THE SURFACE OF THE EARTH

The surface of the earth: an introduction to geotechnical science

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Preface

The explanation of what we observe in the natural environment immediately around us, as well as globally, lies in the behaviour of the individual gaseous, liquid or solid components of the earth's surface. Axiomatic though this may seem, most books in physical geography, or other fields pertaining to the environment, concentrate instead upon the composite characteristics of localities or regions. Yet landscapes, terrain or climate represent the interaction of many different phenomena and materials, and this is also true of quite small features – a small area of ground surface or a particular hillslope, for example. This book is concerned with understanding the natural environment through a detailed examination of what may be called, by analogy with 'microclimate', the 'microenvironment'. This involves consideration of specific material properties and processes.

It is hoped that the book will be useful in respect to a wide range of interests. Architects and engineers normally have a basic understanding of properties of earth materials, but a limited knowledge of how these relate to the characteristics of a locality. The importance of the sequence of events through geological time, in producing existing landforms, is not always realized by those unfamiliar with the earth sciences. For these reasons, the first part of the book includes an elementary review of fundamental principles of geomorphology and surface geology, which may also be useful to beginning students in the earth sciences. The second part of the book considers mechanical properties of earth materials, and properties relative to exchanges of heat and moisture including those of the ground surface. The topics considered are not usually brought together in one book, even though they cannot properly be considered in isolation. Design of energy-efficient buildings, concerns with food production and desertification, and geotechnical development in cold regions are all examples of the diverse technological issues which require a balanced knowledge of thermal and other energy-associated properties, together with a knowledge of the mechanics of earth materials. The quantitative information included will, it is hoped, make the book of value as a reference work. The third part of the book considers various environmental situations, slopes, the ground immediately below the surface, very cold and very hot conditions and demonstrates how scientific interpretations of the environment follow from a precise knowledge of material properties and processes.

University students in geography and geology and in the biological sciences, indeed in the environmental sciences as a whole, often do not have a strong background in the basic sciences and mathematics. Accordingly care has been taken to explain carefully the physical, chemical and thermodynamic concepts used in the text. With a few exceptions which may be passed over if desired, only simple equations are used. The book is intended for students at the undergraduate level, while elements of the book are useful for higher level, more specialized studies. The subject matter and arrangement of the book has been much influenced by my experiences during the last ten years in teaching students, from the second year to post-graduate levels, in the Physical Geography and Geotechnical Science program at Carleton University.

In addition to the many students who have worked with chapters of the book in courses that I have taught, providing many helpful comments, I am indebted to many people for assistance through the last six years. The book was initially drafted during a sabbatical leave spent at the Scott Polar Research Institute, Cambridge, and I am especially indebted to Dr David Drewry for his comments on the early drafts, and to Dr Gordon Robin for his hospitality as Director of the Institute. I have had many enjoyable and productive discussions with Dr Donald Davidson of the University of Strathclyde, who shares my interest in introducing physical science into matters geographical and geotechnical. My colleagues in the Geotechnical Science Program at Carleton University, especially Dr M. W. Smith, and Dr B-E. Ryden (a visitor from Upsala University), have kindly read chapters and provided stimulus in discussions for many years. My father J. G. Williams has provided many comments as an interested layman, which have led to improvements in the clarity of the text, and he has also prepared the index. My successive, able and considerable typists Jane Whiting, Anne Buie and Janet Wilson, have been paid largely through a small grant from the National Research Council of Canada – one of the first for such a purpose. I hope the book will help justify this policy. Activities both in university teaching and geotechnical consulting, have prolonged the writing of this book, probably with advantage. My contacts with many professional colleagues too numerous to name, have been an important influence in defining the content of the book.

