DEVELOPMENTS IN GEOTECHNICAL ENGINEERING VOL 22

SLOPE ANALYSIS

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PREFACE

The subject of slope analysis is a fascinating one both from theoretical and practical points of view and has attracted the attention of researchers and scholars in diverse fields such as soil mechanics, rock mechanics, engineering geology and geomorphology. Over the last few decades excellent books have been written in each of these disciplines with important sections devoted to aspects of slope stability analysis. An integrated treatment covering the analysis of both soil and rock slopes has seldom been presented in sufficient detail. It has sometimes been stated that many slope problems defy a theoretical or analytical treatment. While such statements emphasise the complexity of factors which influence the performance of slopes, they also indicate the need for refinements in available methods of analysis and for the development of new concepts and approaches.

The main aims of this book may be summarised as follows:

1. To outline the fundamental principles of slope analysis and to explore both similarities and differences in soil and rock slopes.
2. To discuss the assumptions underlying both simple and so-called 'rigorous' methods of analysis.
3. To highlight the importance of factors which influence slope performance and especially to consider the role of progressive failure.
4. To discuss the use of alternative methods of analysis and to present information on new concepts and new approaches to analysis.

This book is meant for the senior undergraduate and graduate student, the researcher as well as the practitioner. The material has been arranged in a form convenient for the undergraduate student who may have only an introductory background in one of the disciplines mentioned above. New concepts and approaches are introduced gradually and as a consequence of discussion of conventional ideas and practices. The graduate student and researcher will find many references to the most recent developments. Issues of real significance in research such as progressive failure and probabilistic concepts are dealt with throughout the book and there is a consistent emphasis on the need to distinguish between assumed models and practical realities.

For the practitioner comprehensive information on the choice, use and limitations of conventional methods of analysis is provided in chapters 3 and 4. In Appendix II slope stability charts are included for 'total stress' as well as 'effective stress' types of analysis and information is also provided to enable location of critical slip circles. The practitioner must never lose sight of the assumption of a circular failure surface on which these and similar charts are based. One is tempted to quote from the Terzaghi lecture of Wilson (1970): "... As my first illustration I had intended to use an example of ground movements during a classical circular arc failure. After a diligent search of literally hundreds of case histories in my files, not one such example could be documented. Undaunted I turned to colleagues for help. When their efforts were likewise unproductive, I decided to limit the topic to non-circular failure surfaces, but with particular emphasis on progressive failure ..." It is hoped that this book will stimulate renewed awareness of important issues in slope analysis. Such an awareness is necessary if significant progress is to be achieved in the near future.

Dr. James V. Hamel of Pennsylvania read the first draft of this book with keen interest and conveyed his detailed comments with exemplary promptness. His comments, often supported by references to published and unpublished material, were very useful during the preparation of the final manuscript and resulted in significant revisions of parts of chapters 2, 3 and 4. It is with pleasure and gratitude that I acknowledge his assistance and the contribution he made to a lively correspondence on slopes which started in 1973. I look forward to our first meeting in the second half of 1978. Mr. Brian Cousins very kindly arranged for the use of tracings of his charts and provided information concerning their use. Mrs. Adell Smith typed the manuscript with care and patience and I express my sincere appreciation for her efforts and for those of Roger McAlister who assisted with the line drawings. At the University of Wollongong I have received encouragement from everyone and must mention, in particular, Professor L. Michael Birt, Vice Chancellor, Professor C.A.M. Gray and Associate Professor R.W. Upfold. Finally I record with pleasure the affection and support of my wife Nancy, daughter Rita and especially little son Vivek.

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CHAPTER 1

SLOPES, GEOLOGY AND MATERIALS

1.1 INTRODUCTION

This book is primarily concerned with methods of analysis for slopes. Many of the accepted and popular methods are applicable to natural slopes as well as to man-made slopes, and may be used to assess the stability of embankments and excavations. Similarly many popular methods are applicable to both soil and rock slopes. This may be attributed to the basic unity of many of the principles that are required to be taken into consideration in developing a method of analysis for slopes formed of different geological materials. However, the manner in which a particular method may be applied is strongly dependent on the nature of the slope under consideration. Geology, nature of slope materials and topography are always important factors in the case of natural slopes and often in the case of man-made slopes.

