J.C.HARVEY

GEOLOGY FOR GEOTECHNICAL ENGINEERS

Geology for Geotechnical Engineers

J.C.HARVEY

Lecturer in Geotechnical Engineering, Plymouth Polytechnic, England

CAMBRIDGE UNIVERSITY PRESS

Cambridge

London New York New Rochelle

Melbourne Sydney

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, NY 10022, USA
296 Beaconsfield Parade, Middle Park, Melbourne 3206, Australia

First published 1982

Printed in Great Britain at the University Press, Cambridge

Library of Congress catalogue card number: 82-1289

British Library cataloguing in publication data

Harvey, J. C.
Geology for geotechnical engineers.

1. Geology
I. Title
550'.4624 QE26.2

ISBN 0 521 24629 6 hard covers
ISBN 0 521 28862 2 paperback

Geology for Geotechnical Engineers

Preface

This book describes the fundamental principles of geology that are needed for a study of geotechnics, the science of the physical properties of the material found in the ground in which civil engineers build their constructions. A brief study of the ground will show that it consists of hard or soft material, sometimes separate, sometimes both together. Geotechnical engineers define the hard material as rock, the soft as soil. The studies of the behaviour of these materials are called rock mechanics and soil mechanics, respectively. Geotechnics is the practical application of these sciences to forecast the behaviour of the ground when it is built upon or when excavations and tunnels are made into it.

To understand the behaviour of the ground the geotechnical engineer needs to know some essential geological facts. Rocks, and the soils which are derived from them, are described with special attention paid to those properties which are closely connected with their behaviour under mechanical stress and the chemical forces on the surface of the Earth which bring about decay of solid rock and convert it into soil. For a scientific study of the origins and classification of rock, the student has to learn very many names of the different chemical compositions of the materials which form rock, the names of very many rock types and their internal structures, and the origins and distributions of rocks throughout the world. Whilst a study of the details of the history of the Earth and its component materials can be of very great interest, civil engineers have in the past thought of geology as a science which has such a complicated terminology that they have tended to avoid it. They preferred to concentrate on soil, and their work in this direction over the last 50 years has produced a new branch of science - soil mechanics. Rock was the hard material found in some excavations in the ground. Sometimes it was welcome, making a solid base for the foundations of a building; sometimes it was a nuisance, causing rock trouble, difficult and expensive to excavate, or having unpredictable behaviour when exposed in excavations. Before 1950 civil engineers in general hoped that rock would not cause them any trouble. When there was rock trouble, civil engineers dealt with it as best they could and sometimes called in consultant geologists to help them. The advice they received was often unsatisfactory because the geologists were trained primarily to understand the Earth's history and processes, and to describe and classify rocks and the wide range of chemical substances they contained, including fossils and useful minerals. Geologists were not really interested in predicting rock behaviour, nor in a study of rotted and disintegrated rock making up soil. During the period 1950–1970 however, many geologists turned their attention to the mechanical properties of rock as the demand for reliable prediction of rock behaviour increased, as constructions became larger and the occurrence of rock trouble became more expensive and even led to the bankruptcy of some construction companies which were unable to meet target dates, or whose costs exceeded those stated in the contract. This application of the science to the practical problems of the construction industry became known as engineering geology. This new branch of geology was mostly concerned with rocks and civil engineers continued to be responsible for forecasting the behaviour of soils. The two cannot really be separated because they often occur close together and need to be tested as a whole instead of by separate groups of people. As geologists became more interested in engineering geology and civil engineers in rocks, the new science of geotechnics was born.

Because this treatment of the subject is mainly concerned with the mechanical behaviour of rock rather than its origins and variable chemical composition, the number of geological words has been carefully reduced to those essential for a sufficient knowledge of geological principles to understand the basis of geotechnics. Further information on geology can be found in the literature quoted in the Bibliography.

I should like to record my thanks to my colleague John Clatworthy of the Department of Civil Engineering, Plymouth Polytechnic, for advice and encouragement during the writing of this book, and for his collaboration in the geology training of civil engineering students during the past 20 years.

