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Geology, geomorphology and geotechnics

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The importance of collaboration between geologists and geotechnical engineers is emphasized and the common interest in geomorphology is suggested as a useful link to enable both the geological engineering skills to be mobilized. The role of geomorphology in the understanding of soil movements in the Gulf of Mexico during hurricanes is discussed. Attention is drawn to problems of tropical weathering and changes in soil chemistry which need further study. Some of the problems associated with groundwater lowering in an area underlain by dolomite are described together with the effects on stability of minor changes in surface drainage of an inclined rock layer.

L'article souligne l'importance d'une collaboration plus étroite entre les géologues et les ingénieurs géotechniciens, afin que leurs études combinées puissent améliorer simultanement leurs deux disciplines géologie et géotechnique. Puis est discuté le rôle joué par la morphologie dans la compréhension des mouvements du sol pendant les ouragans dans le Golfe du Mexique. Le besoin existe d'une étude approfondie des problèmes causés par la dégradation dans les zones tropicales et des changements dans la chimie du sol. Finalement l'article décrit quelques-uns des problèmes posés par l'abaissement de l'eau souterraine dans une zone sousjacente de dolomie et discute les effets sur la stabilité de changements de faible importance dans le drainage superficiel d'une couche de roche inclinée.

INTRODUCTION

The subject of my lecture this evening reflects my experience over the past 30 years that engineers and geologists have not yet learned to communicate efficiently with each other. We still do not always ensure that essential geological knowledge and experience is applied to the design and construction of projects.

We still come across problems in construction which could and should have been foreseen at an early stage in the design process. Part of the problem arises from the excessively obscure jargon too often used by geologists and part is due to the fact that the engineer may not know what the geologist has to offer. In addition, both are often unclear about their respective roles. I believe that engineers and geologists need to clarify their respective functions and use of language so that they can work together in a more productive manner. The problem is not new. It was considered by Peck in 1973 and by Legget in the 1977 Terzaghi Lecture. I hope my lecture will promote more efficient communication.

Geologists have for many years recognized that they have an important role to play in the construction of civil engineering works. History provides many examples of the outstanding contribution of geologists to the art of civil engineering, particularly in the fields of dam and tunnel construction.

As long ago as 1801, William Smith suggested that a book he proposed to publish, but never did, would provide geological information to enable the canal engineer 'to choose his stratum, find the most appropriate materials, avoid slippery ground, or remedy the evil' (Sheppard, 1917). We still from time to time encounter slippery ground and on some sites come across the evil which we have to remedy. The problems do not seem to have changed much over the past 180 years.

The straightforward and unambiguous role of the geologist in civil engineering became confused when the term 'engineering geology' was introduced into the geological vocabulary. There have been so many conflicting definitions of that term that even today I am not sure what it means.

In 1961 Terzaghi presented a paper entitled 'Engineering geology on the job and in the classroom' to the Boston Society of Civil Engineers. The term 'engineering geology' appeared to have originated as the name of a course of elementary geology taught to civil engineering students. The discussion on his paper produced a wide spectrum of opinion ranging from the idea that the engineering geologist should fulfil the role of both engineer and geologist to the more rational view that engineering geology was geology and no different from any other branch of applied geology. It was also suggested by Dolmage (1962) that, because a little knowledge was a dangerous thing, it might be easier if the engineer knew nothing about geology and the geologist knew nothing about engineering.

Terzaghi was firmly against the engineering geologist assuming any of the responsibilities of the engineer and drew attention to the writings of

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Berkey (1929). Berkey, a geologist by profession, defined the geologist's role as follows: 'It is his duty to discover, warn, explain without assuming the particular responsibility of the engineer who has to design the structure and determine how to meet all the conditions presented and stand forth as the man responsible for the project.' I believe that the role of the geologist has remained unchanged and that his duty is still to discover, warn and explain.

In spite of all the discussion, the confusion about engineering geology remained, and, in an attempt to resolve the problem at a meeting of the engineering Group of the Geological Society in 1970, Professor Dearman (1971) gave the following definition: 'Engineering Geology is the science or discipline of geology applied to Civil Engineering, particularly as applied to the design construction and performance aspects of engineering structures in and on the ground. The extremes of the subject merge into the disciplines of Soil Mechanics, Rock Mechanics and Materials Science and merge also into some aspects of the extractive industries including quarrying, opencast mining and deep mining.' Dearman also made it clear that engineering geology was not a special kind of geology but covered the whole spectrum of the science.

