Geological Maps: Engineering Geology☆

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Introduction

Engineering geological maps provide ground information of relevance to civil engineering planning, design, and construction. Given that geology and civil engineering deal with three-dimensional structures and how they behave through time, albeit usually on different time-scales (geology 10^1–10^9 years; civil engineering 10^1–10^2 years), it is to be expected that the preparation of maps and plans is an essential component of both disciplines. Hence engineering geology maps have been regarded as an effective means of conveying information between geologists and engineers from the earliest days of the emergence of engineering geology as an identifiable subject. Indeed, the first classic stratigraphic maps and sections of William Smith in the late eighteenth and early nineteenth centuries arose out of his work on canal construction and the need to anticipate ground conditions.

An engineering geological map differs from the standard geological map (Lisle et al., 2011) by not being limited to the categories of bedrock and/or superficial geology, both of which are classically identified in terms of chronostratigraphy. The engineering geological map normally classifies materials based on their similar engineering characteristics (i.e. lithostatigraphy) and will also include relevant data on topography, hydrology, hydrogeology, geomorphology, and geotechnics, plus information on man-made structures such as landfill sites or earthworks (Dearman, 1991). This additional ground information may be shown on the map itself, as shown on **Figure 1** from a road improvement scheme in Sri Lanka, or by using tables, charts, and diagrams accompanying the map, as exemplified by **Table 1** from the Hong Kong Geotechnical Area Studies Programme (GASP). Whilst most maps in the past were cartographically drafted and produced as hardcopy, the modern method is to use computer-based graphical drafting and presentation software, including Geographical Information Systems (GIS), for compiling the data in formats that can be readily updated and analyzed. These systems are also able to incorporate a wide range of data which enables the surface mapping to be supplemented by data from other sources, including ground investigation, thus facilitating the understanding of ground conditions required for engineering design and construction projects. As with any map, the value of the engineering geological map is dependent on the accuracy of the information used in its compilation. Thus, engineering geologists responsible for producing engineering geology maps must have a broad range of skills and be able to recognize and correctly compile data from a wide spectrum of Earth science disciplines (Brunsden, 2002; Fookes, 1997; Fookes et al., 2000; Griffiths, 2001; Hutchinson, 2001). However, the actual use of engineering geological maps in planning and development is variable despite the widely held view amongst engineering geologists that they are fundamental tool to aid the understanding of ground conditions (Griffiths, 2014).

Map Scale

Engineering geological maps are not just academic interpretations of the ground; they are produced to meet the specific requirements of a project. Therefore, the material presented and the scale used on the map will vary to meet the requirements of the end-user. Consequently, there is no unique format or content for an engineering geology map and throughout the mapping programme, the engineering geologist will need to be aware of the end-use to ensure that collection and presentation of the data are appropriate to the project requirements. **Table 2** provides an indication of the application of engineering geological maps at different scales to suit different purposes. For engineering work, mapping may be carried out during feasibility studies, before any site work is started, just prior to or during the site investigation phase, whilst construction is underway, or as a means of compiling data if there have been problems with a structure after it has been built. To meet this range of applications, three broad-scale categories are recognized (large, medium, and small). These categories are presented in **Table 2** and whilst the boundaries to the categories should be regarded as flexible, there are differences in the way the maps are compiled, the techniques employed in their construction, and their intended end-use. A wide range of examples of all the categories of engineering geology map can be found in the published literature, and **Figure 1** is presented as an illustration of a typical large-scale engineering geological map. This map was produced specifically for the investigation of a single stretch of road and provides data of direct relevance to the design of remedial measures.

