1 Engineering geology

1.1 Introduction

Geology can be defined as the scientific study of the Earth and especially the rocks and soils that make up the Earth: their origins, nature and distribution, and the processes involved in their formation. Engineering geology then may be defined as the scientific study of geology as it relates to civil engineering projects such as the design of a bridge, construction of a dam or preventing a landslide. Engineering geologists need to identify the local rock and soil conditions at a site and anticipate natural hazards such as earthquakes so that structures can be designed, constructed and operated safely and economically. He (or she, throughout) needs to work with civil engineers and understand what they are trying to do and the constraints under which they work. His remit and responsibilities can be extensive, covering all of the Earth Sciences, including geophysics, geochemistry and geomorphology.

1.2 What do engineering geologists do?

Engineering geologists make up a high proportion of professional geologists throughout the world. Most of these work in civil engineering: in consulting (designing) or contracting (construction) companies with a team of engineers, some of whom will be specialised in the field of geotechnical engineering, which concerns the interface of structures with the ground.

One of the important tasks of an engineering geologist is to investigate the geological conditions at a site and to present these in a simplified ground model or series of models. Models should contain and characterise all the important elements of a site. Primary geological soil and rock units are usually further subdivided on the basis of factors such as degree of consolidation and strength, fracture spacing and style, hydrogeological conditions or some combination. Models must identify and account for all the natural hazards that might impact the site, as illustrated schematically in Figure 1.1 for a new high-rise

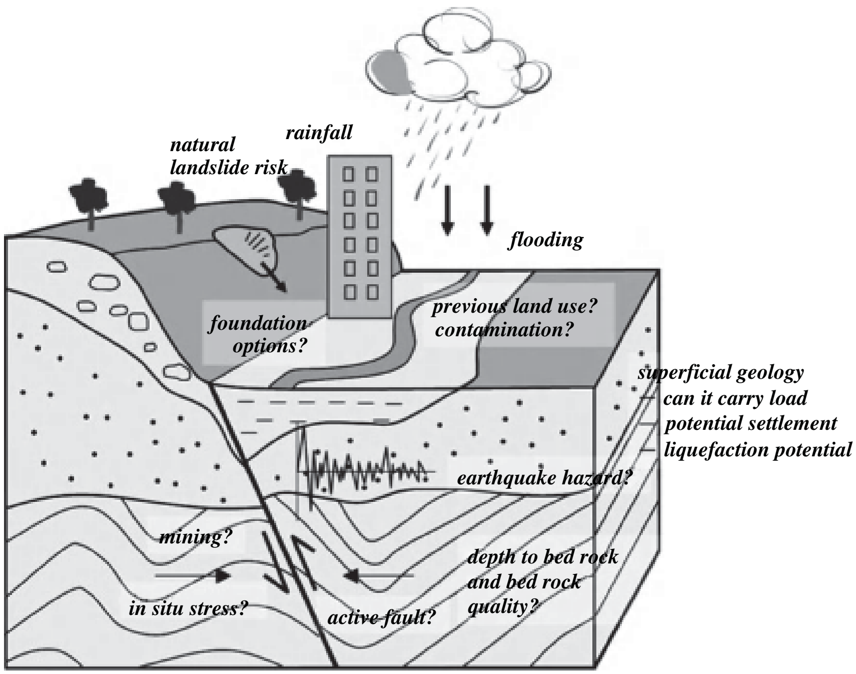


Figure 1.1 Site model for a new building, illustrating some of the factors and hazards that need to be addressed by the engineering geologist.

structure to be sited in a valley threatened by a nearby natural hillside. The ground model, integrated with the civil engineering structure, can be analysed numerically to ensure that the tolerance criteria for a project are achieved. For most structures, the design criteria will be that the structure does not fail and that any settlement or deformation will be tolerable; for a dam, the design criteria might include acceptable leakage from the impounded reservoir; for a nuclear waste repository, it would be to prevent the escape of contaminated fluids to the biosphere for many thousands of years.