Plymouth
October, 1981

John Harvey

Contents

1 The Earth, its structure, and the forces acting inside it and on its surface

The interior of the Earth and dynamic forces

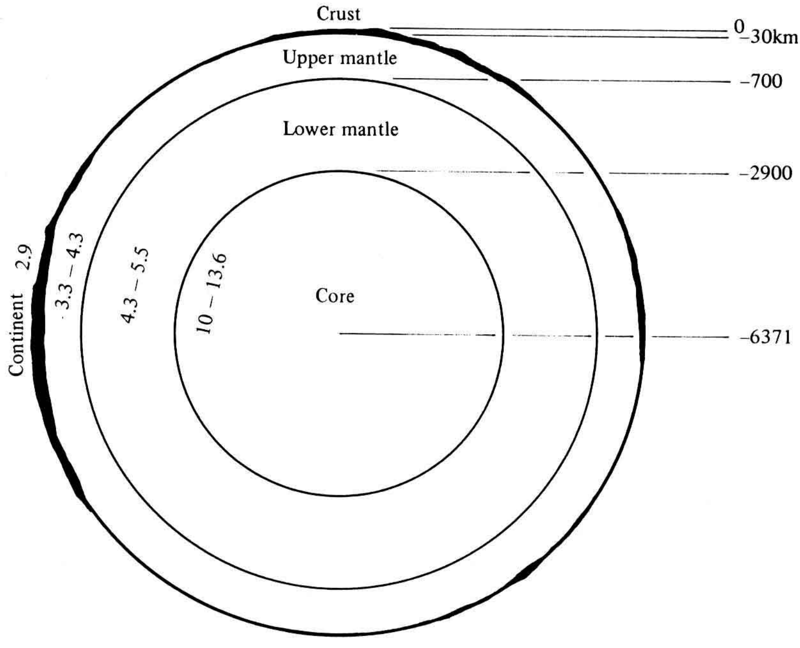
The Earth is not a rigid and static body, but is in a continual state of change, both inside and on the surface. Forces are acting to create new rock material and on the surface other forces are destroying the rock which has been formed in the past. The product of these destructive processes is known as soil, itself a new form of the material, so the forces of destruction may also be thought of as constructive forces. The word soil in geotechnics means any unconsolidated material in the ground and is not used in the same sense as that used by pedologists who study soil as a life-supporting material. The age of the Earth is at present believed to be at least 4500 million years. The ages of some rocks found on the surface of the Earth have been determined to be of the order of 3500 million years by using methods based on the radioactive decay of natural isotopes found in minerals which make up the body of the rock.

The interior of the Earth is believed to be built of concentric shells of rock material, named the crust and the mantle, which surround a central core (Fig. 1). Movement of material within the Earth is believed to be the cause of some of the surface processes which we experience. This movement may be the last phases of the turbulence associated with the creation of the planets in the solar system.

The average specific gravity of the Earth as determined by the mathematics of planetary motion is 5.5, but the specific gravity of the rock found on the surface is only about half this value, 2.7. Therefore the interior must be more dense. The evidence for the existence of a structure consisting of distinct shells of different specific gravities as shown in Fig. 1 comes from measurements on the rates at which shock waves from earthquakes travel through the Earth. There are different types of waves and they move in complicated paths through the interior. Results obtained from the study of these waves (seismology) have shown that there are relatively rapid changes in specific gravity at depths of 35, 700, and 2900 km. These changes are called discontinuities by geophysicists; this word is also used in geotechnics, but in a different sense, to indicate fractures and open spaces within rocks. These relatively rapid changes in specific gravity cause earthquake waves to be reflected and refracted; the subsequent paths followed by the waves can be detected and their study forms the basis of our knowledge of the interior of the Earth. Geotechnical exploration methods can determine the specific gravities of the rock below the surface as part of a site investigation programme to predict the behaviour of the rock below a construction site. Shock waves are generated by falling weights or small explosive charges. The same method on a larger scale is used in the exploration for oilfields.

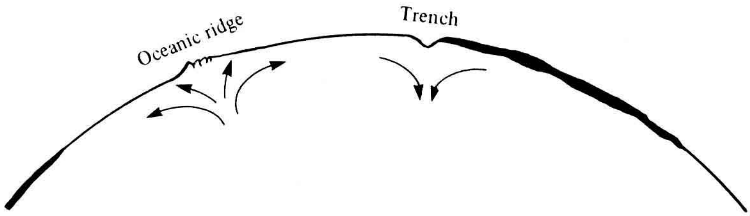
The last 50 years of study of the continents, their structure and histories, have led geophysicists to believe that the continents and oceans are not permanently fixed in position but are moving extremely slowly across the surface of the Earth, a process known as continental drift. The ocean beds are not permanent. The evidence for this belief is that studies of the ages of rocks dredged from ocean beds show that the youngest rocks tend to be found in a world-encircling mid-ocean ridge system in the North and South Atlantic Oceans, Pacific Ocean, and between the Indian Ocean and Antarctica. The rocks farther away from the ridges are older than those within the ridges, from which it is inferred that rock is rising and being pushed sideways as more comes to the surface from the mantle. To maintain balance in the shape of the Earth there must be regions where rock is