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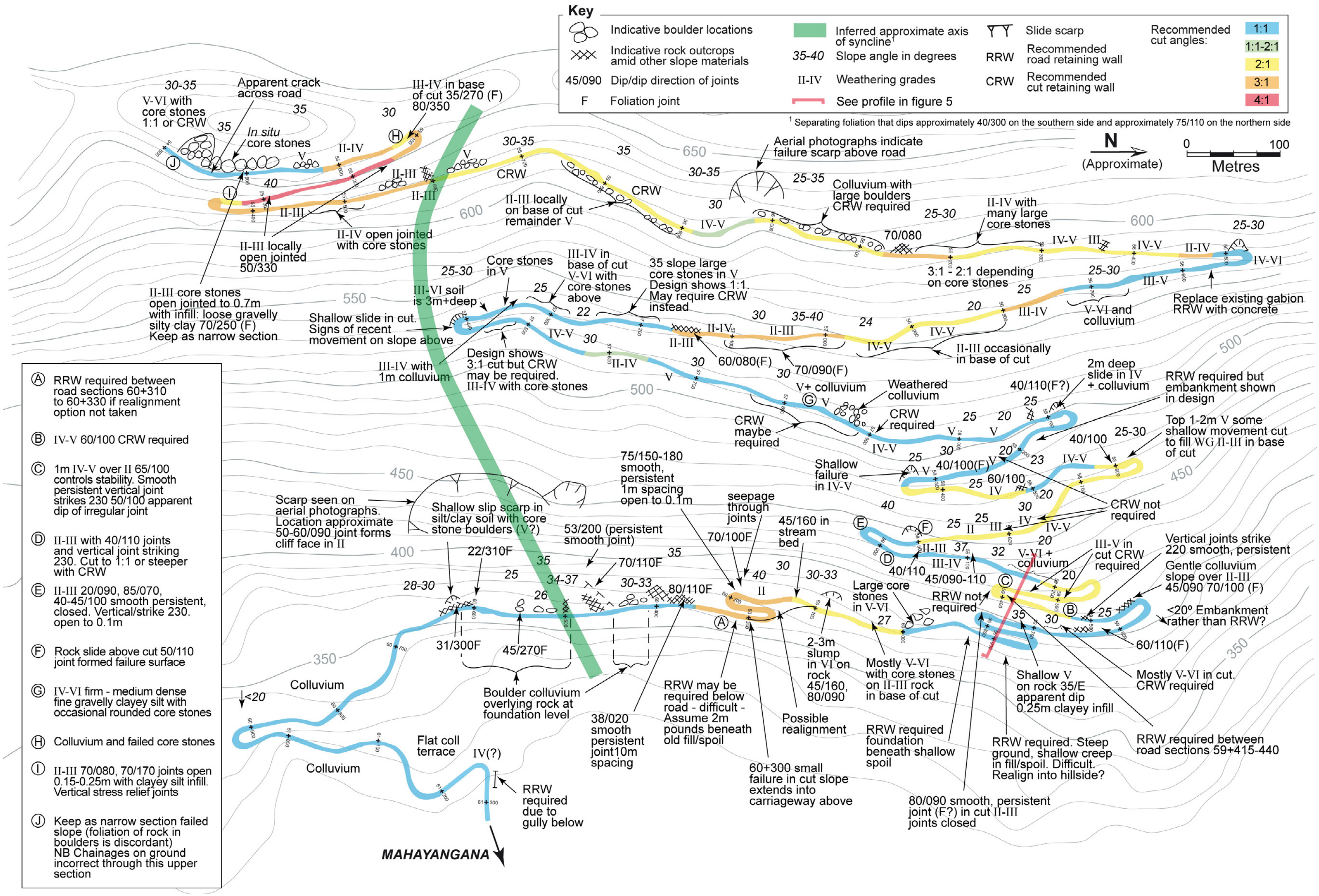

Figure 1 Example of a large-scale engineering geology map of a road section in Sri Lanka. Reproduced with Geological Society of London permission from Hearn (2011).