1.3 What an engineering geologist needs to know

Many authors have attempted to define engineering geology as a subject separate to geology and to civil engineering (e.g. Morgenstern, 2000; Knill, 2002; Bock, 2006), but it is easier to define what a practising engineering geologist needs to know and this is set out in Table 1.1. Firstly, an engineering geologist needs to be fully familiar with geology to the level of a traditional earth sciences degree. He should be able to identify soil and rocks by visual examination and to interpret the geological history and structure of a site. He also needs to have knowledge of geomorphological processes, and be able to interpret terrain features and hydrogeological conditions. He must be familiar with ground investigation techniques so that a site can be

Table 1.1 Basic skills and knowledge for engineering geologists.

It is difficult to define engineering geology as a separate discipline but easier to define the subject areas with which an engineering geologist needs to be familiar. These include:

1. GEOLOGY

An in-depth knowledge of geology: the nature, formation and structure of soils and rocks. The ability to interpret the geological history of a site.

2. ENGINEERING GEOLOGY AND HYDROGEOLOGY

Aspects of geology and geological processes that are not normally covered well in an undergraduate geological degree syllabus need to be learned through advanced study (MSc and continuing education) or during employment. These include:

- Methods and techniques for sub-surface investigation.
- Properties of soil and rock, such as strength, permeability and deformability – how to measure these in the laboratory (material scale) and in the field and how to apply these at the large scale (mass scale) to geological models.
- Methods for soil and rock description and classification for engineering purposes.
- Weathering processes and the nature of weathered rocks.
- Quaternary history, deposits and sea level changes.
- Nature, origins and physical properties of discontinuities.
- Hydrogeology: infiltration of water, hydraulic conductivity and controlling factors. Water pressure in the ground, drainage techniques.
- Key factors that will affect engineering projects, such as forces and stresses, earthquakes, blast vibrations, chemical reactions and deterioration.
- Numerical characterisation, modelling and analysis.

These are dealt with primarily in Chapters 3, 4, 5 & 6.

3. GEOMORPHOLOGY

Most engineering projects are constructed close to the land surface and therefore geomorphology is very important. An engineer might consider a site in an analytical way, for example, using predicted 100-year rainfall and catchment analysis to predict flood levels and carrying out stability analysis to determine the hazard from natural slope landslides. This process can be partially shortcut and certainly enhanced through a proper interpretation of the relatively recent history of a site, as expressed by its current topography and the distribution of surface materials. For example, study of river terraces can help determine likely maximum flood levels and can also give some indication of earthquake history in active regions such as New Zealand. The recognition of past landslides through air photo interpretation is a fundamental part of desk study for many hilly sites. This is dealt with in Chapters 3 and 4.

4. CIVIL ENGINEERING DESIGN AND PRACTICE

An engineering geologist must be familiar with the principles of the design of structures and the options, say for founding a building or for constructing a tunnel. He/she must be able to work in a team of civil and structural engineers, providing adequate ground models that can be analysed to predict project performance, and this requires some considerable knowledge of engineering practice and terminology. The geological ground conditions need to be modelled mechanically and the engineering geologist needs to be aware of how this is done and, better still, able to do so himself. This is covered mainly in Chapters 2 and 6.

5. SOIL AND ROCK MECHANICS

Engineering geology requires quantification of geological models. Hoek (1999) described the process as 'putting numbers to geology'. That is not to say that pure geologists do not take a quantitative approach – they do, for example, in analysing sedimentary processes, in structural geology and in geochronology. However, a geologist is usually concerned with relatively slow processes and very high stress levels at great depths. The behaviour of soil and rock in the shorter term (days and months) and at relatively low stresses are the province of soil mechanics and rock mechanics. Knowledge of the principles and practice of soil and rock mechanics is important for the engineering geologist. This includes strength, compressibility and permeability at material and mass scales, the principle of effective stresses, strain-induced changes, critical states and dilation in rock masses.

characterised cost-effectively and thoroughly. Furthermore, he needs to understand the way that soils and rocks behave mechanically under load and in response to fluid pressures, how they behave chemically, and how to investigate their properties. To carry out his job properly, an engineering geologist also needs to know the fundamentals of how structures are designed, analysed and constructed, as introduced in Chapter 2 and presented in more detail in Chapter 6. Much of this will not be taught in an undergraduate degree and needs to be learnt through MSc studies or through Continuing Professional Development (CPD) including self study and from experience gained on the job.

