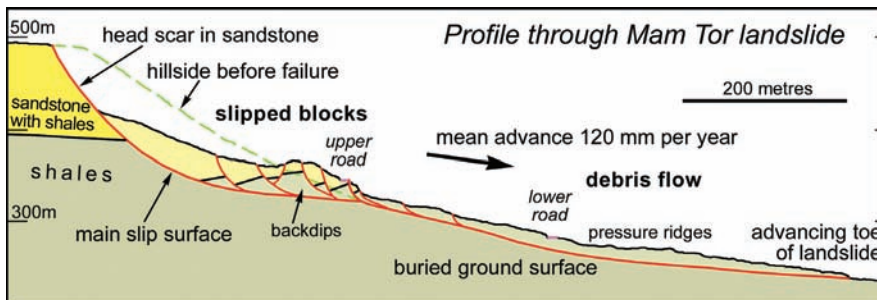
LANDSLIDE MONITORING

Various means of instrumentation; wide range of cost.
- Surface surveying between fixed reference points.
- Crack dilation measured between studs glued to rock.
- Standpipe or electric piezometers, for manual or automatic reading of water table levels.
- Boreholes with installed inclinometers.
- Horizontal or vertical borehole extensometers.
- Photoelastic or electric load cells on installed anchors.
- Geophones that record acoustic emissions (ground vibration due to movement).

Simple, rugged instruments are most reliable.

Reading and interpretation must be over a long time.

Monitoring shows any acceleration of movement; interpretation is difficult as critical values are unknown unless there is documented history of previous events (as in some large quarries). Vaiont slide (*section 33*) was monitored, and failed unexpectedly.

Extensometers, geophones and electric trip wires can be linked to automatic warning systems, as in some railway cuttings in Sweden.
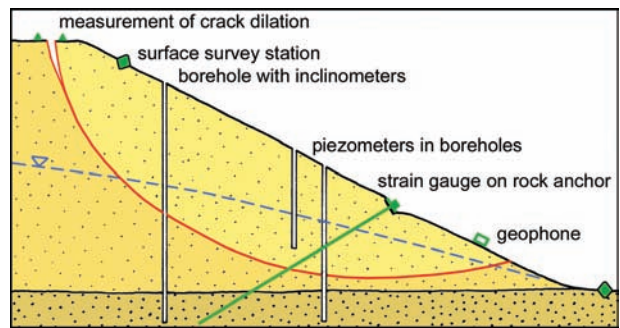
STONE FALL

Almost all rock faces, natural and cut, produce random falls of small rocks due to natural weathering.

Face cleaning, by rope-access technicians, commonly once a year in springtime, can minimize the hazard.

Safety catches are still needed where roads and buildings are threatened; these are generally cheaper than face stabilization works.

Rock trap ditches at foot of slope: bank 1·5 m high, best topped by fence or dense bushes, in front of a ditch 3 m wide (with earth floor for impact absorption), is good for most faces <20 m high; ditch 5 m wide for higher faces, and higher bank for slopes around 60°.

Small ditches or fences alone suffice below low cut faces.

Gabion walls are very effective and economical traps on slopes with lower gradients.

Rock catch nets are effective on steep slopes and cliffs: wire or rope netting hangs in catenary sag between hinged supports, with cable anchors to rockbolts using cable brakes (loops designed to slip through clamps); designed to deform to absorb impact energy.

Rockfall shelters protect roads beneath very loose slopes; massive concrete with roof covered by blanket of crushed rock (or sloping like avalanche shelters).

Profile through Mam Tor landslide
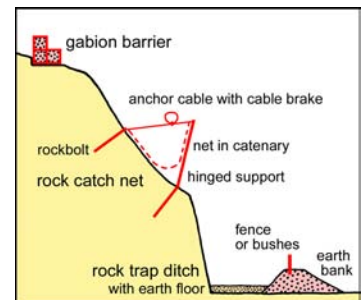
36 Slope Stabilization

Slopes may be stabilized by one or more of:
- modifying the slope profile, where possible;
- supporting or anchoring the existing profile;
- improving or draining the slope material.

PROFILE MODIFICATION

Adding material below neutral line, also removing it from above, increases stability. Neutral line is where slip surface is horizontal beneath an undrained slide; but in drained conditions, the neutral line is displaced upslope to where dip of slip surface $= \phi$.

Berm ledges, about 5 m wide on steps 10 m high, redistribute load and stabilize circular slips in weak rock. Small failures on steep faces of steps land on berms harmlessly, and can be cleared away.

Hanging blocks, slabs and wedges, which rest on daylighting, unfavourably orientated fractures, can be completely removed; this commonly leaves asymmetrical road cuttings in beds with dip $> \phi$.

Toe weight is effective, especially where lower end of slip surface turns up. May be mass concrete, rock fill, earth bank reinforced with geogrids, or thick crib walls. Size must restrain formation of new undercutting slip surface that may reach beneath new toe.

Unloading head of slide generally has less effect.

Original cause of failure should be removed where possible: river bank erosion control or sea wall to prevent continuing toe removal.

DRAINAGE OF SLIDES

Pore water pressure is critical to slide stability, so drainage is usually very effective, and is the only economical method to stabilize large landslides within natural slopes.

Surface drains: concrete diversion ditches intercept surface flows; drains on slides reduce infiltration.

Shallow drains: stone drains in trenches 1–2 m deep lined with geotextile; have limited effect by reducing soil water; granular fill in deeper counterfort drains also provides shear resistance.

Deep drains: most effective; mined adits with leaky walls and sealed floor, or boreholes with perforated casings, inclined to drain out from slide toe.

Relief wells: drain up or down through aquiclude; need pumping unless drain into lower aquifer. Some London Clay slopes have been drained into lower sand, through 100 mm boreholes filled with sand in polypropylene tubing, on 2–5 m centres.

Interception tunnels: cut behind slide to reduce groundwater inflow; used in 1800 to stabilize failing slopes of limestone and clay above city of Bath.

Impermeable clays respond poorly to normal drainage. Electro-osmosis, or heating with ducted hot air, can improve clay stability, but both are expensive.

LLANDULAS LANDSLIDE

New road along North Wales coast and new marine defence works were sited to act as toe weight, improving stability of old slide and restraining formation of new undercutting slip surface.
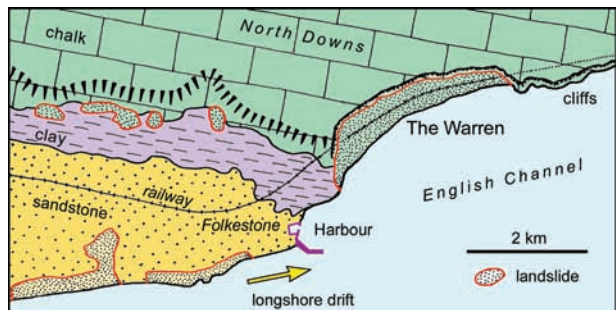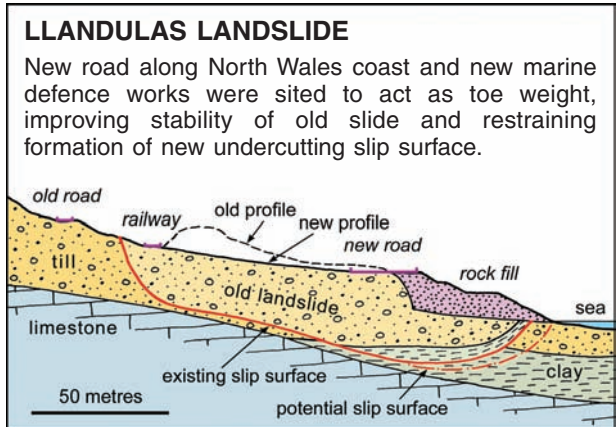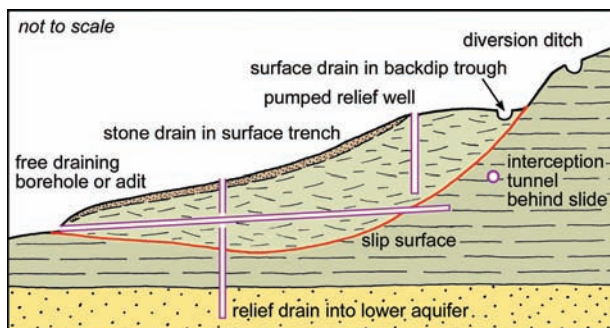
FOLKESTONE WARREN LANDSLIDE

Multiple rotational coastal landslips in chalk over clay, crossed by mainline railway.
- High winter water tables and relaxation of the over-consolidated clay cause renewed movements; the largest slips are triggered by rock falls from chalk cliffs onto the head of the main slide mass.
- Toe erosion increased due to beach starvation after harbour wall was extended in 1905 and thereafter trapped longshore drift of beach sediment.
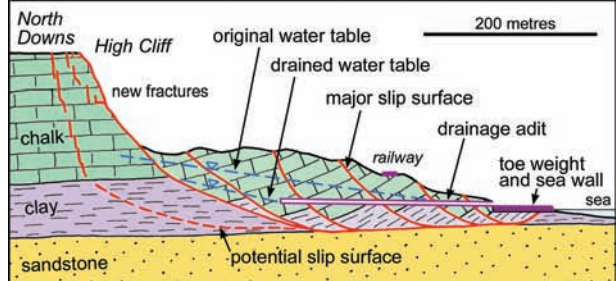
- Stabilization measures were started after major failure in 1915, and have been added to since then: mass concrete toe weights also act as sea wall to reduce toe erosion; drainage adits cut in from sea wall lower water table within the complex slide mass.
- Movements are now reduced to very low rates.
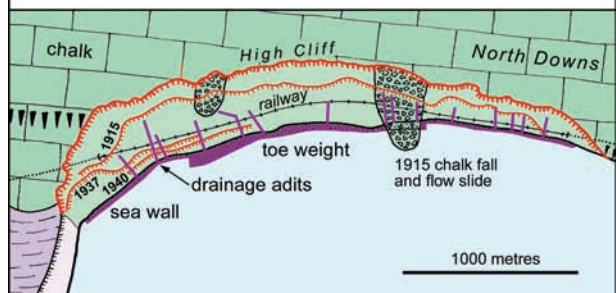
MASS SUPPORT

Retaining walls: common practice and successful on small slopes and cut faces, but not on larger slopes. Large unstable slopes are not easily retained; it is difficult and usually uneconomic to build and found massive retaining walls at the toe of major natural landslides or large unstable slopes.