Peter J. Williams
Ottawa
Canada
April 1981

Symbols

A	area
a	thermal diffusivity
C	volumetric heat capacity; cohesion
c_s	mass heat capacity; soil mineral
c_v	coefficient of consolidation
c_w	mass heat capacity; water
D	soil water diffusivity
e	void ratio of soils
F	factor of safety; frost index
G	Gibbs free energy; heat flux in or out of ground
g	acceleration due to gravity (= 9.8 m s^{-2}); gram
H	enthalpy; sensible heat flux
h *or* H	vertical distance above or below water table; sensible heat flux
i	gradient of potential; angle of slope
$I\downarrow$	radiation, inwards
$I\uparrow$	radiation, outwards
k	hydraulic conductivity
K	degrees Kelvin
L	latent heat of freezing per unit volume soil; length
LE	heat flux associated with evaporation or condensation
ℓ	distance between points of interest; latent heat of fusion; length; litre
n	porosity
P	pressure
P_c	preconsolidation pressure
P_o	saturation vapour pressure for pure, free water
Q	incoming solar radiation; total heat flow
Q_{vap}	vapour flux
q	flow; incoming diffuse radiation
q	mean specific humidity
R	net radiative flux; universal gas constant
r	run-off; reflected radiation
SI	Systeme Internationale
S_r	degree of saturation
S	strength
T	temperature; absolute temperature; time
t	time period; time; temperature
U	pore water pressure; wind speed
u	pore water pressure
u	average wind velocity
V	volume
v	specific volume

Z	depth
β	Bowens ratio; angle of slope
γ	unit weight
γ_d	dry unit weight
γ_w	unit weight of water
ε	emissivity
θ	moisture content; contact angle
λ	thermal conductivity coefficient
ρ	density; soil bulk density
ρ_d	dry bulk density
ρ_w	density of water
σ	normal stress; Stefan-Boltzman constant
σ'	effective normal stress
τ	shear stress
τ_s	shear stress when shear occurs
ϕ	angle, the tangent of which is the coefficient of proportionality of shear strength and normal stress – 'angle of internal friction'
ψ	potential
μ	micron

Units

Units in this book follow the SI System (Systeme Internationale). Conversions between the SI System and other systems are given in, for example, Kaye, G. W. C. and Laby, T. H., 1973, *Tables of Physical and Chemical Constants*, Longman, 386 pp. A convenient guide to SI usage in geotechnical engineering is given in the *Proceedings, 9th International Conference on Soil Mechanics and Foundation Engineering*, 1977, Vol. 3, pp. 153–70 where internationally accepted symbols for use in geotechnical studies are also listed.

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Contents

PART I

The earth's surface as a study in dynamics

1

General nature of the earth's surface

1.1 Introduction

This book is concerned with a thin layer at the surface of the earth. The layer has a thickness less than 0.01 per cent of the earth's radius, and extends only a few metres or tens of metres above and below the ground surface. Nevertheless, it is this layer which constitutes Man's environment in the ecological sense; it provides both the resources and conditions suitable for life as well as the restraints and boundaries which Man by his activities seeks to overcome. Only exceptionally does Man move upwards out of this thin layer, and then he can usually only do so by effectively moving his local environment with him, as in high-flying aircraft. Equally sharp changes in the natural environment occur on moving downwards, for at a depth of 1 kilometre the temperature of the ground has risen by about 25 °C, and at 10 kilometres by 250 °C (Sass 1971).

The approach in this book involves the application of fundamental scientific principles or laws and these of course are equally applicable to the centre of the earth as to the upper atmosphere. But away from the surface regions of the earth, pressures, temperatures, and the nature of materials are substantially different. The interior regions are considered therefore only briefly and in so far as this helps to providing a background for our analysis. Those properties of earth materials which control the natural processes that man directly experiences and to which, frequently, he must react are, together with the processes themselves, the subject matter of this book.

The history of natural science is that of man's inquiry into his physical surroundings. Over the last few centuries much of natural science has involved those natural phenomena, or properties of matter, which can be investigated experimentally, using samples of a larger whole. Yet remarkably, even in this century, much of the earth's natural surface has been investigated in the field, or from the study, without recourse to the laboratory. More precisely, while the surface forms were measured and recorded, and the earth materials were subjected to gross description and classification, scant regard was paid to the large range of mechanical and thermodynamic properties possessed by those materials, let alone to the range of dynamic situations resulting from those properties, even within a small area of ground.

Early earth scientists, once freed of the philosophical and theological inhibitions of the Middle Ages (which persisted in some degree to the nineteenth century), directed their attention to whichever particular natural phenomenon at hand fascinated them. Curious patterns and forms in the rocks were ultimately recognised as fossils. Their marine origin being no longer in dispute, a further period elapsed before their presence at high elevations was understood to be the result of effects still active today. The rejection of abnormal and catastrophic events, such as the biblical flood, in favour of processes that can be observed led to the formulation of Hutton's 'Principle of Uniformitarianism' – that the present is the key to the past. Geological explanation must necessarily be limited if we have only an incomplete understanding of the land forming processes as they are at present observed. We must first educate ourselves about the nature and behaviour of the various materials of which the earth's surface is composed. This will in turn require an understanding of geological history; thus the circle is closed.