The better trained and experienced the engineering geologist, the more he will be able to contribute to a project, as illustrated schematically in Figure 1.2. At the top of the central arrow, interpreting the geology at a site in terms of its geological history and distribution of strata is a job best done by a trained geologist. At the bottom end of the arrow, numerical analysis of the ground-structure interaction is usually the province of a geotechnical engineer – a trained civil engineer who has specialised in the area of ground engineering. There are,

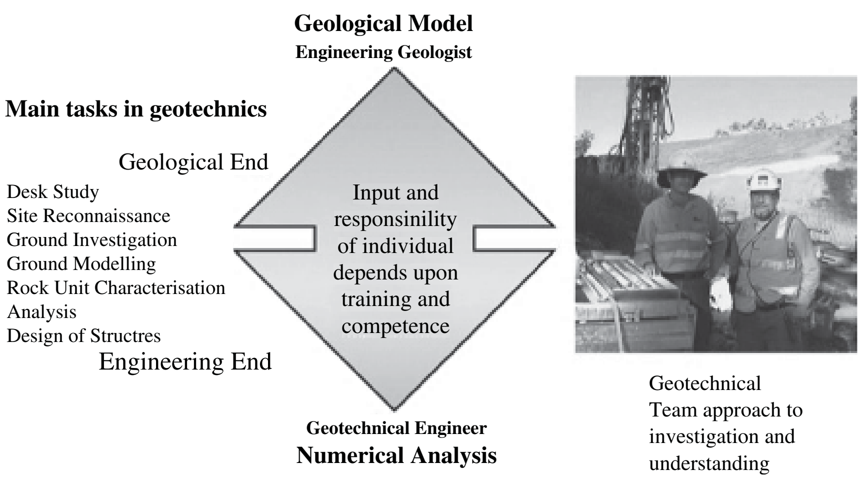


Figure 1.2 Roles of engineering geologists and geotechnical engineers.
The prime responsibilities of the engineering geologist are 'getting the geology right' (according to Fookes, 1997) and 'assessing the adequacy of investigation and its reporting' (according to Knill, 2002), but an experienced engineering geologist with proper training can go much further, right through to the full design of geotechnical structures. Similarly, some geotechnical engineers become highly knowledgeable about geology and geological processes through training, study and experience and could truly call themselves engineering geologists. The photo shows David Starr and Benoit Wentzinger of Golder Associates, Australia, working in a team to investigate a major landslide west of Brisbane.

however, many other tasks, such as design of ground investigations and numerical modelling, that could be done by either an experienced engineering geologist or a geotechnical engineer. Many professional engineering geologists contribute in a major way to the detailed design and construction of prestigious projects such as dams, bridges and tunnels and have risen to positions of high responsibility within private companies and government agencies.

1.4 The role of an engineering geologist in a project

1.4.1 General

As discussed and illustrated later, some sites pose major challenges because of adverse and difficult geological conditions, but the majority do not. This leads to a quandary. If a 'one-size-fits-all' standardised approach is taken to site characterisation and more particularly to ground investigation (Chapter 4), then much time and money will be wasted on sites that do not need it but, where there are real hazards, then the same routine approach might not allow the problems to be identified and dealt with. This is when things can go seriously wrong. Civil engineering projects sometimes fail physically (such as the collapse of a dam, a landslide or unacceptable settlement of a building) or cost far more than they should because of time over-runs or litigation. Often, in hindsight, the root of the problem turns out to be essentially geological. It is also commonly found that whilst the difficult conditions were not particularly obvious, they were not unforeseeable or really unpredictable. It was the approach and management that was wrong (Baynes, 2007).