Concrete walls: need sound footing; prevent from rotation by buttresses, or by combination of heels, toes and shear keys at base; or rock anchors from near top and/or base, or deep foundations; weep holes permit drainage; masonry facing improves appearance.

Dental masonry: hack out weak zone of rock and refill with cemented masonry or concrete with stone facing; may dowel into rock.

Gabion walls: cheap to install, can retain soil slopes and act as toe weight.

Sprayed concrete (shotcrete): may be used with rockbolts (*section 38*); spray over bolted reinforcing mesh, or use fibrecrete containing 50 mm lengths of steel wire within the sprayed mix to give tensile strength.
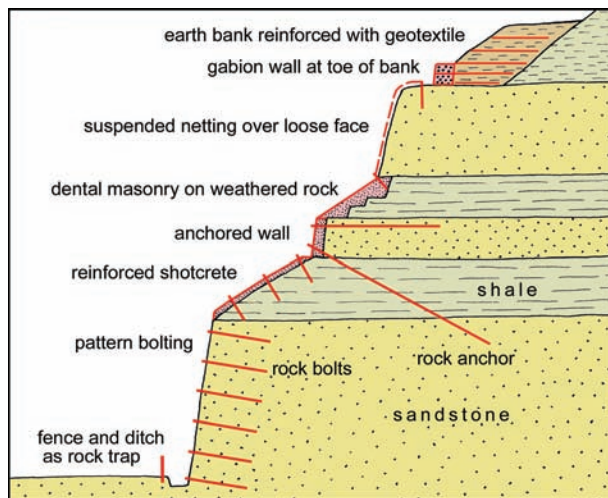
GROUND IMPROVEMENT

Vegetation cover reduces rainwater infiltration, and root mat provides tensile strength in soils – but is destructive on rock faces, as roots force open joints.

Geotextiles, geogrids or wire mesh, anchored to bolts, fixes surface and retains small stonefall; plants grow through and provide long-term strength; biodegradable jute mesh provides short-term support.

Weathering protection by sprayed concrete or fibrecrete, or by chunam (spread mortar); any slope cover must have adequate drain holes.

Pattern bolting creates thick stable layer by tightening the natural rock joints (*section 38*), and also reduces water infiltration.

Grouting fractured rock is expensive and rarely applied; may use to stabilize scree.

Liming clays reduces plasticity; improves unstable sodium montmorillonite by change to calcium variety.

The Folkestone Warren landslide.

Retaining wall under construction, with frontal toe, rear heel and buried shear key, for new road cut in Midlands; exposed bored piles provided temporary support.

GROUND ANCHORS

Tensile support may be provided to oppose directly the landslide driving force.

Rockbolts: steel bars, 25 mm diameter, 3–10 m long, in drilled holes, fixed at inner end by resin or expansion shell, 100 kN load, tensioned to 60 kN (*section 38*). Main purpose to increase normal stress across joints; cannot be placed in heavily shattered rock. Pattern bolting (spaced at length / 2) gives major support; isolated spot bolts retain individual blocks of rock.

Grouted dowels: steel bars in drilled holes through joints provide direct shear resistance.

Bored piles: act as large dowels, but limited success. Concrete piles 6 m long, 1·2 m diameter, placed across slip surface of Portuguese Bend landslide, Los Angeles, had no measured effect; some rotated, some sheared, slide debris flowed round others.

Rock anchors: multiple steel cables, 10–40 m long, in ribbed protective casing for installation in drilled 100 mm holes, up to 2000 kN load, tensioned to 60%; fixed about 5 m resin bonded into rock. Provide tensile support and tighten rock fractures. Most effective where installed at angle of ϕ above slip plane.

Anchored walls, flexible or rigid, distribute load from anchor caps onto weak landslip material.

HOAR EDGE CUTTING

Shallow slide, initiated during construction of Pennine motorway, was stabilized by lowered profile and rock buttress. Subsequent movement, by renewed activation of an old natural landslide, required an anchored wall – crushed rock in geotextile net faced with shotcrete, with 41 cable anchors, each 1000 kN, spaced 1–3 m, bonded for 6 m into stable sandstone.
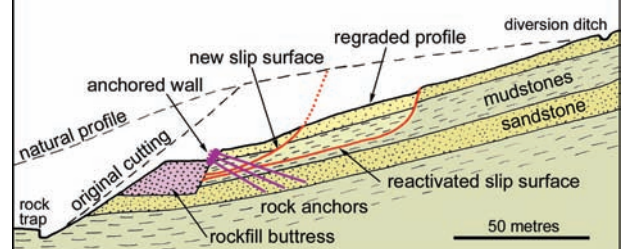
SHEAR KEYS

May be used to stabilize toes of slides in weak soils. Trenches filled with granular material (with high ϕ) reach through slip surface into stable ground.
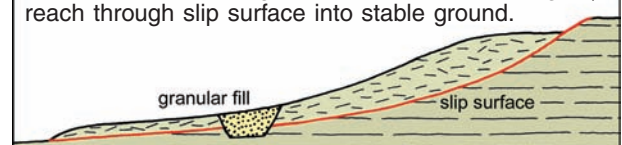
37 Rock Excavation

EXCAVATION METHODS

Method relates to rock strength and fracture density.

- **Direct excavation**: possible in fractured rock of mass class V (*section 25*) and in all soils; using face shovel, backhoe, clam-shell grab or dragline.
- **Ripping**: needed to break up slightly stronger rock, roughly class IV; using tractor-mounted ripper, or breaking with boom-mounted hydraulic pick (pecker).
- **Blasting**: generally required in stronger, less fractured rock. Class III rock is loosened in the ground by undercharged blasting in some quarries; on urban sites can be broken by hand-held pneumatic drill or by pecker. Massive rock of moderate or high strength, class I or II, needs to be fractured normally by blasting; where blasting is unacceptable, breaking by pecker or with hydraulic breaker is very slow.
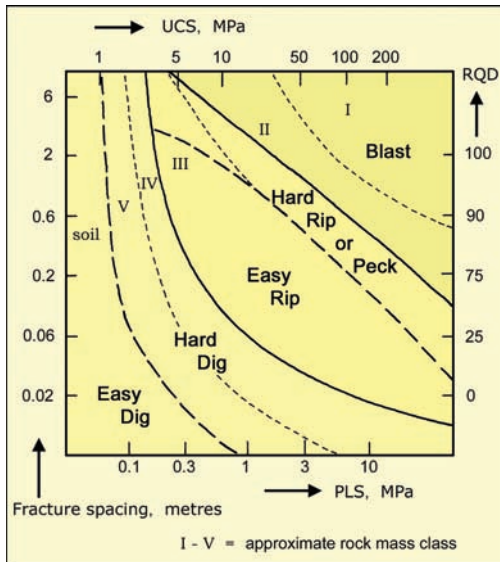
CUT SLOPES IN ROCK

Sound rock can be cut to vertical faces; normally raked back by 10° and benched at 10 m intervals to improve safety. Higher benches cannot be drilled accurately; berms act as rock traps on highway cuttings and in working quarries.

Inclined fractures are main hazard, notably dipping 30–70° and daylighting in face. Dips > 50° normally require cutting face back to clean bedding or fracture.

Shale beds may weather and undercut slopes in strong sandstone or limestone.

Slake durability test measures % retained intact through 10 minutes of wet/dry cycles in a standard drum apparatus. Most rocks have values > 90. Values < 50 for shales indicate susceptibility to weathering and long-term slope degradation.

Hillside excavations may undercut unstable weathered rock, old landslides or soliflucted head.

Floor heave is rare in rock excavations; only likely if unloading stress > 6 × shear strength.

Guidance values for long-term stable slopes
Values in above table are reduced for slopes with poor drainage, steep dips or structural loading, also in areas of deep weathering, mining subsidence or any seismic activity, and also for unbroken heights > 20 m.
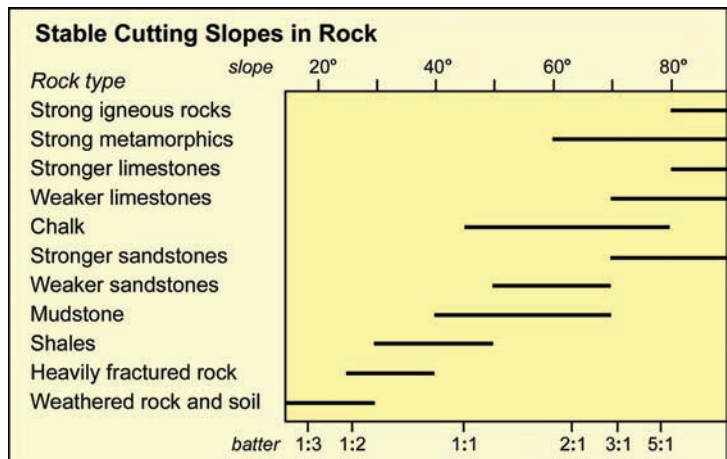
PANAMA CANAL, instability of Culebra Cut
Deep cut planned as vertical, completed with 15° sides. Repeated slides in saturated shales and tuffs were only overcome by American use of steam shovels.
Excavation: planned 46M m³; completed 170M m³.

CUT SLOPES IN CLAY

Drainage changes stability over time where face is cut into clay with initial water table near the surface.
1. Excavation permits stress relief, so pwp decreases.
2. Pwp then rises to regain equilibrium (drained state); strength and stability therefore decrease.
3. Slope ultimately drains (or is artificially drained) to new lower water table; reduced pwp then increases stability.

Rate of change depends on permeability.

Temporary faces in clay can stand vertical to height = 4 × cohesion/unit weight, less the depth of any tension fissures. Walls shear at critical values; base failure undercuts propped faces at slightly greater heights.
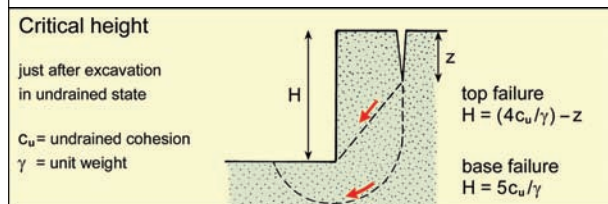
Premature failure occurs where stability is due to temporary pore water suction; failure may be in minutes or hours, so faces are battered back for longer safety. London Clay, unweathered, is cut to 65° on slopes 8 m high where small slips can be tolerated; reduce to 20° for unsupported faces below buildings.