Table 1 Example of an extended engineering geology legend based on bedrock data from the Hong Kong GASP programme (Styles & Hansen, 1989)

	Material description			*Evaluation of material*		
Map unit	*Lithology*	*Topography*	*Weathering*	*Material properties*	*Engineering comment*	*Uses/excavation*
Lower Cretaceous Dolerite (dyke rock)	Black to very dark grey, fine to medium-grained rock. Smooth joints normal to boundaries result of cooling	Generally occurs as linear structural features transecting the volcanic and granite units. May be of slightly depressed or elevated topographic form due to variable resistance of the country rocks. This geological structure often controls local surface runoff and may act as a loci for subsurface water concentrations	Weathers deeply to a dark red silty clay	Weathered mantle will contain a high proportion of clay and iron oxides leading to low Ø values. Intact rock strength will be very high, >100 Mpa when fresh	Restricted extent precludes detailed comment. Weathered mantle will have relative low permeability and will affect groundwater hydrology by forming barriers, and variable boundary conditions. Sub-vertical dykes may dam groundwater leading to unexpectedly high groundwater levels	Restricted extent precludes deliberate borrow or quarry activities. Weathered material would make poor fill but fresh rock would make suitable high density aggregate or railway ballast
Upper Jurassic Hong Kong Granite	Pink to grey medium-grained equigranular, non-porphyritic rock Mineral include quartz, potassium feldspar, plagioclase, biotite and muscovite. Rough sheeting joints and widely spaced tectonic joints widespread	Forms extensive areas of moderate to steep convexo-concave slopes. High-level infilled valeys are common. Drainage pattern is often dendritic in nature and is commonly dislocated by major tectonic discontinuities. These units are characterised by moderate to severe gully and sheet erosion associated with hillcrest and upper sidelong terrain	Shallow to deep residual soils over weathered granite. Local development of less weathered outcrops in stream beds and occasional cliff faces. Residual core boulders common on surface of sidelong ground and gullies. Weathering depths >20 m	Material properties vary with depth within the weathering profile. For completely weathered granite typical values are $c' \approx 0$–25 kPa, $Ø \approx 31$–43°; permeablity $\approx 10^{-6}$–10^{-8} m s^{-1}; dry density 1500 kg m^3. Moisture content 15% near surface, 30% at depth. Fresh rock UCS 80–150 MPa. Rock mass strength dependent on joint characteristics. Roughness angles for tectonic joints 5–10°; for sheet joints 10–15°; basic friction angle $\approx 39°$	Weathered mantle subject to sheet and gully erosion with landslides in steep slopes or if severely undercut. Perched water tables conform with highly permeable upper weathered zones. Rock is prone to discontinuity controlled failures in fresh to moderately weathered state. Stream and drainage lines align with geological weakness. Large structures may require deep foundations. Cut slope design may be governed by the large depths of weathered material	Extensively quarried and used as concrete aggregate. Weathered material widely used as fill as it is easily excavated by machinery. Core boulders can cause problems during excavation
Middle and Lower Jurassic Lok Ma Chau Formation	Metamorphosed sedimentary and volcanic rocks, including schist, phyllite, quarzite, metasediments and marble	Forms hills of moderate to low relief due to its low resistance to erosion. Occurs extensively beneath collluvial and alluvial cover. Local areas of surface boulders and occasional rock outcrops on sidelong ground and in gullies	Metasediments generally weather to produce moderately deep (1–2 m), uniform or gradational red-brown clay	Near-surface completely weathered residual soil acts as a silt with a void ratio 0.25–0.33. Gradings show 5–15% clay, 40–60% silt, 20–30% fine sand. PL 25–35%; LL 34–40%. Typical shear strength $c' \approx 0$–15 kPa, $Ø \approx 35°$. Weathered materials dry density 1600–1800 kg m^3. Fresh rock UCS 40–90 MPa. Discontinuity strength parameters $c' \approx 0$–5 kPa, $Ø \approx 25$–30°	Considerable care is required during investigation, design, and construction. Bearing capacity reasonable for low and moderate loads. Stability is dependent on the very closely spaced discontinuities. Discontinuity surveys are essential for cut slope design. Material prone to failure along discontinuities when weathered and saturated	Material can be used as a source of bulk fill but may break down to silt if over-compacted. Excavation by machine is relatively easy