Engineering geologists can often make important contributions at the beginning of a project in outline planning and design of investigation for a site and in ensuring that contracts deal with the risks properly, as outlined in Chapter 2.

A skilful and experienced engineering geologist should be able to judge from early on what the crucial unknowns for a project are and how they should be investigated. Typical examples of the contributions that he might make are set out in Table 1.2.

1.4.2 Communication within the geotechnical team

The engineering geologist will almost always work in a team and needs to take responsibility for his role within that team. If there are geological unknowns and significant hazards, he needs to make himself heard using terminology that is understood by his engineering colleagues; the danger of not doing so is illustrated by the case example of a slope failure in Box 1-1.

Table 1.2 Particular contributions that an engineering geologist might bring to a project (not comprehensive).

1. Unravelling the geological history at a site. This will come initially from regional and local knowledge, examination of existing documents, including maps and aerial photographs, and the interpretation of exposed rock and geomorphologic expression. Geology should be the starting point of an adequate ground model for design.
2. Prediction of the changes and impacts that could occur in the engineering lifetime of a structure (perhaps 50–100 years). At some sites, severe deterioration can be anticipated due to exposure to the elements, with swelling, shrinkage and ravelling of materials. Sites may be subject to environmental hazards, including exceptional rainfall, earthquake, tsunami, subsidence, settlement, flooding, surface and sub-surface erosion and landsliding.
3. Recognising the influence of Quaternary geology, including recent glaciations and rises and falls in sea level; the potential for encountering buried channels beneath rivers and estuaries.
4. Identifying past weathering patterns and the likely locality and extent of weathered zones.
5. Ensuring appropriate and cost-effective investigation and testing that focuses on the important features that are specific to the site and project.
6. Preparation of adequate ground models, including groundwater conditions, to allow appropriate analysis and prediction of project performance.
7. An ability to recognise potential hazards and residual risks, even following high-quality ground investigation.
8. Identification of aggregates and other construction materials; safe disposal of wastes.
9. Regarding project management, he should be able to foresee the difficulties with inadequate contracts that do not allow flexibility to deal with poor ground conditions, if they are encountered.

Box 1-1 Case example of poor communication with engineers

The investigations into a rock slope failure are reported by Hencher (1983a), Hencher *et al.* (1985) and by Clover (1986). During site formation works of a large rock slope, behind some planned high-rise apartment blocks, almost 4,000 m^3 of rock slid during heavy rainfall on a well-defined and very persistent discontinuity dipping out of the slope at about 28 degrees. The failure scar is seen in Figure B1-2.1. The lateral continuity of the wavy feature is evident to the left of the photograph, beneath the shotcrete cover, marked by a slight depression and a line of seepage points. If the failure had occurred after construction, the debris would have hit the apartment blocks. A series of boreholes had been put down prior to excavation and the orientation of discontinuities had been measured using impression packers (Chapter 4). Statistical analysis of potential failure mechanisms involving the most frequent joint sets led to a design against shallow rock failures by installation of rock bolts and some drains. The proposed design was for a steep cutting, with the apartment blocks to be sited even closer to the slope face than would normally be allowed. Unfortunately, the standard method of discontinuity analysis had eliminated an infrequent series of discontinuities daylighting out of the slope and on one of which the failure eventually occurred. Pitfalls of stereographic analysis in rock slope design are addressed by Hencher (1985), a paper written following this near-disaster.

Examination of the failure surface showed it to be a major, persistent fault infilled with clay-bounded rock breccia about 700 mm thick and dipping out of the slope (Figures B1-2.2 and B1-2.3). In the pre-failure borehole logs, the fault could be identified as zones of particularly poor core recovery; the rock in these zones was described as tectonically influenced at several locations. In hindsight, the fault had been overlooked for the design and this can be attributed to poor quality of ground investigation and

Figure B1-2.1 View of large rock slope failure in 1982, South Bay Close, Hong Kong.