Stiff glacial till may stand close to vertical for some months at less than critical height, so retaining walls can be built in front. Weep horizons on sand layers cause instability.

Lateral stress relief in slopes cut in over-consolidated clay may cause outward movement.

Settlement adjacent to stable cut slope may be 1–2% of excavation depth, reaching back from crest of slope by 2–4 × depth of face.

| material | cohesion | critical height, H | |
		unfissured	fissured
Soft clay	25 kPa	5 m	3 m
Firm clay	50 kPa	10 m	6 m
Stiff soil	12 kPa	24 m	15 m
values for typical fissure depth = z = 1·5 c/y			

OPEN FACE BLASTING

Drilling: method should relate to rock toughness – highest in fine-grained igneous rocks.
In soft rock use pure rotary drills.
In hard rock use rotary percussion drills with tricone or roller bits, or down-hole hammer.

Drill holes: 50–100 mm diameter (D), and preferably at 10–15° from vertical.
Burden is distance of line of drill holes from free face, therefore thickness of rock to be moved. Ideally should be 30–40 × D, generally 2–4 m.
Spacing along line = 50 × D, generally 3–5 m.
Hole depth = 2–4 × burden, commonly 10–15 m.
Subdrilling needed below grade to depth = burden / 3.
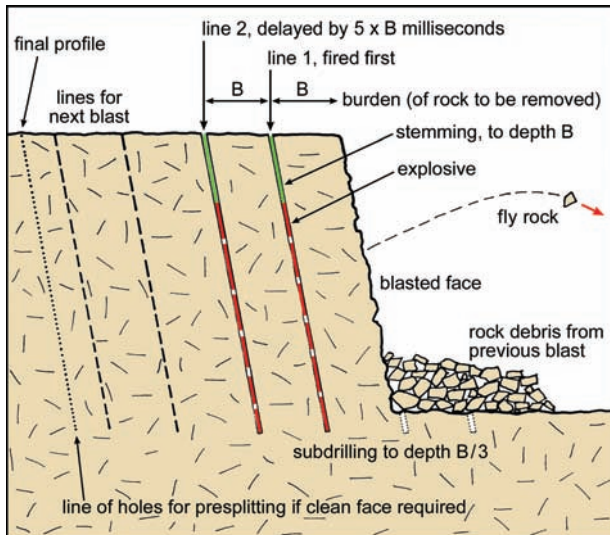
Charging: generally with 0·4–0·6 kg ANFO per m³ rock. Stemming is sand filling of hole above explosive, to depth that matches the burden, to reduce fly rock.
Firing is usually by electric detonator caps; electric delay caps allow firing of multiple lines in one round, each with optimum burden; so second, inner, line is delayed by 5 milliseconds per metre of burden.
Fragmentation of rock is best determined by field trials; improve by smaller spacing and burden, and by shortened delays that superimpose vibrations.
Blast energy travels along joints; quarry faces are most economical parallel to joints.

Controlled blasting of final perimeter line should leave clean wall free of blasting fractures.
Presplitting: line of holes with spacing only 10–20 × D; charged with 10% normal, low density explosive, decoupled (not rammed tight against drillhole walls, so reducing fracturing); fired simultaneously with high burden (before removal of main bulk), to create a single clean break linking the holes.
Line drilling: line of holes with spacing only 2 × D, not charged, so main blasting can work back just to line of perforations; expensive, used only on fragile sites.

MAIN TYPES OF EXPLOSIVES

Black powder (gunpowder) = potassium nitrate, sulphur and carbon; slow expansion, used to extract dimension stone (*section 39*).
Dynamite = 20–60% nitroglycerine, with ammonium nitrate (or nitrocellulose in gelatin dynamites); greater power, lift, fracturing and vibration.
ANFO = 94% ammonium nitrate and 6% fuel oil; cheap, safe to handle, dissolves in water; 40% less powerful than dynamite; more efficient in weak rock.

BLAST VIBRATIONS

Normally measured as peak particle velocity (ppv) in the 5–20 Hz range.
General safe limit of 50 mm/s ppv may be modified for different structures and relates to charge weight (of dynamite) and distance to the structure; graph refers to typical conditions, which may vary slightly with the local geology.
Reduce vibration levels with delayed firing (~10 ms between smaller individual charges within the round) or low density explosives.
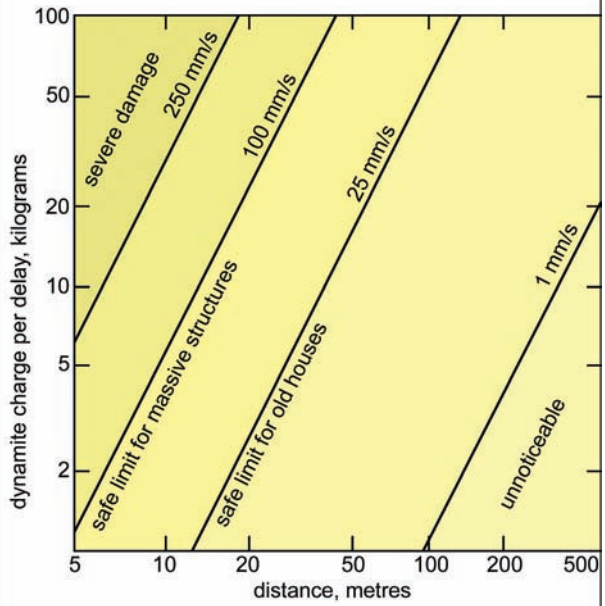
GROUNDWATER CONTROL

Good drainage of any site excavation is essential; it is normally the most cost-effective means of rock slope stabilization (*section 36*).
Pumped drainage allows excavation below water table.

Horizontal drains, with slight outward gradient to provide gravity flow; bored holes 100 mm diameter with perforated casings, on spacing of <10 m, up to 50 m long, drain off site or into pumped sump.

Vertical well points, for temporary de-watering while site is worked inside coalesced cones of depression; well points are jetted into soils, 1–2 m spacing, can lift 5 m with surface vacuum pump. Submersible pumps in bored holes in rock or soil can be deeper – capacity and spacing depends on ground permeability and flows. Seepage water that flows away from the excavation improves slope stability.

Groundwater barriers permit dry excavation without lowering surrounding water table; sheet piles, concrete diaphragm walls, grouted zones or ground freezing (in order of rising costs); grouting or freezing can also control rising groundwater within thick aquifers.

Drainage of a construction site

81

38 Tunnels in Rock

TUNNEL EXCAVATION

Choice of three methods. All cost £2–30M per kilometre.
Drill and blast: in any rock, and for all large caverns.
Roadheader: machine mounted with a rotary milling head (specific to rock type); flexible system best for use in rock with UCS <60 MPa.
Tunnel boring machine: now increasingly used, though often uneconomic in tunnels <1 km long.
Shaft sinking involves tedious debris clearance; raise boring is self clearing and often easier.

DRILL AND BLAST TUNNELLING

Full face in good rock; benched or crown heading with subsequent breakout where bad rock needs support.
Jumbo machines have 2–5 drills on arms; can swing to drill bolt holes.
Drill holes converge round a central wedge which is blasted out first; delay fuses (1–100 ms) then break outer zone into the central hole.
Smooth blasting leaves clean walls with perimeter holes spaced <1 m, lightly charged and fired simultaneously.
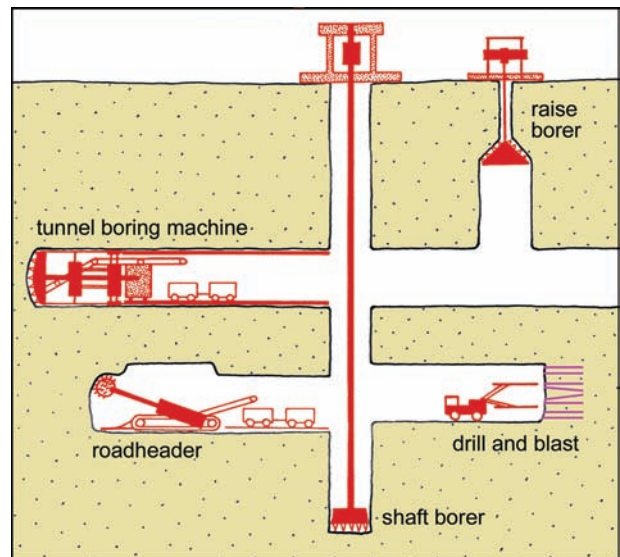
TATES' CAIRN TUNNEL, Hong Kong, 1989

Progress in tunnel 10·7 m wide, 8 m high, was by full face working in strong granite.
Two 10-hour shifts/day, advanced 60 m/week.
Drilling (3 h): round of 90 holes, each 50 mm diameter, 4·5 m deep; each hole took 3 minutes with jumbo.
Charging and firing (2·5 h): 4·5 kg dynamite per hole.
Mucking (4 h): front loader filled 20-tonne dumptruck in 2 minutes; 1000 tonnes per round, bulking 50%.

TUNNEL BORING MACHINES (TBM)

Full-face rotating head, up to 15 m diameter, armed with roller discs or chisel picks, turning 2–10 rpm.
Modern TBMs are capable of working through hard rock.
Progress forward with hydraulic rams pushing against the installed lining of concrete segments, or by jacking against side gripper pads.
Advance: 30 m/day in soft ground, less in hard rock.
Cannot vary diameter; tightest curve = 300 m radius.
Some work as earth pressure balance shields, with a bulkhead providing face support in soft ground.

DIFFICULT GROUND CONDITIONS

Faults can cause many problems – broken ground, increased water flow, and maybe change of rock type.
Groundwater is difficult in high flows; worst are karst fissures with up to 500 l/s, which may need bulkhead sealing and/or flow diversion.
Overbreak in hard fractured rocks is worst in sedimentary and metamorphic along vertical strike.
Squeezing ground = plastic flow, mostly in clays and shales where UCS/overburden stress < 2.
Rockbursts occur mainly at depths > 600 m in rock with UCS >140 MPa.
Swelling ground = wall closure due to any increased water content in clays.
Temperature of ground increases 2–4°C/100 m depth.
Rockhead is major hazard zone; underwater tunnels normally keep >20 m rock cover.
Stress reduction in roof causes loosening of jointed rock and potential delayed failures.
Vertical stress within tunnel walls rises to 3 times overburden load.