The aims of proposed analyses must be and can be clearly stated before a suitable method is chosen for the accomplishment of the stated objectives. Yet little success can be expected unless background information concerning topographical setting, geological conditions and material types has been obtained. Nature imposes a number of limitations on the application of the principles of mechanics and mathematics to problems of slope stability. Therefore, it is desirable to consider and understand significant factors relevant to slope stability before beginning a study of slope analysis itself.

In view of the above, a statement of aims is considered in the next section. This is followed by brief discussions of different kinds of slopes, geomorphology, types of slope movement, geology, and the nature of soil and rock materials. A discussion of basic concepts follows in chapter 2. The arrangement of sections in this chapter was finalised after carefully considering possible alternatives. The writer recognises that readers of a book like this may have widely differing backgrounds and hopes that the presentation of material suits the majority of readers.

1.2 AIMS OF SLOPE ANALYSIS

The primary purpose of slope analysis in most engineering applications is to contribute to the safe and economic design of excavations, embankments, earth dams and spoil heaps. Preliminary analyses assist in the identification of critical geological, material, environmental and economic parameters. Therefore the results are of value in planning detailed investigations of major projects. Subsequent analyses enable an understanding of the nature, magnitude and frequency of slope problems that may require to be solved. Previous geotechnical and engineering geological experience of an area is always valuable in dealing with slopes in general and slope analyses in particular. Evaluation of slope stability is often an inter-disciplinary effort requiring contributions from engineering geology soil mechanics and rock mechanics. The main recognised aims of slope analysis may be summarised as follows.

(a) To assess the stability of different types of slopes under given conditions. Often it is necessary to assess the stability separately for short-term (end-of-construction) and long-term conditions. Analytical studies are essential in many cases before suitable cut or fill slopes can be designed with confidence. Such studies enable economical use to be made of materials, labour and resources.

(b) To assess the possibility of landslides involving natural or existing man-made slopes. The influence of proposed modifications to an existing slope can be studied in an organised manner. Similarly comparative studies can be made to assess the value of proposed preventive or remedial measures. Sensitivity analyses can be made to study how variations in material and field parameters of uncertain magnitude might affect stability.

(c) To analyse slips and landslides that have already occurred and to assist in the understanding of failure mechanisms and the influence of environmental factors. Such analyses can provide reliable information about the average shearing resistance of natural slope materials. Actual failures constitute large-scale shear tests and enable comparison with strength parameters obtained from laboratory tests and field investigations.

(d) To enable the redesign of failed slopes, and the planning and design of preventive and remedial measures where necessary. Data from instrumented slopes, embankments and earth dams can be evaluated with confidence if a suitable method of slope analysis is used.

(e) To enable a study of the effect of exceptional loadings such as earthquakes on slopes and embankments.

(f) To understand the development and form of natural slopes and the processes that have been responsible for different natural features. The manner in which contemporary processes and changes can influence slope form is of general interest in applied geomorphology. At the same time there is increasing recognition of the practical value of such studies with regard to proposed and existing developments in hilly areas.

The analysis of real slopes involves consideration of a variety of factors including topography, geology and material properties. Often some idealisation of problems is required for clarity and for the effective application of basic concepts. In the following sections, attention is given to some of these factors after a brief discussion of individual types of slope problems.

1.3 NATURAL SLOPES AND THEIR STABILITY

Natural slopes in soil and rock are of interest to civil and mining engineers, engineering geologists, applied geomorphologists, soil scientists, and environmental managers. The material composing any slope has a natural tendency to slide under the influence of gravitational and other forces (such as those due to tectonic stresses, seismic activity etc.) which is resisted by the shearing resistance of the material. Instability occurs when the shearing resistance is not enough to counterbalance the forces tending to cause movement along any surface within a slope. Natural slopes which have been stable for many years may suddenly fail due to one or more of the following main causes (which are also discussed in other appropriate sections of the book):

(a) External disturbance in the form of cutting or filling of parts of a slope or of ground adjacent to it resulting in an alteration of the balance between forces tending to cause instability and forces tending to resist it.