Particularly during the nineteenth century, a new type of scientist appeared. His studies were directed towards the soils and rocks, but his interest was motivated by practical aims, of agriculture (Hutton himself operated an experimental farm), of civil engineering, and of mining and quarrying. It took hundreds of years, for science to develop from an exclusively academic pursuit into a largely utilitarian branch of knowledge. In doing so, the development of these practical aims has not only influenced the nature of the knowledge being gained – it has also influenced, sometimes unfortunately, the quality of that knowledge.

Today, soils and rocks enter into the activities of many occupational groups. Foundation engineering, the construction of big buildings, bridges, dams, requires an intimate knowledge of the earth materials, in particular their so-called geotechnical properties. Because the agriculturalist, and the engineer for example are to some extent concerned with the same materials we would expect there to be a substantial body of common knowledge. But, an examination of the terminologies of the published literature, of the organization of universities and research institutes which relate to 'agricultural' soils, and of those which relate to 'engineering' soils, would suggest to those who did not know otherwise that these two groups of materials were quite separate, both in form and function.

Many other examples could be given of how the 'tunnel vision' of scientists is perpetuated by traditional packaging into 'subjects', whether by the effects of history or of practical ends. This is unfortunate because, whatever we study in the so-called 'derivative' or 'secondary' sciences – biology, geology, pedology, hydrology – we must always operate within the established principles and laws of the primary sciences of mathematics, physics and chemistry. We can only benefit by realizing that others may have new and different insights into the phenomena we study in our own 'field'. The integral nature of scientific studies must not be overlooked even though in practical applications such as agronomy, forestry, civil engineering, there may be different emphases. These, and other occupations, all need to know about the materials of the earth's surface region.

This book may be regarded by some as a text in geomorphology, but it could also be considered to be in geotechnical science, that is, describing scientific studies which are ultimately prompted by man's interaction with his surroundings through engineering and other activities. The workings of the earth surface are considered through an analysis of composite parts. The approach is on a microscale; we consider the properties and behaviour of small and well-defined elements of the whole.

Ultimately, the aim is to permit an understanding of why for example, a landslide occurred, why the ground is frozen throughout the summer at one small location but not at neighbouring sites; or why water moves spontaneously from an apparently less wet sand into a wetter clay.

To a great extent we are concerned with findings originally obtained from samples in a laboratory. These findings are then applied to the interpretation of the various processes that define the physical characteristics of the earth's surface region at a particular place. The latter qualification is important. A single description and analysis of this type cannot be applied simultaneously to a large area. This does not mean that a basic understanding of the grosser characteristics and behaviour of the earth's surface region is not important. Such understanding is often essential to the interpretation of the local event or feature, and this and the following chapter provide an elementary review of the global framework.

1.2 Some basic energy relations of the earth's surface

Volcanic lava from the interior of the earth is molten, but the naturally occurring temperatures at the surface of the earth are lower than the melting points of all the common minerals there. The earth as a whole is cooling slowly, because there is a flow of heat from the depths towards the surface which although varying considerably from place to place, has values (Lee and Clark 1966) around 0.05 W m^{-2} (that is, 0.05 watts through a square metre). The sun is radiating energy towards the earth at a power of 10^{17} W of which about 10^{16} W reaches the solid surface (Von Arx 1974). A very rough calculation, based on the area in square metres of the land surface of the earth (approximately 10^{14} m^2) suggests that more solar energy is arriving (at a power of about 100 W m^{-2}) than heat is being lost from the earth (about 0.05 W m^{-2}). Indeed the arrival of energy from above and below might lead us to assume that there must be an accumulation of energy in the earth's surface region. If so, it can hardly be solely in the form of heat for the temperature of the ground would be rising rapidly.

Before examining the possibilities more closely the terms energy and power must be considered. *Energy* is defined as the capability to do work. *Work* is said to be done when a force acts against a resistance to produce motion. Force is defined simply as 'that which changes the state of rest or motion'. The amount of work is the product of the force and the distance moved. We may think of a block sliding down a sloping surface. It is gravity which causes it to slide while the magnitude of the force actually effective in producing the motion depends on the slope as well as the weight of the body. The evaluation of the force will be discussed later. Force is measured in newtons, (N), and if the force to produce sliding is X newtons, on moving the block a distance L metres downslope, work XL newton metres is done. Newton metres are units of work and are represented by the symbols N m. They are also known as joules (symbol: J).