SEIKAN TUNNEL, Japan, 1985

Rail tunnel 54 km long, reaches 250 m below sea level.
In difficult mixture of faulted volcanic rocks, with UCS varying 3–150 MPa.
Cut by drill and blast, with 200 mm shotcrete lining, and steel arches in soft rock; grouting in fault zones after major flooding; cost £2500M.
Kept 100 m below seabed; advance probes all the way.

CHANNEL TUNNEL, Europe, 1992

Rail tunnel 50 km long, twin bores 7·6 m diameter.
In impermeable chalk marl with low fissure density, UCS = 5–9 MPa, close to ideal tunnelling medium.
Cut by 8·7 m TBM, and lined with precast concrete segments 360–540 mm thick; cost £900M.
Kept 20 m sound rock between crown and seabed.

ADVANCE GROUND IMPROVEMENT

Spiling strengthens an arch of rock with advance fans of rockbolts splayed 10° from tunnel axis.
Grout may be injected through a similar fan of holes ahead of tunnel or into exposed zones of weakness.
Drainage control from surface, by well pointing, grouting or freezing; usually only in soils at shallow depths.
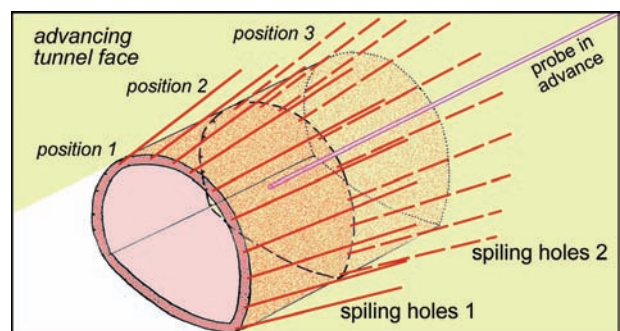
GROUND INVESTIGATION

Costs 0·5–3% of project, most in mixed weak rock.
Variable ground may warrant advance probes, which are successively drilled 20–30 m ahead of face.
Seismic geophysics (*section 22*) can locate zones of poor rock by reduced velocity, beneath land or water.

Rock Tunnel Support Systems

PASSIVE SUPPORT

Use steel ribs (colliery arches), cast concrete, or precast concrete segments (automatically placed by TBM) grouted on outside.

Rock may impose high stress on parts of support.

Cast concrete, on travelling formwork, now mainly used as secondary linings for road tunnels not dug by TBM.

ACTIVE SUPPORT

Strengthens the rock, mainly with rockbolts and shotcrete, to create a stable self-supporting arch within the rock mass over a tunnel opening.

Better than passive support in all but weak soils.

Norwegian Tunnelling Method successfully defines the required support; it is an adaptable system (based on experience), which can be applied to variable rock conditions. Extent of bolting and reinforced shotcrete is defined by rock mass quality and tunnel width.

New Austrian Tunnelling Method (NATM) allows limited rock deformation around tunnel; this redistributes stress to achieve new stable state, but is not enough to permit loosening and weakening. Bolts and thin flexible shotcrete lining are rapidly installed to take only a part of the load; deformation (of 10–100 mm) is permitted as rock takes up remaining stress, before secondary lining is installed.

SELECTION OF SUPPORT SYSTEM

Diagram shows appropriate support system, based on tunnel dimension and rock mass quality.

Q value defines rock mass properties on Norwegian system (*section 40*). Class refers to rock mass (*section 25*).

Equivalent dimension = actual roof span / ESR.

Excavation Support Ratio (ESR) reflects needs of safety in different situations. Guideline values of ESR:

Temporary mine openings	ESR = 2·0 – 5·0
Water tunnels, pilot tunnels	1·6 – 2·0
Access and minor rail tunnels	1·2 – 1·3
Major road and rail tunnels	0·9 – 1·1
Underground stations as public areas	0·5 – 0·8

Further detail on the support systems relates to rock class and tunnel size within full classification, published and periodically updated by Norges Geotekniske Institutt.

SHOTCRETE

Concrete 20–200 mm thick sprayed onto rock wall. Ideal as it interacts with rock, turning fractured rock into stronger rock mass in surface zone of peak stress.

Placed at 10 m³/h, gives rapid flexible support in NATM, and protects rock from weakening on exposure.

Reinforced for tensile strength with steel weldmesh.

Layer 150 mm thick on 10 m diameter tunnel, as lining in compression, safely carries 450 kN load (equivalent to 10 m of roof rock that has effectively failed).

Reinforcing weldmesh within the shotcrete is tied to raised flanges on the rockbolts to create an integral stable arch of both rock and shortcrete.

Fibrecrete contains 50–80 kg/m³ of steel fibres each 40–50 mm long; better than steel mesh on uneven faces, but shaped mesh often better in uniform tunnel profiles.
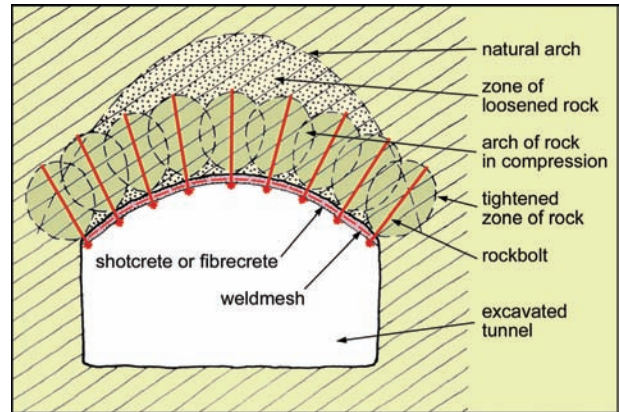
ROCKBOLTS

Mostly 2–5 m long, in 35 mm holes; load to 100 kN.

Three main types of fixing.

- Expansion shell, takes immediate load; cheapest.
- Grouted in with resin or cement; strongest.
- Friction, various types; Swellex deformed steel tube is expanded in hole by 30 MPa water pressure, takes immediate load; simplest.

Roof bolting should have:

- length = 1·4 + (tunnel width / 5) m;
- spacing = length / 2 and < (3 × joint spacing);
- tension against cap plate to 60% capacity.
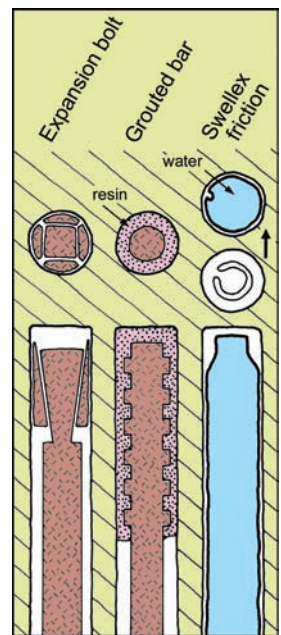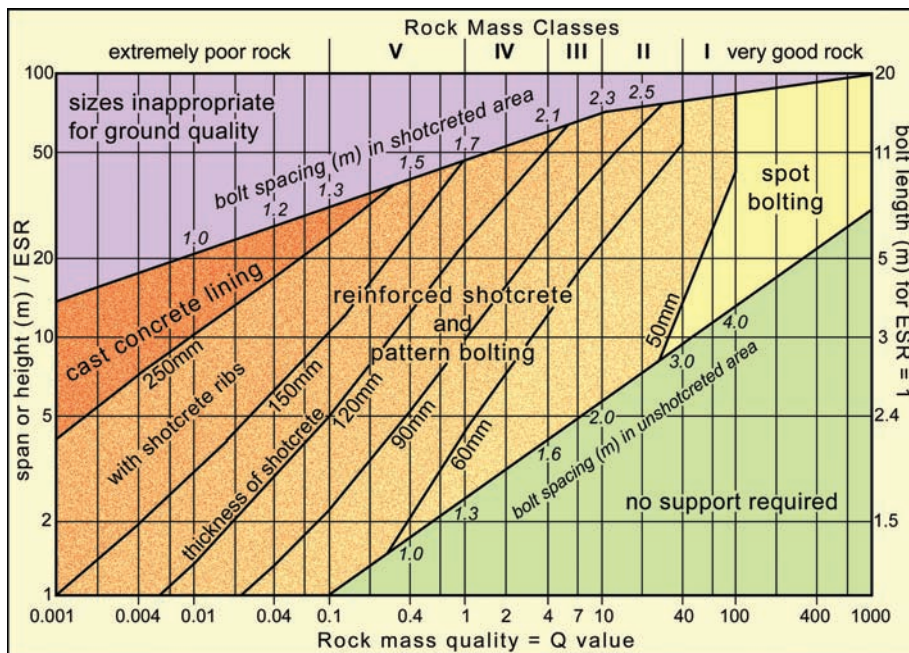
Types of rock bolts.

39 Stone and Aggregate

Demand for stone is around 200 Mt/year in Britain.
Less than 1 Mt/year is used as dimension stone.
All the rest is aggregate, of which roughly:
- half goes to roads, half to concrete construction;
- over half is crushed rock, rest is sand and gravel.

AGGREGATE PROPERTIES

Rock strength is the prime requirement – usually requires UCS >100 MPa or 10% FV >100 kPa.
Main demand is for particle sizes 5–50 mm; screened at quarry and normally sold as single size.
Quality is specified by aggregate tests (*below*).
Aggregate trade groups (*opposite*) provide a useful classification as they group materials by their properties and not by geological origin, and therefore identify some significant features.
- Basalt and gabbro show good tar bonding (to the iron within their minerals).
- Gritstone and granite have very high PSV, and their rough surfaces adhere well to their binders.
- Flint and porphyry have smooth surfaces that can cause poor bonding, may have sharp edges and are more prone to alkali reaction.

Some younger and softer limestones and sandstones fall outside the grouping, along with all other weak sedimentary rocks that cannot be used as aggregate.

Lightweight aggregate may be provided by young volcanic pumice (of which there is none in Britain), or some porous synthetics (notably pulverized fuel ash from power stations, and some furnace slags).

Concrete aggregate generally needs 10% FV >100 for structural work, though 10% FV >60 is adequate for some ground concrete; alkali reaction potential is important; rounded aggregate (from natural gravels) produces a concrete that flows more easily.

Road wearing course needs 10% FV >100, good tar bonding and PSV >60, though PSV also depends on the sorting and the binder, and different road types demand different values; angular material as crushed quarry output is generally better than natural gravel.

Railway ballast needs 10% FV >100 and AIV <18.