(b) External disturbance in the form of seismic activity (earth tremors or earthquakes).

(c) Increase of pore water pressures within a slope (e.g. rise in water table) due to significant changes in the surrounding areas such as deforestation, filling of valleys, disturbance of natural drainage characteristics, urbanisation, construction of reservoirs, exceptional rainfall etc.

(d) Increase of pore water pressures to equilibrium values several years after a cutting (in slope material of low permeability) which resulted in significant post-construction decrease of the pore water pressures below their equilibrium values. This is explained in chapter 2.

(e) Progressive decrease in shear strength of slope materials: This may be due to significant deformations which do not appear to constitute instability but lead to it. Such deformations may occur due to sustained gravitational forces and slope disturbances of an intensity not high enough to cause complete failure. Deformations often occur along major natural discontinuities, ancient slip surfaces and tectonic shear zones within a slope.

(f) Progressive change in the stress field within a slope: Every natural geological formation has an 'initial' stress field which may be significantly different from one considered in terms of the weight of the material alone. Lateral stresses may occur which do not bear any predictable relationship with the vertical stress computed from gravitational considerations. The unique 'initial' stress field of any slope depends on its geological background and other natural factors. The stress history of the slope materials is of tremendous importance. Attempts have been made in recent years to develop methods for the prediction of initial stresses in soils on the basis of laboratoty tests. However, it is recognised that reliable information is best obtained from in-situ measurement in soil and rock. In some cases these measurements present considerable difficulties (Wroth, 1975).

A change in the initial stress field may occur due to causes similar to those which produce a progressive decrease of shear strength. Release of stresses may accompany or follow most forms of slope disturbance. Often this leads to changes in both the magnitude and orientation of the stresses.

(g) **Weathering:** It is now widely recognised that weathering may occur at a rate rapid enough to be of concern in the design of engineering works. Therefore, it is important to consider not only the existence of weathering which has occurred in the past but also the possibility of continued and even accelerated weathering. Weathering of soils and rocks destroys bonds and reduces shear strength. Bjerrum (1967) suggested that the weathering of overconsolidated clays (clays which have experienced a higher overburden pressure in their past than their present overburden pressure) and shales increases their recoverable strain energy and consequently their capacity for progressive failure. This occurs due to the destruction by weathering of diagenetic bonding in these materials. Weathering may be accelerated by slope disturbance and by exposure to atmospheric and other agencies such as stream action.

It must be emphasised that many failures of natural slopes are imperfectly understood and that there may be other critical factors which influence the long-term stability of natural slopes. In rocks a slow and cumulative process of deterioration and destruction depending on climatic factors is always at work and thousands of years may elapse before a slope fails. According to Bjerrum and Jorstad (1968) the following factors are of primary importance in the time-dependent process leading to rock slides:

(a) The presence of a system of joints known as valley joints along which rock masses are often detatched during slides. The occurrence of large residual stresses in natural formations is well known and it is believed that valley joints are often formed by further stress changes and uneven deformations which occur during the formation of valleys. The release of strain energy stored due to large overburden in previous geological periods has thus an important role to play in the development of such joint systems. Each system at a particular depth is associated with a different stage of erosion in a rock mass.

The phenomena of valley stress relief and valley rebound and their geotechnical and geological implication have also been emphasised by Ferguson (1967, 1974), Matheson and Thomson (1973) and Matheson (1972).

(b) The presence of residual ground stresses which have still not been relieved during the formation of valley joint systems.

(c) The presence of water in open joints of rock masses which influences stability by exerting a direct outward force as well as by decreasing the effective stress and hence the shear strength on failure surfaces (refer to chapter 2 for discussion of the principle of effective stress in soil and rock).