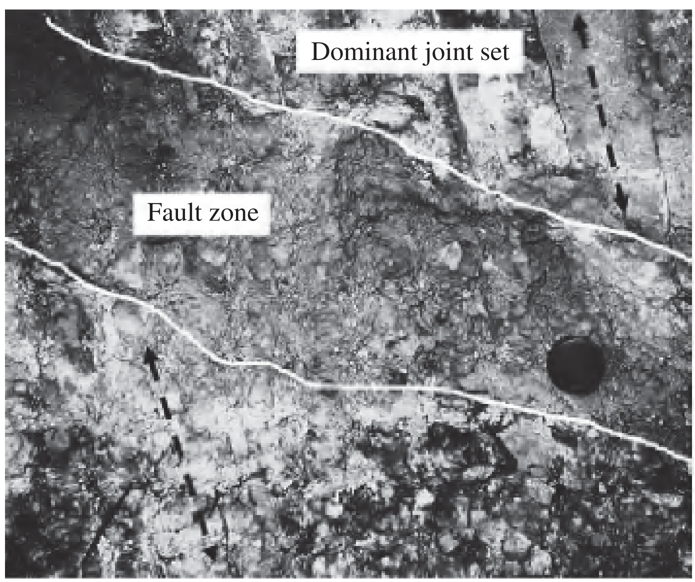


Figure B1-2.2 Exposure of brecciated and clay-infilled feature through mostly moderately and slightly weathered volcanic rock and with very different orientation to most other rock joints.

statistical elimination of rare but important discontinuities from analysis, as discussed earlier, but exacerbated by poor communication. The design engineers and checkers might not have been alerted by the unfamiliar terminology (tectonically influenced) used by the logging geologist; they should have been more concerned if they had been warned directly that there was an adversely oriented fault dipping out of the slope.The feature was identified during construction, but failure occurred before remedial

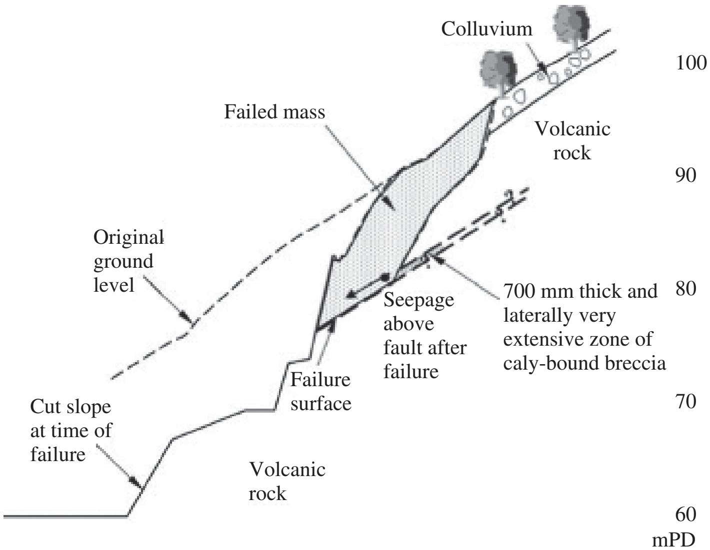


Figure B1-2.3 Cross section through slope showing original and cut slope profile at the time of failure. Geology is interpreted from mapping of the failure scar, but the main fault could be identified in boreholes put down before the failure occurred.

Figure B1-2.4 Slope in 2010 showing anchored concrete beams installed to prevent further failure in the trimmed-back slope above the apartment blocks.

measures could be designed (Clover, 1986). It was fortunate that the failure occurred before construction of the apartment blocks at the toe. The site as in 2010 is shown in Figure B1-2.4. The slope required extensive stabilisation with cutting back and installation of many ground anchors through concrete beams across the upper part of the slope and through the fault zones. These anchors will need to be monitored and maintained continuously for the lifetime of the apartments.