TYPICAL AGGREGATE PROPERTIES

Material	Location	10% FV	AIV	AAV	PSV
Granite	Dartmoor	280	16	5	60
Dolerite	N. Pennines	360	10	4	60
Greywacke	Pennines	220	14	7	65
Gritstone	Peak District	90	40	26	74
Limestone	Pennines	120	20	12	40
Flint	Thames gravel	450	23	1	35

AGGREGATE IMPURITIES

These must generally be avoided, and may be limited by contract specifications.
- Clay and mica: weak, absorptive, expansive.
- Opaline silica: alkali reaction.
- Pyrite: weathers to sulphuric acid and rust.
- Coal and lignite: react with bitumen binders.
- Organic (shell and plant): weak and reactive.
- Salt: corrosion, efflorescence, expansion.
- Sulphate: expansion, efflorescence.

ALKALI AGGREGATE REACTION

A mechanism of concrete deterioration due to reaction between certain types of aggregates and alkaline pore fluids in the concrete. A silica gel is formed, which absorbs water and expands, thereby cracking the concrete. This may take 5–10 years to develop.
Resultant cracks allow more water and salt in, which cause even more corrosion of reinforcing steel and deterioration of concrete.
Main reaction is with hydrated, opaline silica in aggregate – mostly in young acid volcanics, tuffs and some cherts. Reaction can also be with mixture of calcite, dolomite and illite in some limestones.
Avoid by using aggregates already successfully used, or keep cement alkali content <0.6% if acid volcanics or dolomitic limestone have to be used as aggregate.

AGGREGATE TESTS

Various tests are used for contract specifications.
These are summarized in table below, with guidelines to indicate good and bad values, and the limits that are commonly used for wearing course roadstone.
Most test procedures are defined in British Standard EN932-5; other countries have their own similar tests; American tests in annual volumes of ASTM Standards.
All tests are carried out on prepared aggregate samples.

Strength is indicated most closely by ACV. This is rarely quoted directly; instead, 10% fines value is graphically determined from a series of ACV tests with different loads.
10% fines value is in kPa, and is numerically just a little higher than UCS in MPa.

CBR is primarily a field test for placed materials; has been extended to testing sub-grade soils, which have lower values than aggregates. Plastic clays generally have CBR <10; sandy soils typically have CBR = 10–40.
Particle angularity, surface roughness and thermal expansion may also be measured, and may require defining for some situations.

STANDARD AGGREGATE TESTS

Aggregate property	Test procedure (detailed in the appropriate part of BS EN932-5)	Range of values Good	Range of values Poor	Road stone
Aggregate impact value (AIV)	% fines lost by hammering on standard rig	5	35	<20
Aggregate abrasion value (AAV)	% loss by abrasion on standard test	1	25	<10
Polishing stone value (PSV)	Frictional drag recorded on pendulum swing	70	30	>60
Aggregate crushing value (ACV)	% fines lost by uniform load crushing on standard rig	5	35	
10% fines value (10% FV)	Load on standard ACV test rig to give 10% fines loss	400	20	>100
Flakiness index	Weight % particles with minimum thickness < 60% mean	20	70	<3
Water absorption	Weight % increase after immersion in water for 24 hours	0.2	10	<2
Frost heave	Heave of air-cooled column of sample standing in water	3	20	<1
California bearing ratio (CBR)	Resistance to plunger penetration, compared to standard	100	60	>90

CRUSHED ROCK

Angular rock chippings are better for roadstone.
Quality control is simple where a single, uniform rock mass is being quarried.
Weak impurities are reduced to fines in the crushing process, so are easily removed by screening.
Main costs are for blasting and crushing.
Selection often based on distance from quarry to site; land transport costs soon exceed quarry costs.
Remote coastal quarries overcome environmental and cost problems; Glensanda granite quarry in NW Scotland can economically ship aggregate to Bristol and London, and to ports in southern Texas.

NATURAL AGGREGATES

Alluvial gravels are the most important resource, from floodplains and terraces.
Dredged marine gravels and some glaciofluvial gravels are also used; glacial till is too poorly sorted.
Rounded gravel particles are better for concrete.
Quality control is more difficult; alluvial gravel consists of any rocks within the river catchment, so may be varied; River Trent gravels are mainly pebbles of strong quartzite from Triassic conglomerates, but also contain coal fragments; coal is removed at source by washing (density separation in turbulent water).
Main costs are for overburden stripping and screening.

AGGREGATE TRADE GROUP CLASSIFICATION

Group	Including	Characteristics	Quality
Basalt	dolerite	strong, fine-grained, basic igneous	good
Gabbro		strong, coarse-grained, basic igneous	
Porphyry	rhyolite	strong, fine-grained, acid igneous	
Granite	gneiss	strong, coarse-grained, acid igneous	good
Hornfels		strong, fine-grained, uncleaved metamorphic	good
Schist	slate	flakey, sheared or cleaved metamorphic	poor
Quartzite		strong, metamorphized sandstone	rare
Limestone	marble	the stronger limestones and dolomites	good
Gritstone	greywacke	the stronger, well-cemented sandstones	good
Flint	chert	fine-grained silica, mostly as gravel	
Artificial		any synthetic slags	
[Reject]		the soft sedimentary rocks	useless

Granite quarry for dimension stone in Sardinia.

DIMENSION STONE

This is defined as stone that is used in large blocks, whether rough from a quarry or sawn to size; the rock must therefore have a low fracture density to permit extraction of large blocks.
Construction stone may be any locally available rock with UCS >50 MPa. Mostly limestones, sandstones and granites; now largely replaced by concrete.
Freestone is any stone that has neither a preferential fracture direction nor any planar weaknesses, so is best used for carved ornamental work.
Cladding stone is used in sheets, 10–20 mm thick, as facing panels over concrete. Needs UCS >100 MPa, should be attractive, and must normally take a polish. Dominated by marbles and granites.
Armour stone is large, uncut, chunk rock used for erosion defence. Coastal sites exposed to wave action need UCS >150 MPa in large blocks, so granite used; but density >2.8 t/m³ (in dolerite and gneiss) may be specified. Limestone with UCS >100 MPa acceptable for smaller waves on lakes, and for protective riprap of smaller sized blocks on earth dam faces.
The high value of cut and polished dimension stones means they may be shipped greater distances, and are therefore widely available. Notable examples include Carrara marble from northern Italy, larvikite from Larvik (Norway), slate from Wales, Rock of Ages granite from Vermont (USA); but much good stone now comes more cheaply from China or India.

Granites: Very strong, suitable for all uses, but hard and therefore expensive to polish.
Larvikite: Variety of granite with internal reflections from feldspar crystals; makes attractive dark cladding.
Limestones: Strong limestones that take a polish are known in the trade as marble; they are softer and cheaper to polish than granites.
Marble: Along with the strong limestones, make excellent cladding and architectural stone.
Softer limestones: Do not polish, but freestones make excellent building stone – notably Cotswold and Portland stones of southern England. Some may weather badly, but they can case-harden due to redeposition of calcite by pore water on exposure.
Travertine: Soft, easily carved, best for internal use.
Slate: Strong and very durable; may be split along cleavage (normally by hand using just hammer and chisel) into sheets 4–6 mm thick; ideal for roofing.
Best Welsh slate has the highest flexural strength and can be cleaved to 1 mm thick. Some is used in sawn blocks for architectural work.
Sandstone: Much used in the past, less today. Cannot polish, and rough surface blackens with soot.
York Stone is any Carboniferous sandstone from the Pennines of northern England.
Flagstone: Variety that splits into bedding slabs each 40–50 mm thick. Good for paving flags; also used on roofs, but very heavy due to thickness.

40 Appendices

DESCRIPTION OF ROCK MASS QUALITY BY THE NORWEGIAN Q SYSTEM

Ratings are determined visually for the six parameters. The Q value is then calculated as:

$$Q = (RQD/Jn) \times (Jr/Ja) \times (Jw/SRF)$$

Q values may be directly related rock mass properties, and other ratings systems (*section 25*).

Rock Quality Designation	RQD
Values from borehole data	10–100
If RQD <10, use 10 to calculate Q	10

Joint Roughness Number	Jr
Discontinuous joints	4
Rough or irregular, undulating	3
Smooth and undulating	2
Rough and planar	1.5
Smooth and planar	1.0
Slickensided and planar	0.5
No rock wall contact across gouge	1.0

Joint Water Factor	water pressure	Jw
Dry or minor flow	<100 kPa	1.0
Medium inflow	100–250 kPa	0.66
Large flow in sound rock	250–1000 kPa	0.5
Large flow washing out joint infills	250–1000 kPa	0.33
Very high flows	>1000 kPa	0.2–0.05
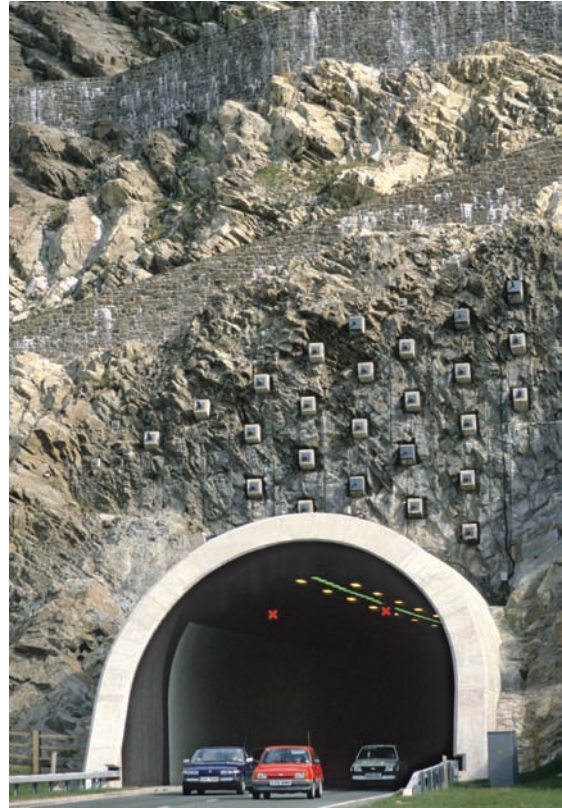
These tables only summarize the Q parameters.

The full system, with many refinements, and its application to the design of tunnel support systems is in Barton, N., Lien, R. and Lunde, J., 1974. Engineering classification of rock masses for tunnel design. *Rock Mechanics*, **6**(4), 189–236.