Fig. 1. Interior of the Earth. The crust is drawn with exaggerated thickness to show the thickening below continents. Specific gravity values are given.



descending into the mantle. Thus the ocean bed is slowly expanding outwards and this process is known as ocean-floor spreading. The driving mechanism is believed to be a system of convection currents forming cells in the top part of the mantle, as shown in Fig. 2. The rock material in the upper part of the mantle must therefore be in a plastic state, but of extremely high viscosity, and over tens and hundreds of millions of years total movements can be of the order of thousands of kilometres. Regions where the currents of rock in convection cells are diverging form ridges above the average ocean-bed level, for example the Mid-Atlantic Ridge; where they are converging, trenches form, going down to nearly 10 000 m. The Aleutian Trench is one example. The land areas of the continents are also moving, being carried by the convectional movement of material below them. These movements in the outer zones of the Earth explain why some parts of the Earth's surface are rising, some sinking, and some are moving horizontally. Upward movements form mountains, but while they are being formed the surface forces of the sun, wind, and rain attack the rock and decompose it from a solid state, forming loose pieces of rock particles (soil) which are removed by erosion and deposited at lower levels. Weathering is the word used to describe the processes of rock decomposition; erosion is the removal of the weathered rock by rivers, wind, and ice to other places, low ground or into the ocean. Rock material is therefore continually moving and during this movement undergoes changes which will be described in Chapter 2. The movements which form mountains are not continuous constant rate processes, but occur at irregular time intervals. Stresses build up in the rock and cause deformation and increase in strain energy. When the rock reaches the elastic limit a fracture occurs and there is a sudden release of energy in the form of earthquake waves. The fracture in the rock is called a fault. The movement during a single earthquake may be of the order of a centimetre, but in a severe earthquake it may be as much as a metre. Much of the released energy travels away from the fracture as a surface wave, like a wave on the sea, and this is the reason why buildings are destroyed during an earthquake. Some parts of the Earth are called seismic areas because there are

Fig. 2. Convection currents in the mantle form trenches at the margins of the continents and ridges in the oceans.

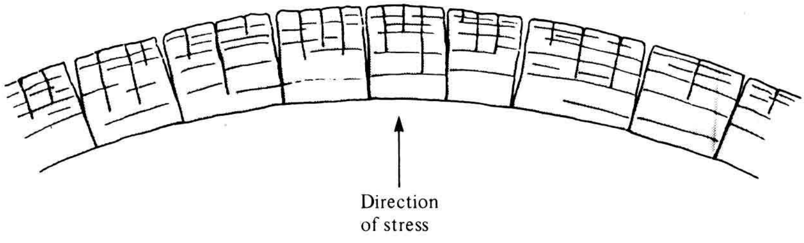


active mountain-building forces in action and earthquakes are common. Other areas are mountainous but the forces which made them have died away and earthquakes are rare, or do not occur. Large areas within the continents are low ground, or are elevated flat areas known as tablelands. Any mountains which were once in these areas have been eroded away and seismic activity has stopped.

All these processes of rock formation, movement and decay have caused rock found at the surface (outcrop) to consist of many different types and to have definite physical properties. The important geotechnical properties are specific gravity, permeability, strength, compressibility, and state of weathering. The last is very important because the other properties are dependent on it. The different properties are also dependent on each other. Measurements of these properties are made at proposed construction sites (*in situ* tests) and on samples taken to a geotechnical laboratory, in the hope that the mechanical behaviour of the rock or soil can be predicted and suitable construction designs made.

The movements described here cause compression and tension forces within large masses of rock. Upward movement causes tension cracks to form in hard rock near to the surface because of the increasing length of arc with greater radius (Fig. 3). Open cracks are in general only seen in the top 10 m of rock, but the rock below this level may contain very many planes of weakness, which only become discontinuities when the rock is near the surface and has the freedom to expand. Relief of compression stress caused by the weight of overlying masses of rock also causes rock when it gets near the top surface to expand radially outwards, forming more discontinuities with a dominantly horizontal direction. Geologists call these fractures joints, but in geotechnical language they are discontinuities. Hard rock in the ground often breaks easily into pieces that have regular geometrical shapes – cubes, rhombohedra – caused by the stresses that have been acting on the rock. Some rocks break into very irregular pieces because in the past they have been affected by several phases of severe stress acting in different directions at different times that have left their mark on the rock.