Table 2 Scale of engineering geology maps suitable for different purposes (Based on Griffiths & Whitworth 2012)

Large scale maps
1:10 000 or greater. Plans and sections up to 1:500 scale can be used in particular circumstances
- Based on: detailed field mapping and ground investigation data. These data will be supplemented by: interpretation of large-scale aerial photographs and high resolution airborne and satellite imagery; development of satellite-derived DEMs; and analysis of airborne and ground LIDAR. Data should be compiled into a suitable spatial database (Geographical Information System - GIS) to enable the creation of a ground model that can form the basis for subsequent ground investigations (Parry et al., 2014)
- Uses: investigating the type, nature and causes of individual hazards (e.g. landslides); designing and interpreting ground investigations; preparing remedial measure were appropriate
- End-users: applied and academic geomorphologists; civil engineers; engineering geologists; geotechnical engineers; quantity surveyors

Medium scale maps
1:10 000 to 1:100 000 scale
- Based on: terrain evaluation and analysis; remote sensing interpretation (aerial photographs and satellite imagery); satellite-derived DEMs; airborne LIDAR; and ground-truth field mapping of selected areas. These data can readily be compiled into a GIS to facilitate interpretation and a range of high quality outputs including natural hazard and risk studies (Lee & Jones, 2014)
- Uses: investigating the types and nature of landscape features by placing them in their 'geomorphological situation'; natural hazard and risk evaluations at local to regional level; locating geohazards for route alignment planning; resource assessment; disaster relief planning; landscape development studies
- End-users: academic geomorphologists and geologists; civil engineers; engineering geologists; local and regional planners; local and regional government; insurers; emergency service; the military

Small scale maps
1:100 000 or smaller
- Based on: terrain evaluation and analysis; remote sensing interpretation mainly of ASTER imagery and Landsat 7 ETM data; and limited reconnaissance of field area usually by vehicle or helicopter. Remote sensing data collected may be suitable for compilation in a GIS to help create hazard and risk maps (e.g. Teeuw, 2007)
- Uses: generalised natural hazard and risk evaluations; regional resources assessment; development planning at the regional or national level; investigations of long term landscape development
- End-users: academic geomorphologists and geologists; local and regional planners; regional and central government; insurers; the military

Medium-scale engineering geological maps are probably the most widely used and excellent examples can be found in the UK, where a national programme of applied geological mapping, predominantly by the British Geological Survey, resulted in over 35 studies and produced a wide range of maps for use in engineering construction and planning development (Smith and Ellison, 1999). These maps were mainly been produced at a scale of 1:25 000 and represented compilations of engineering geological data in map form that could used as the basis for engineering feasibility studies. Similar applied geological mapping programmes were carried out in a number of other countries. In France, the ZERMOS programme produced a number of 1:25 000 scale maps of selected area (Porcher and Guillope, 1979). Originally under the auspices of the Geotechnical Control Office, the former territory of Hong Kong was mapped at 1:20 000 during the GASP programme (Styles and Hansen, 1989).

Small-scale maps are best exemplified by the PUCE (Pattern-Unit-Component-Evaluation) system developed by the Commonwealth Scientific Research Organisation (CSIRO) in Australia, but also used in Papua New Guinea. This innovative programme produced maps at a scale of 1:250 000 that defined broad terrain patterns, within which particular assemblage of landforms, pedological soils, and vegetation sequences occur (Finlayson, 1984). These have been predominantly used in regional planning but there are examples of their use for aggregate resource surveys; route corridor alignment; water resources; military and off-road mobility; flood hazard; land capability assessment; and aesthetic landscape appreciation.

The USA also has a long commitment to engineering geological mapping at a wide range of scales which were originally illustrated in the compilation of maps provided by the US Geological Survey Profession Report 950, entitled 'Nature to be Commanded' (Robinson and Speiker, 1978).