Joint Set Number	Jn
Massive, no or few joints	0.5–1.0
One joint set; if random also, add 1	2
Two joint sets; if random also, add 2	4
Three joint sets; if random also, add 3	9
Four or more joint sets	15
Crushed rock, earthlike	20

Joint Alteration Number	ϕ_r	Ja
Rock walls in contact:		
Clean, tight joints	>25°	0.75-1.0
Slightly altered joint walls	25–30°	2
Silty or sandy clay coatings	20–25°	3
Soft clay coatings	8–16°	4
Gouge or filling < 5 mm thick		
Sandy particles or fault breccia	25–30°	4
Stiff clay gouge	16–24°	6
Soft or swelling clay gouge	6–12°	8–12
Thick continuous clay zones	6–24°	10–20

Stress Reduction Factor		SRF
Fractured rock prone to loosening		
Multiple weakness zones with clay, loose rock		10.0
Multiple weakness zones, no clay, loose rock		7.5
Single weakness zones, cover depth > 50 m		5.0
Single weakness zones, cover depth < 50 m		2.5
Loose open joints		5.0
Sound rock	*UCS/major stress*	
Low stress, near surface	>200	2.5
Medium stress	200–10	1.0
High stress, tight structure	10–5	0.5–2.0
Mild-heavy rock bursts	<5	5–400
Mild squeezing or swelling rock		5–10
Heavy squeezing or swelling rock		5–20

Cover photograph. *The western portal of the Penmaenbach road tunnel, completed in 1989 for the improvements to the North Wales coast road. The tunnel was cut through 660 m of class II and class I rock, a strong rhyolite with three sets of widely spaced joints. Removal of scree and weathered rock from the site of the portal allowed stress relief within the rhyolite. This was countered by 48 rock anchors, each 7 m long, installed before cutting the tunnel, to prevent opening of the joints. Extension of the secondary concrete lining beyond the face, and the masonry rock catches above, are to prevent small stone fall reaching the road.*

MINING SUBSIDENCE PREDICTION CALCULATIONS

Approximate predictions are read from graph that shows maximum values of subsidence strain and tilt related to h, w and t. These are typical values only; better predictions are made with graphs for specific coalfields based on their own records and rock characteristics.
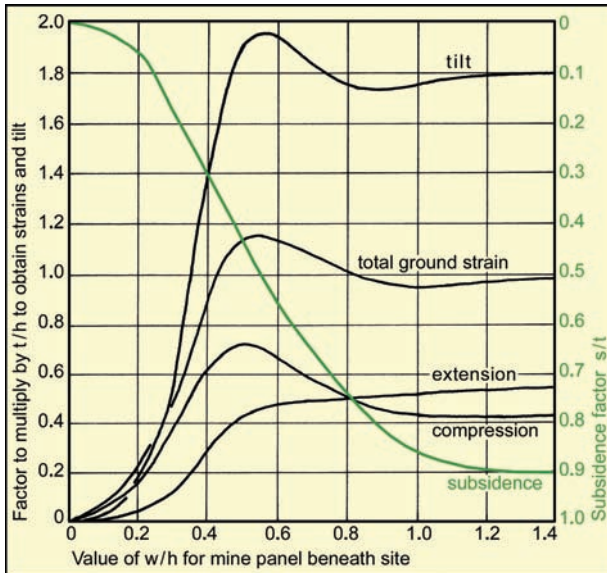
Example of calculations using this graph:
Site factors (from mine plans): thickness = t = 1·2 m; panel width = w = 160 m; depth = h = 400 m.
Ratios: w/h = 160/400 = 0·4; t/h = 1·2/400 = 0·003.
 • Reading factors off graph for value of w/h = 0·4:
Extension (E) = 0·28 × t/h = 0·28 × 0·003 = 0·00084.
Compression (C) = 0·62 × t/h = 0·62 × 0·003 = 0·00186.
Strain = E + C = 0·00084 + 0·00186 = 0·0027 = 2·7 mm/m.
Tilt = 1·4 (graph) × t/h = 1·4 × 0·003 = 0·0042 = 1 in 238.
Subsidence factor (direct from graph) = s/t = 0·3.
Subsidence (s) = 0·3 × t = 0·3 × 1·2 = 0·36 m = 360 mm.
This graph gives maximum values; partial subsidence and strain, which occur further outside panel margins, can be read off more detailed graphs.

STRUCTURAL DAMAGE RELATED TO STRAIN

Damage relates to both ground strain and structural size.
Potential distortion = strain × structural strength.

Class distortion	Typical features of damage
Very slight <30 mm	Barely noticeable, hair cracks in plaster
Slight 30–60 mm	Slight internal fractures, doors and windows may stick
Appreciable 60–125 mm	Slight external fractures, service pipes may fracture
Severe 125–200 mm	Floors slope and walls lean, doors frames are distorted
Very severe >200 mm	Floors slope, walls bulge, beams lose bearing; needs partial or total rebuild

SUBSIDENCE COMPENSATION

Longwall mining has compensation for inevitable subsidence damage incorporated in its budget, but compensation law varies between countries.
In Britain, Coal Authority pays costs of damage repairs, except to recent structures where precautionary measures were appropriate but were not installed. Coal Authority does not pay cost of precautionary works, even if these are required by local planning law.

ABBREVIATIONS AND NOTATION

ABP	acceptable bearing pressure
C	centigrade
c	cohesion
c′	effective cohesion
c_r	residual cohesion
CPT	cone penetration test
E	Young's modulus of elasticity
Fe	iron
g	acceleration due to gravity
GPa	1,000,000,000 pascals
GPR	ground probing radar
ha	hectare, area of 10,000 square metres
Hz	hertz, frequency of 1 cycle per second
K	coefficient of permeability
kg	kilogram
km	kilometre
kN	1000 newtons
kPa	1000 pascals
LI	liquidity index
LL	liquid limit
l/s	litres per second
M	1,000,000
M	earthquake magnitude
m	metre
mm	millimetre
MN	1,000,000 newtons, about 100 tonnes
MPa	1,000,000 pascals, about 100 t/m²
m_v	coefficient of compressibility
My	million years
N	newton, force to accelerate 1 kg to 1 m/s², so under influence of gravity, 1 kg = 9·81 N
N	number of blows on SPT test of soil
NATM	new Austrian tunnelling method
NGR	national grid reference
OD	ordnance datum, effectively mean sea level
Pa	pascal, unit of stress or pressure, N/m²
PFA	pulverized fuel ash
PI	plasticity index
PL	plastic limit
PLS	point load strength
Q	rock mass rating value on Norwegian system
Q	flow
RMR	rock mass rating on Geomechanics system
RQD	rock quality designation
s	second
SBP	safe bearing pressure
SiO_2	silica, silicon dioxide
SPT	standard penetration test
t	tonne
TBM	tunnel boring machine
u	pore water pressure
UCS	unconfined compressive strength
U100	100 mm diameter soil sample
w	water content
3-D	three-dimensional
γ	unit weight of material
μ	micro, a millionth part
Σ	sum of
σ	stress
σ′	effective stress
$σ_n$	normal stress
τ	shear strength
φ	internal friction angle
φ′	effective internal friction angle
$φ_r$	residual internal friction angle

Further Reading

As references are not cited throughout the text, the most relevant literature is cited below for each section of this book. The first citations are the major source books and useful papers in the subject area. These are followed by the primary papers on the case studies, cited in the sequence in which they are mentioned within the text.

01
Kiersch, G.A. (ed), 1991. The heritage of engineering geology: the first hundred years. *Geol. Soc. Am. Centennial Special*, **3**, 605pp.
Duff, D. (ed), 1993. *Holmes' principles of physical geology*. Nelson Thornes, 816pp.
Legget, R.F. & Hatheway, A.W., 1988. *Geology and engineering*. McGraw Hill, 613pp.
Bell, F.G., Cripps, J.C. & Culshaw, M.G., 1995. The significance of engineering geology to construction. *Geol. Soc. Eng. Geol. Spec. Publ.*, **10**, 3–29.
Bennett, M.R. & Doyle, P., 1997. *Environmental geology*. Wiley, 501pp.
Murck, B.W., Skinner, B.J. & Porter, S.C., 1996. *Environmental geology*. Wiley, 534pp.
Waltham, T., 1978. *Catastrophe: the violent Earth*. Macmillan, 170pp.

02
Vernon, R., 2000. *Beneath our feet: the rocks of planet Earth*. Cambridge University Press, 216pp.
Goodman, R.E., 1993. *Engineering geology: rock in engineering construction*. Wiley, 412pp.
Thorpe, R. & Brown, G., 1985. *The field description of igneous rocks*. Wiley, 154pp.

03–04
Greensmith, J.T., 1989. *Petrology of the sedimentary rocks.* Unwin Hyman, 262pp.
Blatt, H., 1992. *Sedimentary petrology*. Freeman, 514pp.
Stow, D.A.V., 2005. *Sedimentary rocks in the field*. Manson, 320pp.
Goodman, 1993. see #02.
Vernon, 2000. see #02.
Tucker, M.E., 1996. *Sedimentary rocks in the field*. Wiley, 153pp.

05
Mason, R., 1990. *Petrology of the metamorphic rocks*. Unwin Hyman, 230pp.
Goodman, 1993. see #02.
Vernon, 2000. see #02.
Fry, N., 1984. *The field description of metamorphic rocks*. Wiley, 110pp.

06
Park, R.G., 1997. *Foundations of structural geology*. Nelson Thornes, 202pp.
Twiss, R.J. & Moores, E.M., 1992. *Structural geology*. W H Freeman, 532pp.
Spencer, E.W., 1988. *Introduction to the structure of the Earth. McGraw-Hill*, 551pp.
Ramsay, J.G. & Huber, M.I., 1987. *The techniques of modern structural geology; volume 2: folds and fractures*. Academic Press, 400pp.

07–08
Lisle, R. J., 1995. *Geological structures and maps*. Butterworth Heinemann, 104pp.
Bennison, G.M. & Moseley, K.A., 2003. *An introduction to geological maps and structures*. Arnold, 160pp.

Thomas, P.R., 1991. *Geological maps and sections for civil engineers*. Blackie, 106pp.
McClay, K., 1987. *The mapping of geological structures*. Wiley, 161pp.
Dearman, W.R., 1991. *Engineering geological mapping*. Butterworth Heinemann, 580pp.

09
Kearey, P. & Vine, F.J., 1996. *Global tectonics*. Blackwell, 333pp.
Ollier, C. & Pain, C., 2000. *The origins of mountains*. Routledge, 345pp.