(d) Fluctuation of water pressure in a joint system causing cumulative opening of joints during periods of high pressure following precipitation. The wedging of crushed rock in joints often prevents them from returning to their original position after opening under high water pressures. Fatigue failure may also result due to fluctuations of pressure leading to further extension of open joints through intact rock. Thus gradually the proportion of a potential failure plane passing through jointed rock is increased to a critical value. At such a stage further decrease of the area of intact rock is no longer consistent with slope stability.

The foregoing remarks were made in the context of hard rock slopes. However, there are similar processes at work in soil slopes. The cumulative influence of natural processes on long-term stability can rarely be quantified. In many instances concerning both soil and rock slopes a significant level of uncertainty exists with regard to stability and this has been emphasised by Peck (1967, 1977b).

It is most important to draw a clear distinction between natural slopes with or without existing slip surfaces or shear zones. A knowledge of the existence of old slip surfaces makes it easier to understand or predict the behaviour of a slope. Such surfaces are often a result of previous landslide or tectonic activity. Morgenstern (1977) has emphasised that shearing surfaces may also be caused by other processes including valley rebound, glacial shove, periglacial phenomena such as solifluction and non-uniform swelling of clays and clay-shales. The shearing strength along surfaces produced by these phenomena is reduced to residual values (see chapter 2 for discussion of the concept of residual strength). It is not always easy to recognise landslide areas (while post-glacial slides are readily identified, pre-glacial surfaces may lie buried beneath glacial sediments) or locate existing shear surfaces on which previous movements have occurred. However, once pre-sheared strata have been located, evaluation of stability can be made with confidence.

There are two main reasons for this: (1) renewed movements in these slopes are likely to occur along existing slip surfaces and (2) residual strengths operative on such surfaces can be determined or inferred with greater certainty than shear strengths of unsheared, in-situ soils and rocks. On the other hand, evaluation of stability of slopes with no previous landslide activity and no existing shear surfaces is a far more difficult task.

1.4 MAN-MADE SLOPES

These may be considered in three main categories: (a) Cut slopes, (b) embankments including earth dams and (c) spoil or waste heaps.

(a) Shallow and deep cuts are of major interest in many civil and mining engineering operations. The aim is to design a slope with such a height and inclination as to be stable within a reasonable life span and with as much economy as possible. Such design is influenced by geological conditions, material properties, seepage pressures, the possibility of flooding and erosion, the method of construction as well as the purpose of a particular cutting. In mining operations excavations may be carried out in several steps or benches and the stability of individual benches must be ensured as well as of the entire cut. Steep cuts may sometimes be necessary in many engineering applications so that preventive and protective measures are part of the initial design. In some situations the stability at the end of construction of a cutting may be critical. On the other hand many cut slopes are stable in the short-term but may fail without much warning many years later. The reasons for such failure have been given in the previous section concerning natural slopes. The most well known example is that of failures of cut slopes in London clay (Skempton 1964, 1970). For a discussion of relevant concepts and case histories refer to chapters 2 and 9). Making cut slopes so flat that they are stable for an indefinite period of time would often be uneconomical and sometimes impractical. On the other hand slopes which are too steep may remain stable for only a short time and pose real danger to life and property. Frequent failures would also involve tremendous inconvenience and the expense of repairs, maintenance and stabilisation measures.

(b) Fill slopes involving compacted soils include railway and highway embankments, earth dams and levees. The engineering properties of materials used in these structures are controlled by the method of construction and the degree of compaction. The analysis of embankments does not involve the same difficulties and uncertainties as does the stability of natural slopes and cuts. However, independent analyses are required for the following critical conditions: (i) end-of-construction (ii) long-term condition (iii) rapid draw-down (for water-retaining structures like earth dams) and (iv) seismic disturbance. In recent years the advantages of an observational approach have been demonstrated and it is usual to monitor the performance of embankments and earth dams during and after construction (Peck, 1969, Casagrande, 1965). The construction of test sections of embankments is particularly useful for large projects.

It is often necessary to consider the stability of an embankment-foundation system rather than that of an embankment alone. In major projects it is often economically feasible to conduct comprehensive and detailed investigations of foundation conditions. However, in many cases embankments have to be built on weak foundations so that failures by sinking, spreading and piping can occur irrespective of the stability of embankment slopes. Terzaghi and Peck (1967) have given guidelines for assessing and ensuring stability against such failures.