This was a good, clear definition of the function of engineering geology—very similar to that adopted by the Association of Engineering Geologists. Definitions were concerned with the areas of civil engineering activity in which the discipline of geology should be applied but did not face the central question of how the geological involvement was to be achieved.

Ten years later the Engineering Group of the Geological Society held a meeting to discuss the question 'Should engineering geology be taught and if so how?' The discussion produced no common viewpoint but the teaching of engineering subjects to geologists was suggested as a step in the process of teaching engineering geology to geologists. There was, however, still confusion over what the engineering geologist needs to be able to do. In my view engineering geology has its roots in the field and can only be learnt by painstaking field observations of how a site works.

The way to clarify the situation is to leave the arguments of the classroom and the lecture theatre and look at what is needed from the geologist to enable the geotechnical engineer to define and solve his design and construction problems at a particular site.

The geotechnical engineer needs answers to the following questions.

(*a*) What soils and rocks are there on the site, how have they been formed and what are their

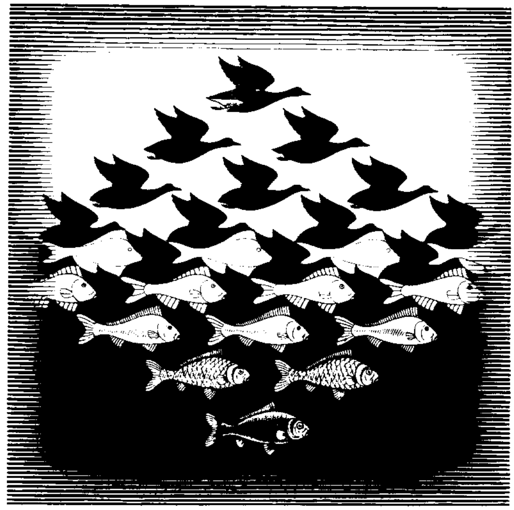


Fig. 1. Sky and water (M. C. Escher)

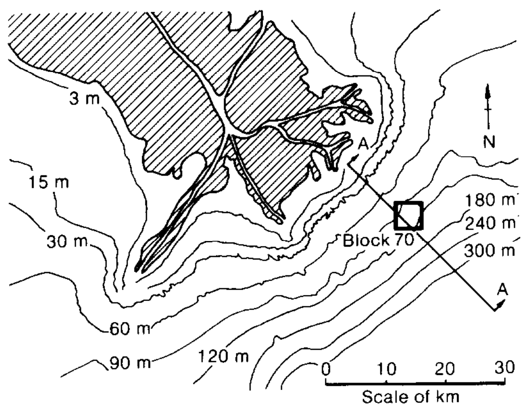


Fig. 2. Birdfoot Delta; contours indicate water depth (Shepard, 1955)

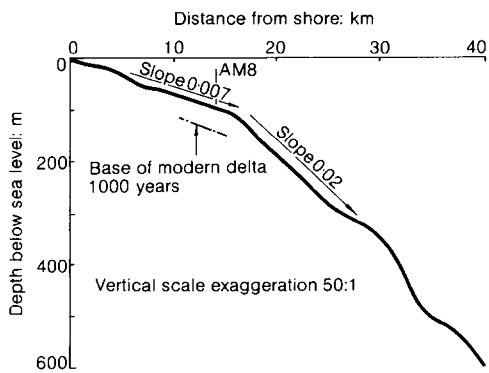


Fig. 3. Section AA, 1940 data

properties?
(*b*) What is the relationship between the shape and form of the site and the geological processes at work?
(*c*) How will the proposed engineering works change the geomorphological environment and what will be the consequences?

The skills and knowledge needed to answer all these questions cover a wide range of the subjects included in the science of geology and indicate the wide background needed by any geologist who wishes to practise in the professional field of engineering geology?

A study of these questions indicates that they are also a partial prescription for the often neglected branch of physical geology known as geomorphology: the study of the origin, evolution and shape of the earth's surface. As well as considering the present land form, it is necessary to take account of earlier land forms which might be buried beneath the present land surface.

If design problems are approached in the light of three basic questions—What is there? Why does it have its present form? What will happen if any of the environmental factors are changed?—a rational framework for the integration of geotechnical and geological skills can be provided. These questions fit in well with Berkey's ideas of discovering, warning and explaining. If the engineering geologist is asked these specific questions rather than asked to produce a geological report both he and the civil engineer will understand more clearly their roles in the design and construction process.