10
Bolt, B.A., 1999. *Earthquakes,* W H Freeman, 366pp.
US Geological Survey, 2008+. *Earthquakes hazards program*. www.usgs.gov/earthquake
Francis, P., 1993. *Volcanoes*. Clarendon, 443pp.
Smithsonian Institution, 2008+. *Global volcanism program*. www.volcano.si.edu/gvp
Waltham, T., 2005. Volcanic landscapes. 633–661 in Fookes et al., see #14.

11
Benchley, P.J. & Rawson, P.F., 2006. *The geology of England and Wales*. Geological Society, 559pp.
Toghill, P., 2000. *The geology of Britain*. Crowood, 192pp.

12
Stearns, C.W., Carroll R.L. & Clark, T.H., 1979. *Geological evolution of North America*. Wiley, 545pp.

13
Bland, W. & Rolls, D., 1998. *Weathering: an introduction to the scientific principles*. Arnold, 271pp.
Gerrard, A.J., 1988. *Rocks and landforms*. Unwin Hyman, 319pp.

14
Charlton, R., 2008. *Fundamentals of fluvial geomorphology*. Routledge, 234pp.
Ahnert, F., 1996. *Introduction to geomorphology*. Arnold, 352pp.
Knighton, D., 1998. *Fluvial forms and processes: a new perspective*. Arnold, 383pp.
Fookes, P.G., Lee, E.M. & Milligan,G. (eds.), 2005. *Geomorphology for engineers*. Whittles, 851pp.
Lee, M., 2005. Rivers. 263–286 in Fookes et al., see above.
Forster, A., Culshaw, M.G., Cripps, J.C., Little, J.A. & Moon, C.F., 1991. Quaternary engineering geology. *Geol. Soc. Eng. Geol. Spec. Publ.*, **7**, 724pp.
Brookes, A., 1985. River channelization: traditional engineering, physical consequences and alternative practices. *Progress in Physical Geography.*, **9**, 44–73.
Kidson, C., 1953. The Exmoor storm and the Lynmouth floods. *Geography*, **38**, 1–9.

15
Benn, D.I. & Evans, D.J.A., 1998. *Glaciers and glaciation*. Hodder Arnold, 744pp.
Menzies, J. (ed), 1996. *Postglacial environments: sediments, forms and techniques*. Butterworth Heinemann, 598pp.
Owen, L.A. & Derbyshire, E. 2005. Glacial environments. 345–375 in Fookes et al.. see #14.
Eyles, N. & Sladen, J. A., 1981. Stratigraphy and geotechnical properties of weathered lodgement tills in Northumberland. *Quart. Journ. Eng. Geol.* **14**, 129–141.

Skipper, J., Follett, B., Menkiti, C.O., Long, M. & Clark-Hughes, J., 2005. The engineering geology of the Dublin Boulder Clay. *Quart. Journ. Eng. Geol. Hydrogeol.*, **38**, 171–187.

Trenter, N.A., 1999. Engineering in glacial tills. *CIRIA Report*, **C504**. 259pp.

Waltham, T., Lotschberg – geology for tunnellers. *Geology Today*, **23**, 101–107.

Bryan, A., 1951. Accident at Knockshinnoch Castle Colliery, Ayrshire: report. HMSO, London, 48pp.

16

Livingstone, I. & Warren, A., 1996. *Aeolian geomorphology: an introduction*. Longman, 211pp.

Cooke, R.U., Brunsden, D., Doornkamp, J.C. & Jones, D.K.C., 1982. *Urban geomorphology in drylands*. Oxford University Press, 370pp.

Lee, M. & Fookes, P., 2005. Hot drylands. 419–454 in Fookes et al.. see #14.

Watson, A., 1985. The control of wind blown sand and moving dunes. *Quart. Journ. Eng. Geol.*, **18**, 237–252.

Archer. D., 2007. *Global warming: understanding the forecast*. Blackwell, 194pp.

Intergovernmental Panel on Climate Change, 2007. *IPCC 4th assessment report*. http://www.ipcc.ch/ipccreports/assessments-reports.htm

Ballantyre, C.K. & Harris, C., 1994. *The periglaciation of Great Britain*. Cambridge University Press, 330pp.

Matsuoka, N., 2001. Solifluction rates, processes and landforms: a global review. *Earth Science Reviews*, **55**, 107–134.

Coxon, R.E., 1986. *Failure of Carsington embankment*. Dept. Environment Report, HMSO, London, 180pp.

Skempton, A.W. & Vaughan, P.R., 1993. The failure of Carsington dam. *Geotechnique*, **43**, 151–173.

Waltham, T. & Fookes, P., 2001. Ice wedges of the Dalton Highway, Alaska. *Quart. Journ. Eng Geol. Hydrogeol.*, **34**, 65–70.

17

Pethick, J., 1984. *An introduction to coastal geomorphology*. Arnold, 260pp.

Haslett, S.K., 2000. *Coastal systems*. Routledge, 218pp.

Barrett, M.G. (ed), 1992. *Coastal zone planning and management*. Thomas Telford, 327pp.

Pethick, J., 2001. Coastal management and sea level rise. *Catena*, **42**, 307–322.

British Standards, 2000. Maritime structures: guide to the design and construction of breakwaters. *BS* 6349, 254pp.

Waltham, T., 2005. The Asian tsunami, 2004. *Geology Today*, **21**, 22–26.

18

Grassington, R., 1998. *Field hydrogeology*. Wiley, 248pp.

Price, M., 1996. *Introducing groundwater*. Nelson Thornes, 304pp.

MacDonald, A., Davies, J., Calow, R. & Chilton, J., 2005. *Developing groundwater*. ITDG, 358pp.

Mackay, R., Riley, M. & Williams, G.M, 2001. Simulating groundwater contaminant migration at Villa Farms lagoons. *Quart. Journ. Eng. Geol. Hydrogeol.*, **34**, 215–224.

19

British Standards, 1999. Code of practice for site investigations. *BS* 5930, 204pp.

Simons, N., Menzies, B. & Matthews, M., 2001. *A short course in geotechnical site investigation*. Thomas Telford, 250pp.

Fookes, P.G., Lee, E.M. & Griffiths, J.S., 2007. *Engineering geomorphology*. Whittles, 281pp.

Griffiths, J.S. (ed.), 2001. Land surface evaluation for engineering practice. *Geol. Soc. Eng. Geol. Spec. Publ.*, **18**, 244pp.

Fookes, P.G., 1997. Geology for engineers: the geological model, prediction and performance. *Quart. Journ. Eng. Geol., 30, 293–431*.

Hoek, E., 1999. Putting numbers to geology – an engineer's approach. *Quart. Journ. Eng. Geol.*, **32**, 1–19.

Hutchinson, J.N., 2001. Reading the ground: morphology and geology in site appraisal. *Quart. Journ. Eng. Geol. Hydrogeol.*, 34, 7–50.

20

Culshaw, M.G., 2005. From concept towards reality: developing the attributed 3D geological model of the shallow subsurface. *Q. Journ. Eng. Geol. Hydrogeol.*, **38**, 231–284.

21

Weltman, A.J. & Head, J.M., 1983. *Site investigation manual*. CIRIA, London, 144pp.

22

Milsom, J., 2000. *Field geophysics*. Wiley, 187pp.

Telford, W.M., Geldart, L.P. & Sheriff, R.E., 1991. *Applied geophysics*. Cambridge Univ. Press, 790pp.

McDowell, P.W., Barker, R.D. & Butcher, A.P. (eds.), 2002. Geophysics in engineering investigations. *Geol. Soc. Eng. Geol. Spec. Publ.*, **19**, 252pp.

23

Waltham, A.C., Vandenven, G. & Ek, C.M., 1986. Site investigations on cavernous limestone for the Remouchamps Viaduct, Belgium. *Ground Engineering*, **19** (8), 16–18.

24

Goodman, R.E., 1989. *Introduction to rock mechanics*. Wiley, 563pp.

Wyllie, D.C., 1999. *Foundations on rock*. Spon, 401pp.

25

Hoek, E., 2000+. *Practical rock engineering*. www.rockeng.utoronto.ca

Barton, N., Lien, R. & Lunde, J., 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, **6**, 189–236.

Bieniawski, Z.T., 1974. Geomechanics classification of rock masses and its application in tunnelling. *Proc. 3rd Int. Cong. Rock Mech.*, **2** (2), 27–32.

Bieniawski, Z.T., 1989. *Engineering rock mass classifications*. Wiley, 251pp.

Hudson, J.A. & Harrison, J.P., 1997. *Engineering rock mechanics*. Pergamon, 444pp.

Wyllie, 1999. see #24.

British Standards, 1986. Code of practice for foundations. *BS* 8004, 160pp.

Bell, A.L., 1994. *Grouting in the ground*. Thomas Telford, 590pp.

26

Jefferson, I., Frost, M., & Ghataora, G.S., 2009. *Foundations of geotechnical engineering*. Taylor & Francis, 96pp.

Craig, R. F., 2004. *Soil mechanics*. Taylor & Francis, 480pp.

27

Waltham, A.C., 1989. *Ground subsidence*. Blackie. 202pp.

Derbyshire, E., 2001. Geological hazards in loess terrains, with particular reference to the loess regions of China. *Earth Science Reviews*, **54**, 231–260.

Ege, J.R., 1984. Mechanisms of surface subsidence resulting from solution extraction of salt. *Geol. Soc. Am. Reviews in Eng. Geol.*, **6**, 203–221.

Johnson, K.S. & Neal, J.T., 2003. Evaporite karst and engineering/environmental problems in the United States. *Oklahoma Geol. Surv. Circular*, **109**, 353pp.

Cooper, A.H. & Saunders, J.M., 2002. Road and bridge construction across gypsum karst in England. *Engineering Geology*, **65**, 217–223.

Stephens, J.C., Allen, L.H. & Chen, E., 1984. Organic soil subsidence. *Geol. Soc. Am. Reviews Eng. Geol.* **6**, 107–122.

Hutchinson, J.N., 1980. The record of peat wastage in the East Anglia fenlands at Holme Post, 1846–1978 AD. *Journ. Ecology*, **68**, 229–249.

Samson, L. & La Rochelle, P., 1972. Design and performance of an expressway constructed over peat by preloading. *Can. Geotech. Journ.*, **9**, 447–466.

28

Peck, R.B. & Bryant, F.G., 1953. The bearing capacity failure of Transcona elevator. *Geotechnique*, **3**, 201–214.

Burland, J., 1997. *Propping up Pisa*. Royal Academy of Engineering, London. 20pp.