The most recent example of a major slope failure due to piping and internal erosion is that of the Teton Dam, Idaho, USA on June 5, 1976 (US Dept. of Interior, 1977). Internal erosion and piping occurred in the core of the dam deep in the right foundation key trench. Soil particles moved through channels along the interface of the dam with the highly pervious abutment rock and talus. The volcanic rocks at the site were intensely fissured and water was able to move rapidly during reservoir filling. The wind-deposited clayey silts of very low permeability used for the core and key trench are highly erodible. An independent review panel concluded that the use of this material adjacent to intensely jointed rock was a major factor in the failure. They also felt that the geometry of the key trenches favoured arching, reduction of normal stress and consequent development of cracks in the erodible fill. Cracking by hydraulic fracturing was considered to be another possibility since calculations showed that water pressure at the base of the key trench could have exceeded the sum of lateral stresses in the impervious fill and its tensile strength. Whatever the initial cause of cracking, it led to the opening of channels through the erodible fill. Once piping began it progressed rapidly through the main body of the dam leading to complete failure.

(c) The stability of spoil heaps consisting of mining and industrial waste is being recognised as a problem of major importance in view of (i) the many recent disasters which have been a consequence of failures of spoil heaps (ii) the growing magnitude of wastes requiring to be disposed in this manner and (iii) the scarcity of adequate sites for waste dumps. Until recently (about 10 years ago) spoil heaps had little or no compaction control and in many cases compaction was not even considered. Similarly there was little control on the composition of material of dumps. In the last five or six years considerable government regulatory control has been exercised on refuse and mine waste piles, tailings dams and industrial waste disposal areas in USA, Canada and some other developed countries. In many cases there is increasingly effective control on material composition and compaction. There are some instances in which particulate wastes may be uniform in composition and engineering properties. However, in general, the problems are somewhat different from those concerning embankments due to differences in methods of construction, uncertainties in geotechnical characteristics and foundation conditions which are often unfavourable. The solution of these problems is greatly complicated where there is inadequate control on composition, location and compaction of the refuse materials. (See Blight, 1977).

Where refuse materials are placed in a loose state, shear failure is often followed by liquefaction (complete loss of strength) with catastrophic consequences. Fortunately such occurrences are now rare because of increasing awareness leading to regulation and control. Initiation of instability is often a result of inadequate drainage in wet, saturated dumps. Failure may also occur due to overtopping caused by inadequate spillway capacity in tailings dams.

Bishop (1973) discussed the stability of tips and spoil heaps with special reference to his wide experience in the U.K. He pointed out that the failure of tips is controlled not only by the character of the tipped material but also by the mechanical properties of the natural strata on which tips are located. The brittleness of both natural and artificial material has a significant influence on whether failure is likely to be catastrophic or not (brittleness index and its significance are discussed in chapter 2). Unfavourable geological conditions (such as those in which high excess pore water pressures can develop within the natural strata due to loading by tips and spoil heaps) are significant in the development of extreme forms of movement e.g. flowslides. Materials of high brittleness index are especially liable to progressive failure (see chapter 2). An appreciation of the possibility of progressive failure is necessary for the safe design of spoil heaps. Particular care is required when waste dumps are located on sloping ground (such locations are sometimes unavoidable). In seismically active areas the stability of spoil heaps must be carefully evaluated for dynamic loading conditions.

1.5 GEOMORPHOLOGY AND SLOPES

Geomorphology is concerned with the nature and origin of landforms, with the study of processes of landform development and with material composition. Geomorphologists are concerned not only with types of processes but also with the rate and frequency of each process. For instance, in relation to slopes they are concerned with (i) transport - limited processes in which weathering rates are potentially more rapid than transport processes resulting in development of thick soil cover and (ii) weathering - limited processes in which transport processes are potentially more rapid than weathering so that only a thin soil cover can develop. Traditionally, geomorphology has been theoretical in its aims. However, there is growing evidence of interest in 'applied' aspects of the subject among geomorphologists, engineering geologists and geotechnical experts. Applied geomorphology is concerned with contemporary processes and their influence on landforms and as such it also embraces the role of man in changing or altering the physical environment. An appreciation of geomorphology is useful in understanding the complex phenomena with many interacting factors which control landforms. It is also very useful in establishing a geological framework of sites for many aspects of geotechnical work. This is particularly so in un-glaciated areas with steep slopes as discussed by Hamel (1970) in relation to Western Pennsylvania, USA.