Inadequate site investigation that fails to identify the true nature of a site and its hazards can result in huge losses and failure of projects. Similarly, poorly directed or unfocused site investigation can be a total waste of time and money whilst allowing an unfounded complacency that a proper site investigation has been achieved (box ticked). The engineering geologist needs to work to avoid these occurrences. He needs to be able to communicate with the engineers and to do that he needs to understand the engineering priorities and risks associated with a project. Those risks include cost and time for completion. This book should help.

1.5 Rock and soil as engineering materials

In geology all naturally occurring assemblage of minerals are called rocks, whatever their state of consolidation, origins or degree of weathering (Whitten & Brooks, 1972). For civil engineering purposes it is very different. Geological materials are split into soil and rock, essentially on differences in strength and deformability. To make it more difficult, the definitions of what is soil and what is rock may vary according to the nature of the project. For many purposes, soil is defined as material that falls apart (disaggregates) in water or can be broken down by hand but, for a large earth-moving contract, materials may be split into soil and rock for payment purposes according to how easy or otherwise the material is to excavate; rock might be defined as material that needs to be blasted or that cannot be ripped using a heavy excavating machine. For engineering design, the distinctions are often pragmatic and there may be fundamental differences in approach for investigation and analysis. This is illustrated for slope stability assessment in Figure 1.3. In the left-hand diagram, the soil, which might be stiff clay or completely weathered rock, is taken as having isotropic strength (no preferential weakness directions), albeit that geological units are rarely so simple. To assess stability, the slope is searched numerically to find the critical potential slip surface, as explained in Chapter 6. In contrast the rock slope to the right is, by definition, made up of material that is too strong to fail through the intact material, given the geometry of the slope and stress levels. In this case, site investigation would be targeted at establishing the geometry and strength characteristics of any weak discontinuities (such as faults and joints) along which sliding might occur. If an adverse structure is identified then the failure mechanism is analysed directly. This conceptual split is fundamental to all branches of geotechnical engineering, including foundations, tunnels and slopes, and it is important that the engineering geologist is able to adapt quickly to seeing and describing rocks and soils in this way.

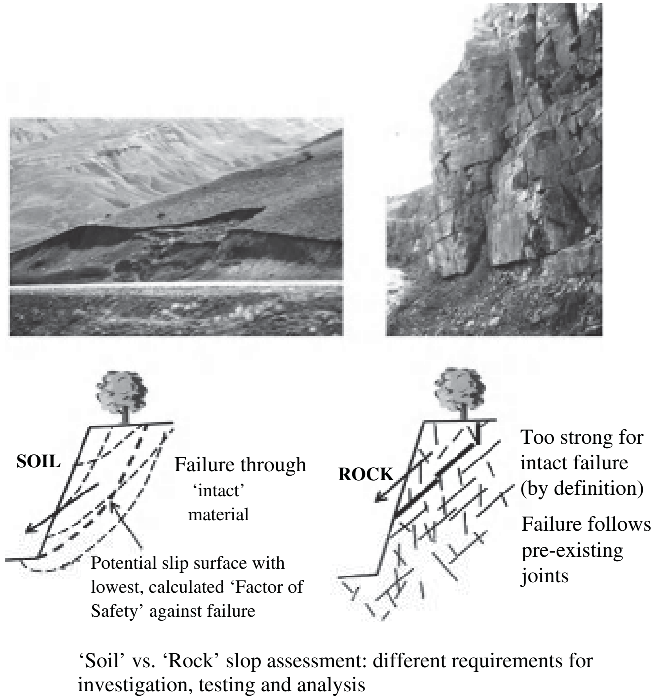


Figure 1.3 Distinction between soil and rock at a pragmatic level for slope stability analysis. Soil failure is near Erzincan, Turkey. Analysis involves searching for the slip plane that gives the lowest FoS for the given strength profile. The rock slope is in a limestone quarry, UK, and failure is totally controlled by pre-existing geological structure (bedding planes and joints).