The interface between the separate disciplines of geology and geotechnical engineering is epitomized by the remarkable drawing by Escher entitled 'Sky and water' (Fig. 1). The birds and the fishes retain their separate identities away from the geomorphological boundary between sky and water but, at the interface, they are indistinguishable. In order to understand the nature of the air–water interface we need to view it from above as well as from below. We need the input from both the birds and the fishes. There will, of course, be maverick flying fish and diving birds that can exist fleetingly in another medium but, in the end, they have to return to their native element.

At this geomorphological interface we need to abandon the complex and often unnecessary jargon of geology and geotechnics and communicate in common words to be found in contemporary English dictionaries. The geomorphological approach is particularly important when we are working away from the particular geotechnical conditions with which we are familiar. The engineer's work extends from the permafrost of the polar regions, through the temperate zones and the baking deserts to the tropical rain forest. In all these diverse conditions we need to be aware of the geomorphological processes at work.

Over the years I have been involved in a wide variety of construction projects and those which have proved to be most demanding and stimulating and have contributed most to my education have always been associated with the need to bring together geology, geomorphology and geotechnical engineering. In order to emphasize the prime importance of the interplay between geomorphology and geotechnics I now describe a number of projects which require a multidisciplinary approach so that the engineering problems are understood.

THE MISSISSIPPI DELTA

During the early 1960s there were a number of breakages of offshore oil pipelines in the Mississippi Delta which were associated with the major hurricanes that had swept across the delta, the most important being Carla in 1961, Hilda in 1964 and Betsy in 1965. In addition flare pile had been destroyed during Carla and a small well jacket was lost during Betsy.

In 1967 the Shell Oil Company was planning to install production platforms in the area known as South Pass Block 70 and I became involved with the Shell Development Company in considerations of the geotechnical problems on the site.

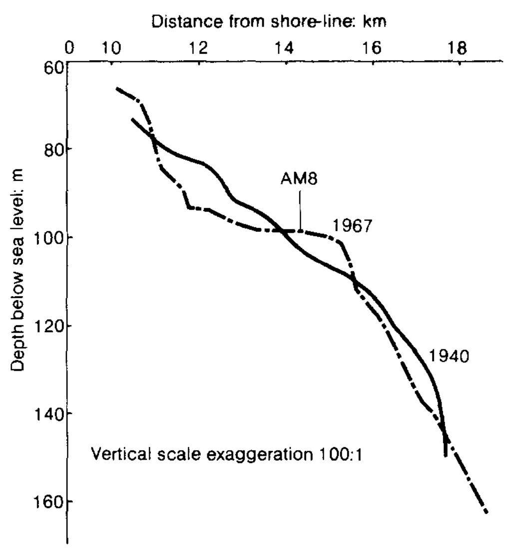


Fig. 4. Section AA, comparison of 1940 and 1967 data (Bea & Arnold, 1973)

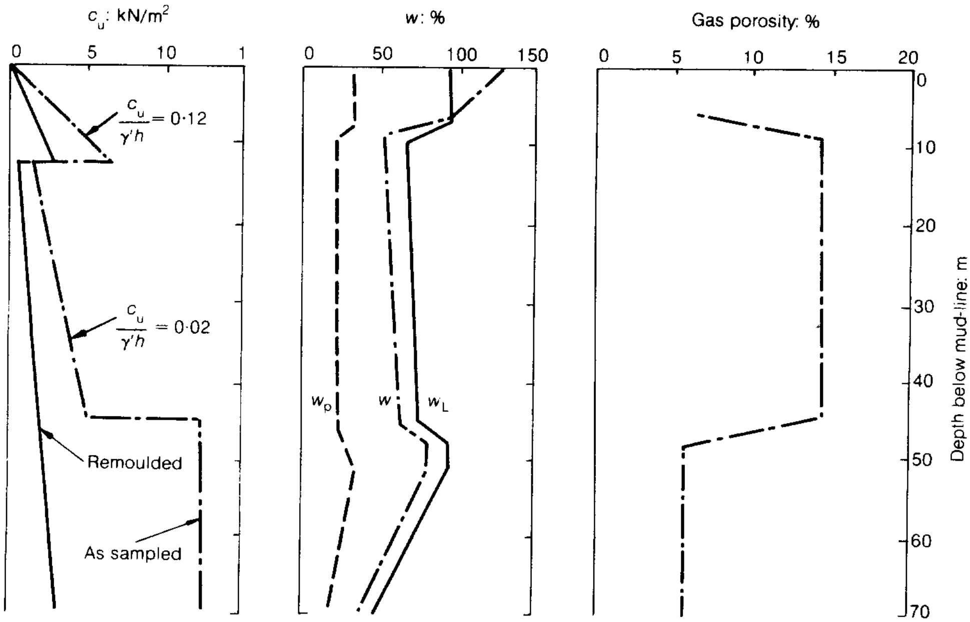


Fig. 5. Soil properties measured in borehole AM 8 (Bea & Audibert, 1980)