The Type of Data to be Recorded

Although the specific content of any one engineering geological map will depend on the application, the main aim of an engineering geological mapping programme is to produce a map on which the mapped units are defined by engineering properties or behaviour. The limits of the units are determined by changes in the physical and mechanical properties of the materials. The boundaries of the mapped units may not correlate or coincide with the underlying geological structure or the chrono-stratigraphic units as depicted on conventional geological maps. However, experience has shown that the lithology of engineering soils and rocks can often be effective in defining the engineering geological map units. Apart from these map units, **Table 3** presents the type of additional data that are relevant and could be recorded on the engineering geological map through observations made in the field, supplemented by desk studies and ground investigations using exploratory pits and geophysics.

Whilst **Table 3** provides an indication of the range of data that might be compiled, the requirements for an individual engineering geological map will be tailored to suit the specific issues to be investigated. For example, in an area of earthquake risk there is likely to be more emphasis on the location of active faults, extent of soils liable to liquefy under dynamic loading,

Table 3 Data to be recorded on an Engineering Geology Map

Geological data
- Map units (chronostratigraphy and lithostratigraphy)
- Geological boundaries (with accuracy indicated)
- Description of soils and rocks (using standard engineering geological codes of practice – see Norbury, 2010)
- Description of exposures (cross referenced to field notebooks)
- Description of state of weathering and alteration (note depth and degree of weathering)
- Description of discontinuities (as much detail as possible on the nature, frequency, inclination and orientation of all joints, bedding, cleavage, etc.)
- Structural geological data (folding, faulting, etc.)
- Tectonic activity (notably neotectonics, including rates of uplift)

Engineering geology data
- Engineering soil and rock units (based on their engineering geological properties)
- Subsurface conditions (provision of subsurface information if possible, e.g., rockhead isopachytes)
- Geotechnical data of the engineering soil and rock units
- Location of previous site investigations (i.e., the sites of boreholes, trial pits, and geophysical surveys)
- Location of mines and quarries, including whether active or abandoned, dates of working, materials extracted, and whether or not mine plans are available
- Contaminated ground (waste tips, landfill sites, old industrial sites)
- Man-made features, such as earthworks (with measurements of design slope angles, drainage provision, etc.), bridges and culverts (including data on waterway areas), tunnels and dams

Hydrological and hydrogeological data
- Availability of Information (reference to existing maps, well logs, abstraction data)
- General hydrogeological conditions (notes on: groundwater flow lines; piezometric conditions; water quality; artesian conditions; potability)
- Hydrogeological properties of rocks and soils (aquifers, aquicludes, and aquitards; permeabilities; perched watertables)
- Springs and Seepages (flows to be quantified wherever possible)
- Streams, rivers, lakes, and estuaries (with data on flows, stage heights, and tidal limits)
- Man-made features (canals, leats, drainage ditches, reservoirs)
- Geomorphological data (see Smith et al, 2011)
- General geomorphological features (ground morphology; landforms; processes; Quaternary deposits)
- Ground Movement Features (e.g., landslides; subsidence; solifluction lobes; cambering)

Geohazards
- Mass movement (extent and nature of landslides, type and frequency of landsliding, possible estimates of runout hazard, snow avalanche tracks)
- Swelling and shrinking, or collapsible, soils (soil properties)
- Areas of natural and man-made subsidence (karst, areas of mining, over-extraction of groundwater)
- Flooding (areas at risk, flood magnitude and frequency, coastal or river flooding)
- Coastal erosion (cliff form, rate of coastal retreat, coastal processes, types of coastal protection)
- Seismicity (seismic hazard assessment)
- Vulcanicity (volcanic hazard assessment)

unconsolidated deposits that can amplify ground shaking, and zones potentially liable to the affects of tsunami or seiche. Similar specific details will be appropriate for different types of geohazard evaluation. For example, **Figure 1** is an example of a large-scale engineering geological map/plan of a series of hairpins for a road in Sri Lanka, which has been affected by landsliding. Because the concern of the engineering geologist in this study is slope instability, the map emphasises the landslides and notes both the geological details of relevance with observations on the engineering implications.