If the block is lifted from the surface after sliding distance L, and replaced at its initial position on the slope, we restore its ability to slide over L. Its capability of performing the work is restored. This increment of energy is called *potential energy*, and potential energy is that associated with position. In this case we are concerned with gravitational potential energy which results from position in the earth's gravitational field. This increment of energy will be utilized when the block again slides through L.

If the distance L is traversed in a certain time t s (i.e. seconds), the work is clearly being done at a rate of $\frac{XL}{t}$ N m s^{-1}, or $\frac{XL}{t}$ J s^{-1}. If XL has a different value work is being done at a different rate. The rate at which work is done is called the *power*. The power is therefore the rate of energy dissipation. It is equally the rate at which energy is being supplied for dissipation. Thus when we speak of the power of the sun, we are speaking of that part of the energy dissipated by the sun, that is reaching the earth where it is again dissipated.

If we again consider the sliding block, we would expect, if we had an accurate enough thermometer, to observe a temperature rise at the base of the block due to friction. Heat is a form of energy, and part of the energy being dissipated is going to heating. The fact that energy may be dissipated as work or as heat means that work and heat have a fundamental equality. When we say that energy is dissipated we do not mean that it disappears. On the contrary a fundamental principle is that of the conservation (or indestructibility) of energy. Dissipation refers to energy in transit and this is revealed as either heat or work. In the course of the transit, the one may be changed into the other (even though a fundamental law tells us that a simple 100 per cent conversion of heat to work is not possible). Work was not originally, and is not always, measured in the same units as heat. But with the acceptance in recent years of the 'Systeme Internationale' (SI) system of units the relationship is made clearer. The unit of energy is the joule, which is the unit of heat as well as of work, and 1 J s^{-1} is called a watt.

The transfer of 4.18 J in the form of heat, to a gram of water causes its temperature to rise by *1* °C, and likewise, when a gram of water falls in temperature by 1 °C, 4.18 joules have in some manner been lost from it. Reflection over this suggests that temperature is analogous in this respect to potential energy. In fact when the temperature is changed there is a change of *internal energy*.

It is not possible, in this brief introduction, to consider these concepts in detail. The reader is referred to Davidson 1978, and to basic texts in physics and thermodynamics of which examples are given in the bibliography. However, an elementary grasp of the relationships between energy, power, work and heat are sufficient for further considerations of the effects of solar radiation, and also of the other energy sources which are involved in the processes operating at the earth's surface. In addition, the more detailed considerations of the properties of earth materials in Part II will make the understanding more precise.

Of the energy arriving from the sun, some is immediately returned to space by reflection in the atmosphere from clouds and other particles with reflecting surfaces, and some is scattered (or deflected) by the gaseous constitutents of the air. Absorption (that is conversion to heat) by constituents of the atmosphere also takes place. Reflection of a further part of the incoming solar radiation occurs at the surface of the earth. The amount reflected depends on the reflectivity or *albedo* of the surface. Snow reflects much radiation, while dark surfaces, bare soil for example, reflect less, having a lower albedo. The albedo of the earth's surface is usually determined by the vegetation cover, since this commonly shields much of the soil. The radiation, reaching the earth's surface from the sun, which is not reflected is energy that is dissipated in various ways. It may cause a warming of the ground, the plant leaves, or the air and is then referred to as 'sensible heat': the heating effect can be measured as a temperature change. During night time temperatures fall because there is radiation outwards. This does not constitute reflection, since the energy has been converted to internal energy, and then re-emitted. Furthermore the emitted radiation includes not only energy received the previous day, but also perhaps the previous summer, or much earlier. Some of the energy being lost must be that associated with the cooling of the interior of the earth. Of course the energy cannot be 'tagged' – we cannot usually physically recognise energy by some characteristic which reveals that it has its origin, for example, in the centre of the earth. Nevertheless when we seek to explain certain observed temperature changes, or certain work done, it is necessary to compute the magnitudes of *all* the energy flows to or from the system.

This kind of analysis is referred to as the study of energy balances. An energy balance is simply an equation, in which as in a bank account, one identifies incomings, outgoings,