The Mississippi River is one of the world's largest rivers and carries an enormous sediment load to the sea every year. Shepard (1955) has shown that between 1870 and 1940 the delta advanced into the Mexican Gulf by between 1 km and 3 km, giving an average distance rate of about 30 m/year.

A plan of the Birdfoot Delta area of the Gulf is shown in Fig. 2. The contours of water depth extend to 300 m below sea level. Below 120 m the contours are smooth and evenly spaced but in the shallower waters the complex nature of the contours is apparent. Shepard (1955) considered that this complexity was the result of a series of underwater landslides and his geological interpretation was confirmed by Terzaghi in 1956. Terzaghi showed that the large excess pore-water pressures associated with this high rate of deposition were consistent with slides on the flat delta slopes.

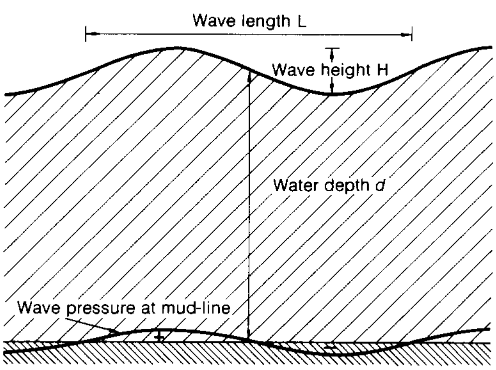


Fig. 6. Effect of waves on mud-line pressures

A section through the delta, on line AA in Fig. 2, based on the United States Coastal and Geodetic Survey of 1940, is shown in Fig. 3. The significant features of the section are the very flat sea bed slopes down to a depth of about 100 m and the abrupt change at this depth from a slope of 0·007 rad to one of 0·02 rad. It has been estimated that the base of the modern delta lies at a depth of about 50 m below the mud-line and that this level represents about 1000 years B.P. (Bea & Audibert, 1980).

A further topographic survey of the delta floor in the vicinity of Block 70 was carried out by Shell in 1967. The two surveys are compared in Fig. 4, again on the section line AA. Even allowing for possible navigational inaccuracies between the 1940 and 1967 surveys there is clear evidence of significant changes in underwater topography. The bulge at about 17 km from the shore-line, shown on the 1940 section, had disappeared by 1967 and there was a substantial reduction in elevation between 11 km and 14 km from the shore-line. A new bulge had developed 15 km from the shore-line.

Borehole AM 8 (Fig. 4) was put down for Shell in 1967; the results of soil tests on the samples are

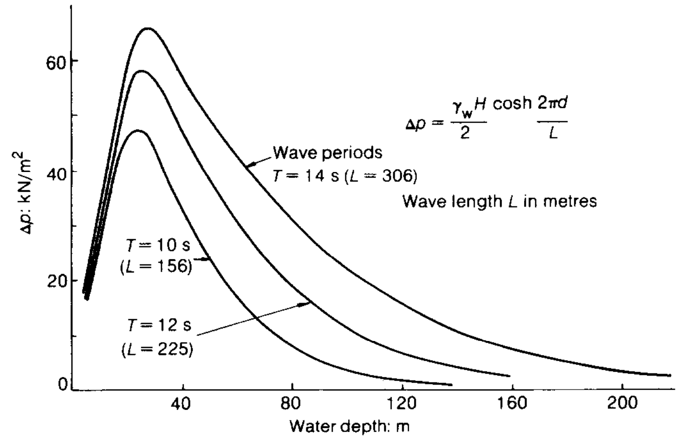


Fig. 7. Wave pressures at mud-line for 20 m wave height

shown in Fig. 5 (Bea & Audibert, 1980). The variation in undrained shear strength with depth is also shown. The major change in strength, which is at a depth of about 45 m, has been identified as the base of the modern delta. Above this elevation the shear strength depth profile is divided into an upper strong crust, with a ratio of $c_u/\gamma' h$ of 0·12, which extends to a depth of about 12 m, and a lower zone, which has a value of $c_u/\gamma' h$ of 0·02 and extends to the base of the modern delta. The value of 0·02 for $c_u/\gamma' h$ is very low and reflects the fact that below the crust the clays are underconsolidated and that there are very large excess pore water pressures. Prior & Suhayda (1979) report cases in other parts of the delta where only about 2% of the submerged overburden pressure is carried by the effective stresses in the clays.