Some of the engineering geological data may be used to identify 'zones'. These areas on the map have approximately homogenous engineering geological conditions, usually defined by more than just the lithostratigraphy. The zoning system would be derived from the factual data contained on the base map. It would not, therefore, normally form part of the original mapping programme and represents a derivative or interpretative engineering geological map. Zoning maps can be particularly effective in geohazard studies where the magnitude of a particular hazard can be represented by an interpretative map containing data on probability of occurrence or frequency. However, interpretative zoning maps can be used in many ways relevant to engineering and examples can be found of maps showing: foundation conditions, excavatability of materials, sources of construction material, bearing capacity of soils and rocks, and general constraints to development.

Data Collection

Primary mapping for engineering geology follows the same basic rules and uses the same techniques established for conventional geological mapping (Lisle et al., 2011). However, a number of additional decisions need to be made when undertaking engineering geological mapping. These are to identify the types of data that are to be collected to meet the survey requirements (**Table 3**); the scale of the mapping (**Table 2**); the methods to be used for data collection; and the intended final map products.

In most engineering situations there will be four phases in the preparation of an engineering geological map: desk study; field mapping; interpretation; and reporting. During the desk-study phase all existing data are compiled, remote sensing interpretation is carried out, a preliminary field reconnaissance may be undertaken, and the field programme is planned. Field mapping requires the collection of primary data in the field. Even if the available data is quite comprehensive and it is only intended to produce small-scale maps, some primary field mapping will be necessary. Interpretation of the data involves bringing together the field and desk study data, compiling the data in a database/GIS, and then preparing the suite of maps that meet the project requirements (Shilston et al., 2012). Finally, the maps will need to be supplemented by a written report for the end-user that expands on the details shown on the map and, in engineering situations, may provide some design guidance or recommendations.

Map Presentation

The presentation of engineering geological maps follows normal cartographic rules over scale, north arrow, and locational data, but the information displayed will be based on end-user requirements. Because the information on the map is variable, it is usually necessary to create a bespoke legend for the map, as exemplified by the key to **Figure 1**. However, general guidance on the typical symbols to use can be found in the standard literature on engineering geological maps (e.g. Dearman, 1991).

Often, with engineering geological maps, it is necessary to include quite comprehensive data in the map legend. These data will not have just been compiled from field observations but will include data from the desk studies and any detailed ground investigations carried out in the area. An example of a comprehensive, or extended, legend is provided in **Table 4**, from the UK Applied Geological Map for Stoke-on-Trent. This uses the superficial geological map as the basis for identifying the engineering geological units. **Table 1** provides an example of a similar compilation of data based on bedrock properties of the type used in the

Table 4 Example of an extended engineering geology legend based on the superficial geology map data in the Applied Geology Map of Stoke-On-Trent (Smith and Ellison, 1999)

			Planning & engineering considerations			
	Description	*Characteristics*	*Slope stability*	*Excavation*	*Foundations*	*Engineered fill*
Alluvium	Silts & clays 0.6–9 m thick. Occurs mainly in the Trent valley and tributaries	Very soft to firm, low to high plasticity, medium to high compressibility. May be desiccated near top	Not applicable as occurs in flat areas	Diggable by excavator. Heave may occur at base of excavations. Trench support required	Low acceptable bearing capacity (<75 kPa)	Generally unsuitable
	Organic in places, with peat lenses	Very soft to soft, intermediate to extremely high plasticity. Highly compressible			Sulphate protection usually required for concrete	
	Sands and gravels often occur at base	Loose to very dense. Water bearing		Running ground conditions will require cut-offs or dewatering		
Periglacial head	Variable soils derived from bedrock other superficial deposits. Composition varies according to the parent material. Generally consists of sandy, silty clays with gravel and cobbles. Forms a thin veneer on slopes and may thicken downslope. Perched water tables may occur within coarser horizons	Variable. Usually cohesive, soft to stiff, with low to high plasticity. Compressibility usually intermediate, but may be high. Pre-existing shear surfaces may be present, with low residual friction angles	Natural slopes often marginally stable	Diggable by excavator	Consolidation settlement usually small. Differential settlement likely where soft compressible zones present	Generally unsuitable