Since the geomorphologist is concerned with the relationship of slope form to stability he is interested in the inclination, length, curvature and aspect of natural slopes. Slopes similar in inclination, materials and geology may behave differently depending on their aspect which may control moisture, seepage and pore water pressures. Surface drainage patterns often directly reflect the nature of underlying soil or rock (Eckel, 1958).

Some workers have suggested a morphometric approach to the study of landslides (Crozier, 1973). This consists of defining a number of unique indices based on the form of a landslide e.g. the depth to length ratio is considered to be critical in indicating the process responsible for a slide. Identification of landslide-prone situations and sites on the basis of (i) aerial photographs, (ii) land-systems mapping and (iii) geomorphological mapping is one of the most useful contributions geomorphology can make in practical problems involving slopes (Brunsden et al, 1975). Geomorphological mapping attempts to identify and classify slopes, recognise past and present processes and the relationship between form and processes occurring within the slope materials (i.e. soil and rock). The role of geomorphology in environmental management has been discussed with practical examples by Cooke and Doornkamp (1974). Carson and Kirkby (1972) have produced a work on slopes from a geomorphological view point.

1.6 TYPES OF SLOPE MOVEMENT AND LANDSLIDES

Many classifications of landslides have been given e.g. Eckel (1958), Hutchinson (1968), Skempton and Hutchinson (1969), Zaruba and Mencl (1969). Recently Varnes has revised his earlier classification for publication in a forthcoming report to be issued by the Transportation Research Board, USA. It is important to distinguish among slides, falls and flows (see Fig. 1-1). In each category movement can be and often is extremely rapid, although some slides occur slowly. Rates of movement range from very slow to extremely rapid. Varnes (1958) suggested the range 0.06m/year (slow movements) to 3m/second (very rapid movements).

Slides involve shear failure and may be translational or rotational in character (or a combination of rotation and translation). Translational slides often involve movement along marked discontinuities or planes of weakness. Rotational slips have a failure surface which is concave upwards and occur in both soil and rock formations. Falls are confined to surface zones in soil (soil falls) or rock (rock falls) and are preceded by the formation and enlargement of cracks and removal of base support of individual blocks or masses. Rockfalls may be caused by frost shattering, chemical decomposition, temperature variations, the wedging effect of roots and water pressure. Toppling failures of rock are common in situations where the vertical line through the centre of gravity of individual blocks (which have lost lateral support) falls outside of their respective bases (Fig. 1-1).