The relationships between the Atterberg limits and the natural water contents are normal for the recently sedimented clays, but an odd feature is the high gas porosities found between depths of 12 m and 45 m.

It can be shown that for gentle slopes equilibrium under gravity forces requires that $c_u/\gamma' h$ is equal to β, the slope angle in radians. The general slope angles in Block 70, on the 1940 section, were about 0·007 rad, while the minimum value of $c_u/\gamma' h$ in borehole AM 8 was 0·02. The changes between 1940 and 1967 could not therefore be explained in terms of gravity slides as the factor of safety against gravity sliding was about 3.

The earlier evidence of the association of pipeline breaks with storms prompted the attempt to find a possible connection between storm waves and sea bottom instability.

When a wave passes over a point on the sea bed there is an increase in pressure beneath the crest of the wave and a decrease in pressure beneath the trough of the wave as shown in Fig. 6. The pressure on the sea bed depends on wave height, wave length and water depth. The real problem is extremely complicated but, as is often the case in engineering, a simplification of the problem, to one in which an analytical solution can be obtained, throws light on the mechanisms at work.

If it is assumed that a sinusoidal wave is travelling across a rigid sea bed, the pressure changes on the sea bed may be calculated easily. The pressure change or wave pressure Δp is given by $\Delta p = (\gamma_w H/2) \cosh (2\pi d/L)$ where γ_w is the unit weight of sea water, H is the wave height, d is the water depth and L is the wave length.

Storm waves with a height of 20 m are not uncommon in the Gulf and as these waves move in towards the shore their height and wavelength are influenced by the water depth. When allowance is made for these factors the wave pressures, as a 20 m high wave moves from deep water into shallow water, change as shown in Fig. 7. Longer waves have a greater influence on wave pressure; the maximum wave pressures occur in water depths of 20–30 m. These maximum wave pressures correspond with the most complex underwater contours and suggest that there is a causative link.