(*Continued*)

Table 4 (Continued)

	Description	Characteristics	*Planning & engineering considerations* — *Slope stability*	*Excavation*	*Foundations*	*Engineered fill*
			The variability of this deposit necessitates careful site investigation, preferably by trial pitting, to determine the site characteristics in relation to any proposed development. Clayey slopes may require drainage and other stabilisation works prior to construction			
Glacial sand and gravel	Coarse sand and subangular to subrounded gravel Occasional subrounded cobbles	Loose to dense granular deposit. Water bearing	Not applicable as occurs in flat areas	Diggable by excavator Support and groundwater control required	Consolidation settlements small. Pile driving may be difficult in cobbles. Sulphate protection may be required for concrete	Suitable for use in embankments if the soft clay zones are removed
	Some horizons of laminated clay/silt occur	Clay/silt horizons are usually soft to stiff, of low to intermediate plasticity				
Glacial till (boulder clay)	Variable deposit, generally sandy, silty clays with gravel, cobbles and occasional boulders	Generally firm to stiff, with low to intermediate plasticity and intermediate compressibility	Cut slope of 1V : 2.5H generally adequate for long term stability	May be difficult to dig and can require ripping. Excavations generally stable in the short term but deteriorate on exposure and wetting. Support required for deep excavations, and where sand lenses occur	Usually forms a good founding medium with acceptable bearing capacities typically 150–600 + kPa)	Suitable if placed in dry weather when moisture content is low
	Water bearing lenses of sand and gravel may occur					
Landslide debris	In the field area all known occurrences occur in weathered mudstones of the Etruria Formation	Deposits contain shear surfaces with low residual strengths. Remoulded clay debris is generally poorly drained with possible perched water tables	Areas of landslide debris should be avoided if possible. Constructional activity is likely to reactivate slope movement unless appropriate remedial measures are taken			Unsuitable
			Detailed site investigation is essential with extensive use of exploratory holes and geophysics. If construction is unavoidable groundwater and ground movement monitoring is essential			

tropical weathering environment investigated during the Hong Kong GASP programme. In both examples, additional data on the geotechnical and engineering characteristics of the various materials are included in the tables as well as comments on engineering issues, such as slope stability, excavatability, and groundwater conditions. These data should be shown in summary on the actual map, linked to a database held within a GIS, or they can be presented in an accompanying report. However, when working with hardcopy material there is always a concern that a report can become separated from its maps and, as a general recommendation, the map itself should be able to stand alone and be understood by all potential users, without having to refer to a separate report.

Another method of conveying engineering geological data that can be included on the map, held in the GIS, or presented in an accompanying report is shown in Figure 2. This three-dimensional block diagram, compiled to show typical engineering geological