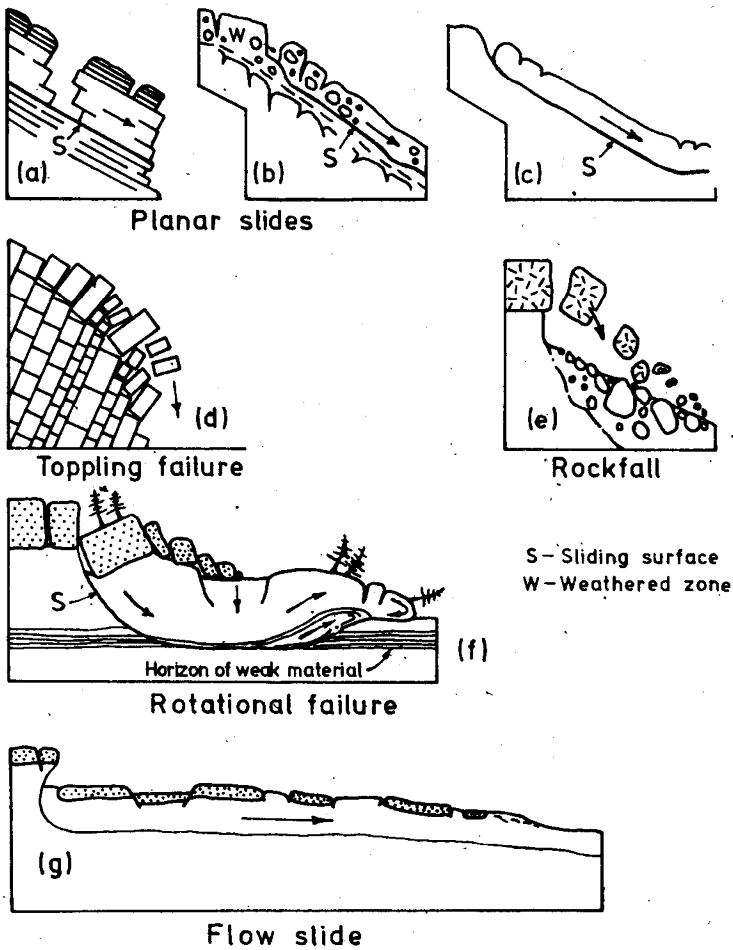

Fig. 1-1. Types of slope movement (after Blyth and de Freitas, 1974).

Depending on the relative orientation of a slope and its discontinuities, failures may involve detachment of small or large wedges in rock, so that failure is essentially three-dimensional in character. On the other hand movement along only one main discontinuity gives a two-dimensional, slab-type failure. Flows range from slow to extremely rapid and occur mostly in unconsolidated materials. Varnes (1958) mentions (i) rock fragment flows (ii) sand run (iii) loess flow (iv) sand or silt flow (v) slow earth-flow (vi) rapid earth flow (vii) debris avalanche and (viii) debris flow.

Slopes also undergo creep movements which are often so slow as to be imperceptible (e.g. 0.1 cm to few cms per year). Distinction must be drawn between surface creep of a seasonal nature and continuous or depth creep. Continuous creep occurs under the action of low shear stresses and may continue for long periods without resulting in failure. Many slides occur as a result of the acceleration of creep movements which have been going on for a long time (sometimes many years). Thus creep may be part of a process of progressive failure. Continuous creep is more common in argillaceous (clayey) soils and rocks than in granular soils and harder rocks.

Solifluction movements occur in periglacial areas due to annual freeze-thaw processes. Such movements are a form of seasonal creep and their influence generally extends only to shallow depths. In certain areas there may be no present-day periglacial activity but such processes may have occurred in the past. Previous periglacial activity is often evidenced by zones and surfaces of weakness in a soil mass which are re-activated by any form of development or disturbance. These surfaces may be located at significant depths below the present-day ground surface. Geotechnical aspects of periglacial features in Britain have been discussed by Weeks (1969) and Higginbottom and Fookes (1971).

Finally it is important to point out that slope movement and landsliding is a continued process and often multiple as well as complex landslides occur. Skempton and Hutchinson (1969) have suggested a classification of (a) basic types of mass movement on clay slopes shown here in Fig. 1-2 and (b) multiple and complex landslides in clay slopes, shown here in Fig. 1-3.

Pre-failure movements are of considerable interest and may give a warning of impending danger. Consequently observations of such movements are often very valuable as indicated by Wilson (1970). Magnitude of movements depends on the thickness of soil or rock involved. Movements may be hardly noticeable for thin soil layers but quite large for deep masses. Saito (1965) has suggested that pre-failure movements may be used to estimate the time to failure on an empirical basis. Broadbent and Ko (1972) studied rheological aspects of rock slope behaviour and found that (a) movements are usually initiated by a temporary excess in external forces (b) velocity of movement decays if this excess is eliminated (c) repeated applications of an impulse cause successive increases in velocity and displacement (d) displacement is a function of the failure surface characteristics (e) empirical rules can be devised to formulate action concerning control and prevention of active slope failure. Rock slope performance has also been discussed by others in Cording (1972).