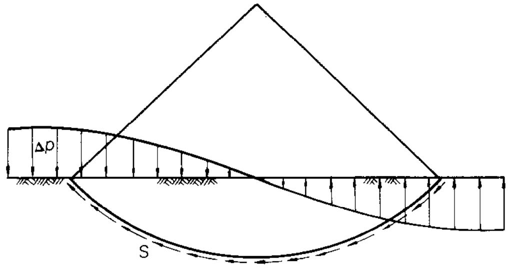


Fig. 8. Limit equilibrium model for stability

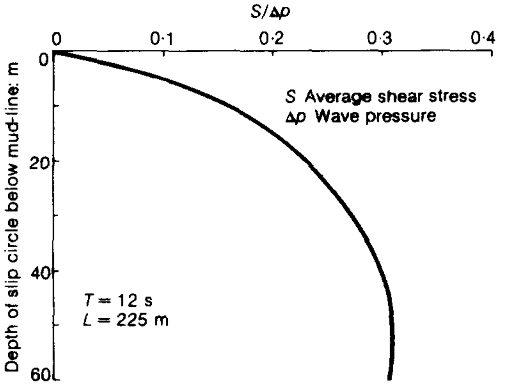


Fig. 9. Ratio of average shear stress to maximum wave pressure

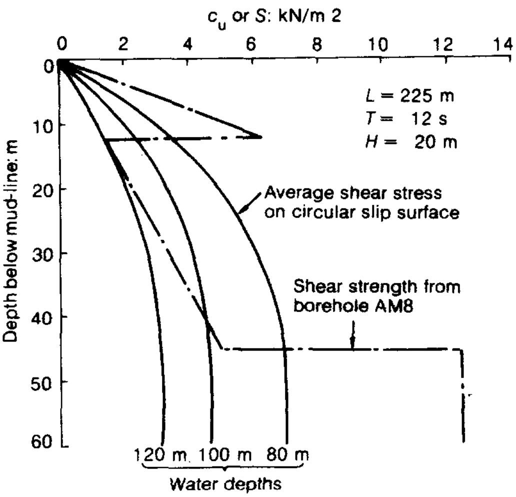


Fig. 10. Variation of average shear stress with depth of slip circle

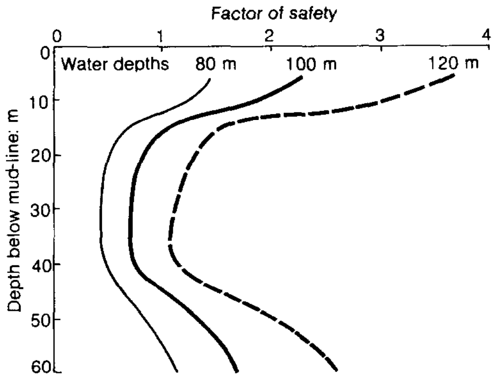


Fig. 11. Variation of factor of safety with depth

The stability of the sea bed may be investigated in a simple way by considering a circular arc failure surface and a sinusoidal wave pressure loading as shown in Fig. 8. For any depth of slip circle below the sea bed, the relationship between the average shear stress on the circular surface and the wave pressure Δp can be calculated. The result of calculations for a wave with a period of 12 s and length of 225 m is shown in Fig. 9. The maximum average shear stress is about 0·3 times the wave pressure and occurs for a depth of slip surface of about 50 m below the mud-line or at about a quarter of the wave length.

In order to compare the shear stresses imposed by the wave and gravity forces with the shear strength of the sediments the 20 m high wave with a period of 12 s and length of 225 m is again used. The ground slope is taken as 0·007 rad. The shear stresses induced in the clay by the wave and gravity forces are plotted in Fig. 10 against the depth of penetration of the slip surface below the mud-line. The shear strengths measured in borehole AM 8 are included and the results for water depths of 80 m, 100 m and 120 m are also shown.

It is difficult to compare the shear stresses and the shear strength directly in Fig. 10 as one needs to compare the average shear strength on the slip surface with the average induced shear stresses. This has been done and the resulting factors of safety are plotted in Fig. 11 against depth for the three water depths. Within the limits of the simplifying assumptions that have been made, it can be seen that, in water depths of less than 100 m, shear failure can be induced by the passage of 20 m high waves with a wavelength of 225 metres.

This simple analysis is concerned with the statics of a dynamic problem which involves the propagation of a stress wave through the sediments as water waves pass across the surface of the sea. The physical consequences of the passage of a wave of shear stresses through the sediment are very difficult to handle analytically and so to help in the understanding of the complex interaction between waves and the sea bed some small-scale experiments were carried out at Cornell University.

A 10% by weight suspension of Bear Paw shale in water with a sodium chloride concentration of 34 g/l was prepared and, after thorough mixing, allowed to sediment. During sedimentation small cracks developed on the surface of the clay, and where these intersected small mud volcanoes were formed. It was not possible to determine how deep the cracks were but the presence of the mud volcanoes showed that the vertical permeability near the surface was rather high.

Gravity slides were initiated at various times after sedimentation started by tilting the tank until