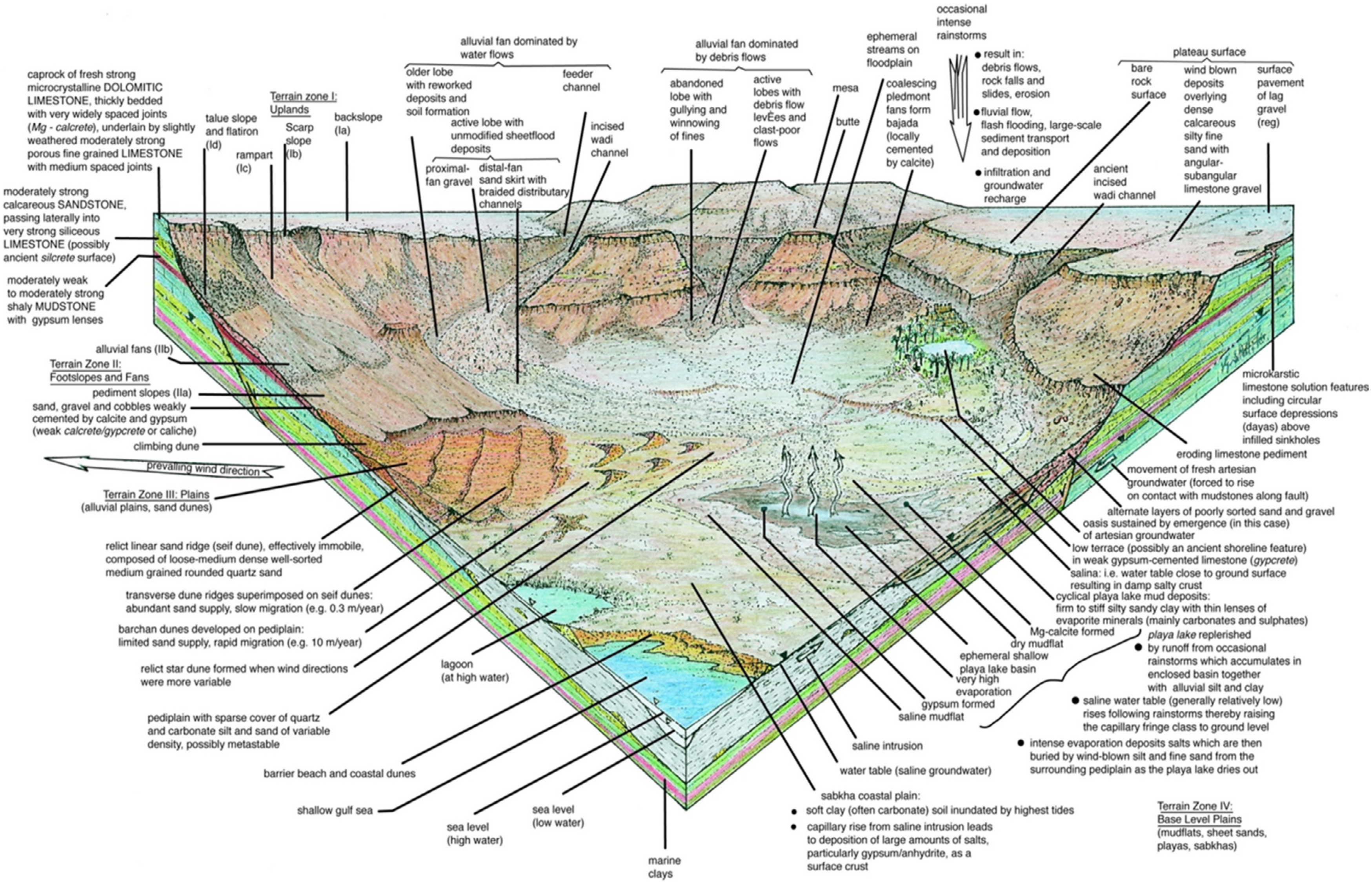

Figure 2 Three-dimensional engineering geology ground model developed for hot deserts. Reproduced with permission by Whittles Publishing from Fookes et al. (2007).

conditions in hot deserts, provides a synopsis of the ground conditions that illustrates how the bedrock geology, superficial geology, and geomorphology create a landscape that contains a number of technical problems for the engineering geologist. This type of figure is generally referred to as a 'ground model' (Parry et al., 2014).

Integration with Site Investigation

Site investigation for engineering is the process by which data appropriate for the design and construction of structures is collected. Whilst this primarily involves the exploration of the ground using invasive techniques such as drilling and trial pitting, it is recommended that engineering geological mapping be integral to the process. Along with engineering geophysics, mapping has proved itself to be extremely cost effective and can be used to design a more efficient ground investigation by defining the engineering geological units that will represented by the exploratory holes (Dearman, 1991; Griffiths, 2002). The maps, particularly if complied in a GIS, should be integrated with all the ground investigation data to provide the basis for preparing full three and possibly four-dimensional ground models, which are fundamental to safe, cost-effective and efficient civil engineering design.

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