The compartmentalisation of soil and rock mechanics is quite distinct in geotechnics, with separate international societies, which have their own memberships, their own publications and organise their own conferences. Details and links are given in Appendix A. Textbooks deal with soil mechanics or rock mechanics but not the two together. In reality, this is a false distinction and an unsatisfactory situation. Engineering geologists and geotechnical engineers need to appreciate that in nature there is a continuum from soil to rock and from rock to soil. Soil deposited as soft sediment in an estuary or offshore in a subsiding basin is gradually buried and becomes stronger as it is compressed by the weight of the overlying sediment, and strong bonds are formed by cementation, as illustrated in Figure 1.4. Conversely, igneous rock such as granite is strong in its fresh state but can be severely weakened by weathering to a soil-like condition, as illustrated in Figure 1.5, so that it might disintegrate on soaking and even flow into excavations below the water table.

An engineering geologist must be familiar with the full range of geological materials and understand the principles and methods of

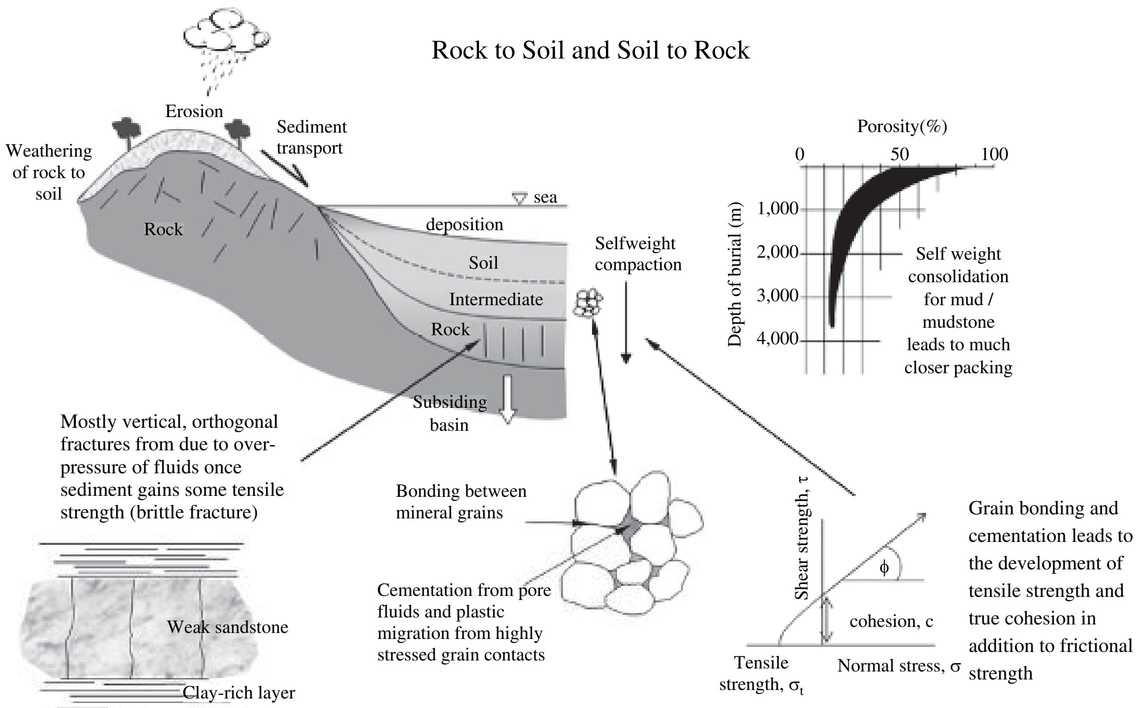


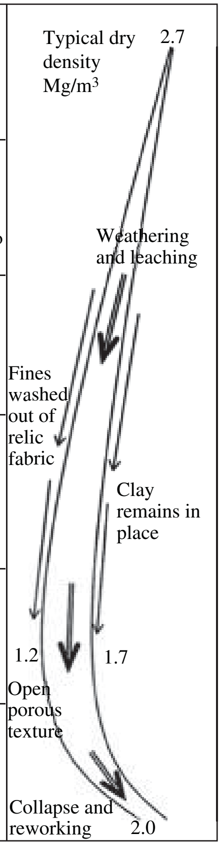
Figure 1.4 The cycle of rock to soil and soil to rock. Diagenetic and lithification processes cause soft sediment to transform into strong cemented rock during burial. Exposed rock breaks down to soil by weathering.

both soil and rock mechanics, which are tools to be adopted, as appropriate, within the engineering geological model.