Fig. 3. Tension cracks forming in rising and expanding rock.



These discontinuities are described in the section on engineering description of rocks in Chapter 6. A study of rock exposed in a deep excavation shows that the number of discontinuities per unit volume decreases with depth and the deeper rock appears to be more solid. One exception to this is limestone, which can easily be dissolved by water in the ground and which usually contains many fissures, often large.

Weathering and decay of the Earth's surface

The natural tendency of rock near the surface to break into small pieces causes it to have a greater surface area per unit volume, and water can enter the discontinuities. In humid climates this accelerates the rate of decomposition of rock at the surface. Weathering in humid climates is chiefly a chemical process. Rainwater is very slightly acid because of dissolved carbon dioxide from the atmosphere; plants emit carbon dioxide from their roots, which also manufacture humic acids, and the interaction of these with rock releases solutions of plant nutrients, phosphorus, potassium, calcium, and trace elements, that are necessary to the plant. Water acts as the solvent in these processes by which plants decompose rocks and break them down into soil. The removal of these elements from the body of the rock leaves very small spaces into which water enters and the decay process accelerates. The rock first becomes porous, then breaks into small pieces which become progressively smaller as the rock is changed into soil. The chemical processes are complex and depend on the various minerals of which the rock is composed. Silica (SiO_2) in the form of the mineral quartz is stable in temperate climates, but in equatorial climates the high temperatures help it to decompose. Minerals that contain iron decompose to form iron hydroxides, which give the rock a brown colour, an indicator of weathering when fresh, unaffected rock is not naturally brown. Plant roots enlarge discontinuities by forcing the rock surfaces apart, helping the weathering process.

In the cold climates of high latitudes, and in mountains, the sequence of freeze and thaw of water breaks up rock because of the expansion of water when it freezes. The process may be seasonal, wet rock after the summer may be frozen for the whole winter, one cycle per year, or the process may be partly diurnal when rock exposed to the sun thaws during the day and freezes again at night.

Wind forces may be strong enough to blow away pieces of rock that have become loose because of other weathering processes. The greatest wind erosion effects are seen in dry climates where the wind can blow strongly enough to carry with it tiny pieces of rock, grains of sand or dust. This has an abrasive effect, sand blasting, which carries away large quantities of rock as more dust. Wind erosion produces some spectacular rock shapes in desert climates, for example Monument Valley in the United States of America.

The total effect of all these processes is to build up a mass of loose rock material above a more solid body of rock below (bedrock). The boundary between the two different masses is called rockhead, and is shown in Fig. 4. The top layer is called the weathered or superficial zone, or overburden. The depth of the weathered zone may be very important in construction works. Towards the level of rockhead there is usually a greater proportion of larger pieces of the underlying rock, contained in soil which binds the whole together. The superficial zone material is not always produced in the place in which it is found (*in situ*). The material may have been brought in from another area by rivers, forming alluvial deposits, or by glaciers, forming glacial deposits, or by wind, forming aeolian deposits. The material below rockhead may not be hard rock, but soft. It will have different mechanical properties from those of the weathered rock above.

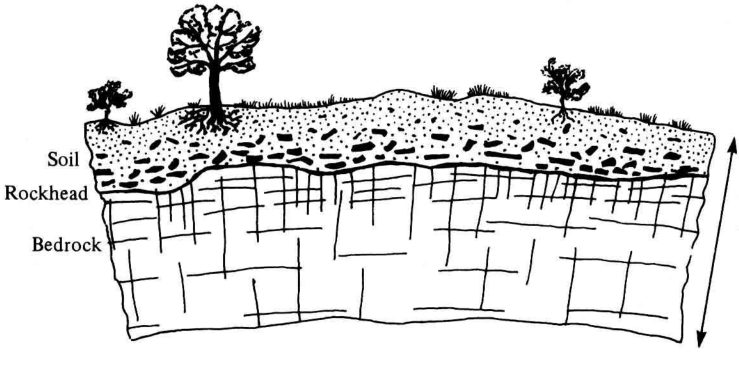
This superficial zone of broken and partly-decomposed rock is usually that in which civil engineers have to build their constructions. The material found in this zone is described in detail in Chapter 3.

This very simplified account of Earth processes describes the origin of the rock material and the rock structures which the civil engineer will meet during the course of his work on construction sites. It will help towards an understanding of the various forms of rock trouble which can occur during and after construction.