Figueroa Vega, G.E., 1984. Land subsidence case history: Mexico. *Unesco Studies and Reports in Hydrology*, **40**, 217–232.

Zeevaert, L., 1957. Foundation design and behaviour of the Tower Latino Americana in Mexico City. *Geotechnique*, **7**, 115–133.

Waltham, T., 2002. Sinking cities. *Geology Today*, **18**, 95–100.

Carbognin, L. & Gatto, P., 1986. An overview of the subsidence of Venice. *Int. Ass. Hydrol. Sci. Publ.*, **151**, 321–328.

29

Sowers, G.F., 1996. *Building on sinkholes*. American Society Civil Engineers, 202pp.

Newton, J.G., 1987. Development of sinkholes resulting from man's activities in the eastern United States. *U. S. Geol. Surv. Circular*, 968, 54pp.

Waltham, A.C. & Fookes, P.G., 2003. Engineering classification of karst ground conditions. *Quart. Journ. Eng. Geol. Hydrogeol.*, **36**, 101–118.

Waltham, T., Bell, F. & Culshaw, M., 2005. *Sinkholes and subsidence; karst and cavernous rocks in engineering and construction*. Springer, 382pp.

Waltham, T., 2008. Sinkhole hazard case histories in karst terrains. *Quart. Journ. Eng. Geol. Hydrogeol.*, **41**, 291–300.

Waltham, T. & Lu Z., 2007. Natural and anthropogenic rock collapse over open caves. *Geol. Soc. Spec. Publ.*, **279**, 13–21.

30

Littlejohn, G.S., 1979. Surface stability in areas underlain by old coal workings. *Ground Engineering*, **12**(2), 22–30.

Littlejohn, G.S., 1979. Consolidation of old coal workings. *Ground Engineering*, **12**(4), 15–21.

Waltham, 1989. see #27.

Culshaw, M.G. & Waltham, A.C., 1987. Natural and artificial cavities as ground engineering hazards. *Quart. Journ. Eng. Geol.*, **20**, 139–150.

31

Whittaker, B.N. & Reddish, D.J., 1989. *Subsidence: occurrence, prediction and control*. Elsevier, 528pp.

National Coal Board, 1975. *Subsidence engineer's handbook*. NCB, 112pp.

Donnelly, L.J., 2006. A review of coal mining induced fault reactivation in Great Britain. *Quart. Journ. Eng. Geol. Hydrogeol.*, **39**, 3–50.

Charles, J.A., 1993. *Building on fill: geotechnical aspects*. Building Research Establishment Report, 163pp.

Hester, R.E. & Harrison, R.M. (eds), 1997. *Contaminated land and its reclamation*. Thomas Telford, 160pp.

British Standards, 2001. Investigation of potentially contaminated land. *BS* 10175, 82pp.

32

Bromhead, E.N., 1997. *The stability of slopes*. Spon, 411pp.

Cruden, D.M. & Varnes, D.J., 1996. Landslide types and processes. 36–75 in Turner & Schuster, see #32.

Turner, A.K. & Schuster, R.L. (eds), 1996. Landslides: investigation and mitigation. *Transportation Research Board Special Report*, 247, 673pp.

Voight, B., 1978–9. *Rockslides and avalanches; volumes 1 and 2.* Elsevier, 833+850pp.

Hadley, J.B., 1978. Madison Canyon rockslide, Montana, USA. 167–180 in Voight vol 1, see #32.

Voight, B., 1978. Lower Gros Ventre slide, Wyoming, USA. 113–166 in Voight vol 1, see #32.

Wieczorek, G.F., 1996. Landslide triggering mechanisms. 76–90 in Turner & Schuster, see #35.

Brunsden, D. & Lee, E.M., 2004. Behaviour of coastal landslide systems: an interdisciplinary review. *Zeit. Geomorphologie*, **134**, 1–112.

Plafker, G. & Ericksen, G.E., 1978. Nevados Huascaran avalanches, Peru. 277–314 in Voight vol 1. see #32.

33

Bromhead, 1997. see #32.

Cruden, D.M. & Krahn, J., 1978. Frank rockslide, Alberta, Canada. 97–112 in Voight, see #32.

Ehlig, P.L., 1992. Evolution, mechanics and mitigation of the Portugese Bend landslide, Palos Verdes Peninsula, California. *Assoc. Eng. Geologists (Southern California Section), Spec. Publ.* **4**, 531–553.

Hendron, A.J. & Patton, F.D., 1986. A geotechnical analysis of the behaviour of the Vaiont slide. *Civil Eng. Practice (Boston Soc. Civ. Eng.)*, **1**(2), 65–130.

34

Dixon, N. & Bromhead, E.N., 2002. Landsliding in London Clay coastal cliffs. *Q. Journ. Eng. Geol. Hydrogeol.*, **35**, 327–343.

Watson, R.A. & Wright, H.E., 1969. The Saidmarreh landslide, Iran. *Geol. Soc. Am. Sp. Paper,* 123, 115–139.

Torrance, K.J., 1987. Quick clay. 447–473 in Anderson, M. G. & Richards, K. S. (eds). Slope stability. Wiley.

Crawford, C.B. & Eden, W.J., 1963. Nicolet landslide of November 1955, Quebec, Canada. *Geol. Soc. Am. Eng. Geol. Case Histories*, **4**, 45–50.

Anon., 1967. *Report of the tribunal appointed to enquire into the disaster at Aberfan on October 21, 1966*. HMSO, London, 148pp.

Siddle, H.J., Wright, M. D. & Hutchinson, J. N., 1996. Rapid failures of colliery spoil heaps in the South Wales coalfield. *Quart. Journ. Eng. Geol.*, **29**, 103–132.

Siddle, H.J., Bromhead, E.N. & Bassett, M.G. (eds.), 2000. Landslides and landslide management in South Wales. *National Museums & Galleries of Wales Geol. Series*, **18**, 116pp.

35

Lee, E.M. & Jones, D.K.C., 2004. *Landslide risk assessment*. Thomas Telford, 464pp.

Bromhead, 1997. see #32.

Derbyshire, E., Fort, M. & Owen, L.A., 2001. Geomorphological hazards along the Karakoram Highway. *Erdkunde*, **55**, 49–71.

Norrish, N.I. & Wyllie, D.C., 1996. Rock slope stability analysis. 391–425 in Turner & Schuster, see #32.

Waltham, A.C. & Dixon, N., 2000. Movement of the Mam Tor landslide, Derbyshire, UK. *Quart. Journ. Eng. Geol. Hydrogeol.*, **33**, 105–123.

Ritchie, A.M., 1963. Evaluation of rockfall and its control. *Highway Research Board Record (Canada)*, **17**, 13–28.

36

Bromhead, 1997. see #32.

Bromhead, E.N., 1997. The treatment of landslides. *Proc. Inst. Civ. Eng. Geotech. Eng.*, **125**, 85–96.

Hoek, E. & Bray, J., 1981. *Rock slope engineering*. Inst. Min. Met. London, 402pp.

Turner & Schuster, 1996. see #32.

Hutchinson, J.N., 1969. A reconsideration of the coastal landslides at Folkestone Warren, Kent. *Geotechnique*, **19**, 6–38.

Wyllie, D.C. & Norrish, N.I., 1996. Stabilization of rock slopes. 474–504 in Turner & Schuster, see #32.

British Standards, 1994. Code of practice for earth retaining structures. *BS* 8002, 144pp.

British Standards, 2001. Geotextiles: characteristics required for earthworks, foundations and retaining structures. *BS* EN13251, 34pp.

British Standards, 1989. Code of practice for ground anchorages. *BS* 8081, 180pp.

37

Franklin, J.A. & Desseault, M.B., 1991. *Rock engineering*. McGraw Hill, 401pp.

Hudson & Harrison, 1997. see #25.

Peffifer, G.S. & Fookes, P.G., 1994. A revision of the graphical method for assessing the excavatability of rock. *Quart. Journ. Eng. Geol.*, **27**, 145–164.

Lutton, R.J., Banks, D.C. & Strohm, W.E., 1979. Slides in Gaillard Cut, Panama. 151–224 in Voight vol 2. see #32.

Nicholson, D.T., 2004. Hazard assessment for progressive weathering-related breakdown of excavated rockslopes. *Quart. Journ. Eng. Geol. Hydrogeol.*, **37**, 327–346.

Bhandari, S., 1997. *Engineering rock blasting operations*. Balkema, 375pp.

38

Whittaker, B.N. & Frith, R.C., 1990. *Tunnelling: design, stability and construction*. Inst. Min. Met., 460pp.

Franklin, J.A. & Desseault, M.B., 1991. *Rock engineering applications*. McGraw Hill, 431pp.

Muir Wood, A., 2000. *Tunnelling: management by design*. Spon, 307pp.

Tsuji, H., Sawada, T. & Takizawa, M., 1996. Extraordinary inundation accidents in the Seikan undersea tunnel. *Proc. Inst. Civ. Eng. Geotech. Eng.*, **119**, 1–14.

Harris, C.S., Hart, M.B., Varley, P.M. & Warren, C.D., 1996. *Engineering geology of the Channel Tunnel*. Thomas Telford, 520pp.

Barton, N. & Grimstad, E., 1994. Rock mass conditions dictate choice between NMT and NATM. *Tunnels and Tunnelling*, October, 39–42.

British Standards, 1996. Specification for rock bolting in coal mines. *BS* 7861, 38pp.

39

McNally, G.H., 1998. *Soil and rock construction materials*. Spon, 403pp.

Smith, M.R. & Collis, L. (eds.), 2001. Aggregates: sand, gravel and crushed rock for construction purposes. *Geol. Soc. Eng. Geol. Spec. Publ.*, **17**, 339pp.

Latham, J.P. (ed), 1998. Advances in aggregates and armourstone evaluation. *Geol. Soc. Eng. Geol. Spec. Publ.*, **13**, 201pp.

British Standards, 2000. Texts for general properties of aggregates. *BS* EN932–5, 18pp.

British Standards, 2002. Aggregates for concrete. *BS* EN12620, 50pp.

Jefferson, D.P., 1993. Building stone: the geological dimension. *Quart. Journ. Eng. Geol.*, **26**, 305–319.

British Standards, 1976. Code of practice for the use of masonry. *BS* 5628, 80pp.

Prikryl, R. & Smith, B.J. (eds.), 2007. Building stone decay; from diagnosis to conservation. *Geol. Soc. Spec. Publ.*, **271**, 330pp.

Index

94