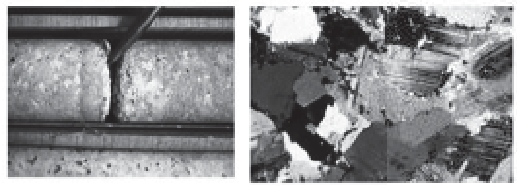
1.6 Qualifications and training

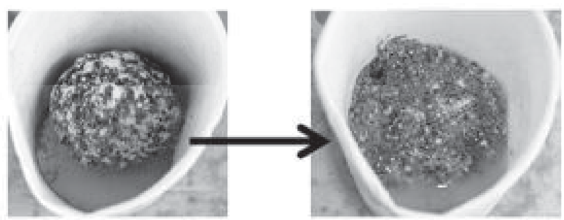
Engineering geologists generally begin their careers as earth science graduates, later becoming engineering geologists through postgraduate training and experience. Within civil engineering, in many countries including the UK, Hong Kong and the USA, there is a career pathway that is measured through achievement of chartered status or registration as a professional, as summarised in Table 1.3. The aim is that engineering works should only be designed and supervised by competent persons who have received adequate training and experience. Chartered or registered status generally requires a recognised university degree followed by a period of training under the supervision of a senior person within a company. The practice of engineering is often legally defined and protected by government regulations. In some countries, only registered or chartered engineers or engineering geologists are permitted to use the title and to sign engineering documents (reports, drawings and calculations), thus taking legal responsibility. Details for career routes for various countries are set out in Appendix A, together with links to a number of learned societies and details of professional institutions that an engineering geologist might aspire to join.

Fresh	'out of the oven' – not seen at Earth's surface UCS up to about 250 MPa
Slightly Weathered	Looks fresh in hand sample but joints may be stained Several hammer blows to break sample
Moderately Weathered	Discoloured, weakened and jointed but still 'rock' Needs hammer to break
Highly Weathered	Becoming soil like but doesn't disintegrate if placed in water Many micro-cracks Broken by hand
Completely Weathered	Feldspars soft – grooved with pin and sample disintegrates in water Micro-cracks may be sealed with clay
Residual Soil	Original texture lost Much of quartz has been dissolved. Typically red, clay rich



Slightly weathered grainte as recovered from a borehole and in thin section under microscope





completely weathered granite with texture retained (feldspars decomposed to white kaolin). After adding water it completely disaggregates (slakes)

Figure 1.5 Typical stages of chemical weathering for an igneous rock.

Table 1.3 Typical routes for a career in geotechnical engineering (UK).

Engineering geologist	*Geotechnical engineer*
• First degree geology or other earth sciences (BSc or MSc) • MSc in engineering geology • 5+ years experience and training • Chartered Geologist (straight-forward route) – Geological Society of London • Chartered Engineer (more difficult route) – Institution of Civil Engineers or Institution of Mining, Metallurgy and Materials	• First degree civil engineering (BEng or MEng) • MSc in geotechnical subject (e.g. soil mechanics or foundation engineering) • 5+ years experience and training • Chartered Engineer (Institution of Civil Engineers)
Distinctive skills at early stage in career development	
• Knowledge of the fabric and texture of geological materials and geological structures and how these will influence mechanical properties (more so for rock than soil) • Observation and mapping of geological data • Interpreting 3-D ground models from limited information following geological principles • Identifying critical geological features for a ground model	• Numerate, with sound basis for analysis and the design of engineering structures • Good understanding of mechanics (more so for soil than rock) • Understanding of project management and business principles