Earth history

The history of the Earth goes back over a very long period of time, of the order of thousands of millions of years, and during that time certain events occurred which left their mark on the structure of the upper parts of the crust, which we see today. This structure includes the present-day distribution of

Fig. 4. Superficial weathered zone above rock which shows expansion joints.



continents, mountains, relics of old mountains that have been worn down by erosion, unconformities, and the record of the evolution and extinction of certain forms of animal life preserved in the rocks as fossils.

Geological periods and time scale

Geologists divide Earth history into eras, divisions of which are known as periods. The names used for the periods are based on names for rocks, place or area names, and the kinds of fossils found in the rocks. The sequence of all the evolutionary stages in life, and the sequence of rock formation has been compiled by geologists working over more than a hundred years in all parts of the world, firstly in Europe, then in North America, and the other continents. The internationally recognized periods are given in the form of a vertical sequence, the geological column, with the oldest rocks at the bottom (table 1). This is the standard way of presenting rock information. The oldest rocks in the area described are placed at the bottom of the column. This column can be compared with a core of rocks extracted from a borehole, where the earliest formed rocks

Table 1. *Geological periods and time scale. (Based, with permission, on* The Phanerozoic Time Scale. *Geological Society of London 1964)*

Era	Period		Age (million years before present)
	Quaternary	Recent Pleistocene	
			2
Cainozoic	Tertiary	Pliocene Miocene Oligocene Eocene Palaeocene	
			66
Mesozoic	Cretaceous Jurassic Triassic		
			226
Palaeozoic	Permian Carboniferous Devonian Silurian Ordovician Cambrian		
			570
Pre-Cambrian			

are lower down, and the more recently formed rocks are above the older. It is possible during Earth disturbances for whole sequences of rock groups to be turned over and inverted, so it is not an invariable rule that the rock at the bottom of a borehole is older than the rock at the top. The geological column is a model of Earth history in terms of rock groups, which are known as formations. Rocks of all the geological periods are not necessarily found in any area because that area may have been land during a particular period and rock would not have been forming there at that time but would have been in a state of decay and erosion and providing material for the formation of new rock in another area, possibly hundreds of kilometres away.

Study of Earth movements or disturbances, uplift of mountains, or intrusions of great masses of igneous rock under them, shows that the intensities of these movements build up to peaks and then decay and disappear, leaving mountain ranges and relics of volcanoes which are then eroded down to sea level. The geological column given here states the approximate ages of the time boundaries between the periods. The eras are known as Pre-Cambrian, Palaeozoic (ancient lift), Mesozoic (medium life) and Cainozoic (recent life). The term Tertiary originated from an earlier historical arrangement which divided rock formations into Primary, Secondary and Tertiary groups. The Pre-Cambrian era is so named because it pre-dates a group of rocks found in Wales (Cambria) which contain the earliest forms of quite large marine animals. Subsequent research has shown that more primitive forms of life were abundant in rocks older than the Cambrian.

Geological periods are further divided into stages and zones on a basis of the different fossils found in the rocks. These smaller divisions of geological time are not of much importance to the civil engineer unless the rocks themselves have markedly different characteristics from those above and below, which will affect their behaviour during engineering works. These divisions of periods can be seen in geological maps for all areas, but the smaller time divisions have names related to more restricted area distribution and vary from one country to another. The civil engineer may find such terms included in the geological maps of the area in which he is working, but he is more concerned with the rock type and its structure than with the precise age in terms of the fossil animals it contains. The period names are very widely used and may have some geotechnical significance. The oldest rocks, the Pre-Cambrian, may have been subjected to several earth movements, which may have left them in a severely crushed state and full of discontinuities with very irregular spatial distribution patterns. Palaeozoic rocks are generally hard rocks, but from Mesozoic times onwards some rocks (sands and clays) are still in their original unconsolidated state. The younger rocks of the Tertiary and Quaternary periods are very often unconsolidated formations of gravel, sand, and clay, except for those rocks which were cemented during their formation by precipitated cementing material, calcite and silica, which has formed the hard rock types sandstone and limestone. The term '**consolidated**' is used here in a general sense meaning solid rock, distinct from soft rock; another term used is indurated. The term 'consolidated' is used in a special way in the science of soil mechanics. Clay can be **normally consolidated** or **over-consolidated**.

The igneous rocks produced by lava flows from erupting volcanoes harden on cooling and come into the hard rock group. They are found in all ages of rock formation from the Pre-Cambrian to the Recent, and can indeed be seen in the process of formation at the present day.