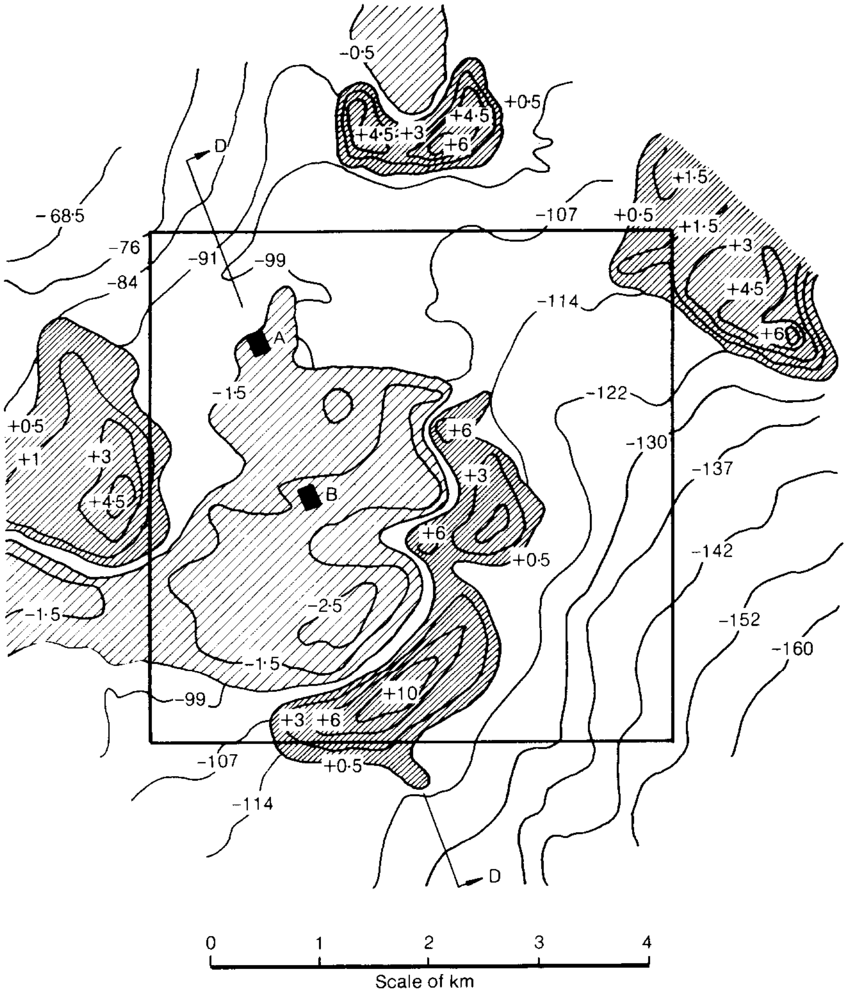


Fig. 12. Changes in bed level in metres due to Camille (Bea et al., 1975)

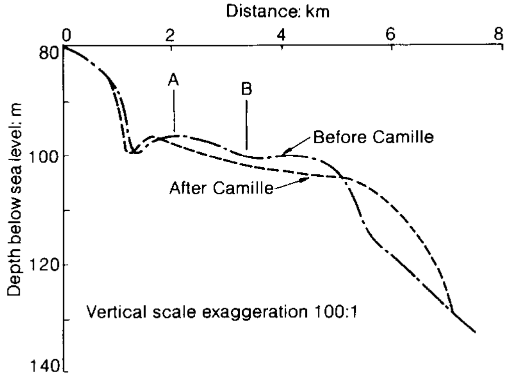


Fig. 13. Change in section DD due to Camille (Bea & Audibert, 1980)

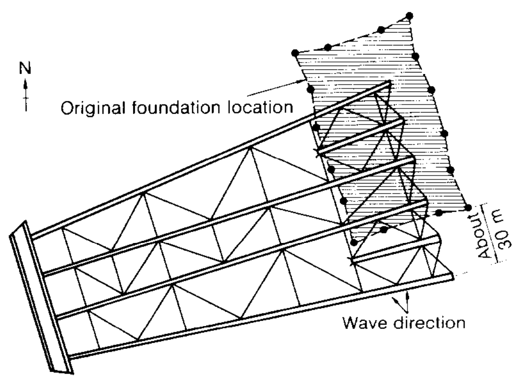


Fig. 14. Platform B after Camille (Bea & Audibert, 1980)

a slide occurred. This procedure, which was essentially a measurement of shear strength against time, suggested that the best way to measure very low shear strengths might well be by using a tilting tank.

After the relationship between consolidation time and shear strength had been established by observing the onset of gravity slides, wave loadings were introduced into the tank. At small wave heights the sediments oscillated in sympathy with the waves. However, when wave heights sufficient to cause shear failure on a sloping bed were generated an unsymmetrical movement in the sediment resulted and a series of mud snouts migrated down the slope. There was good agreement between the calculated shear stresses from the wave loading and the clay shear strength measured in the static tests.

The changes that took place in Block 70 between 1940 and 1967 were very similar to the change in the wave tank as the mud snouts advanced and it seems highly probable that the changes in the profile at Block 70 were due to the effects of storm waves. It also seems probable that the change in slope at a depth of 100 m occurred at the point at which the wave-assisted transport of sediment gave way to the more usual gravity slide.

Studies of gas in recent sediments (Oppenheimer & Kornicker, 1958; Volkmann & Oppenheimer, 1962; Anderson, Harwood & Lovelace, 1971) have shown that gas is formed as bacteria decompose the organic materials available to them. In the absence of any disturbance in the sediment the process of gas generation slows down as the supply

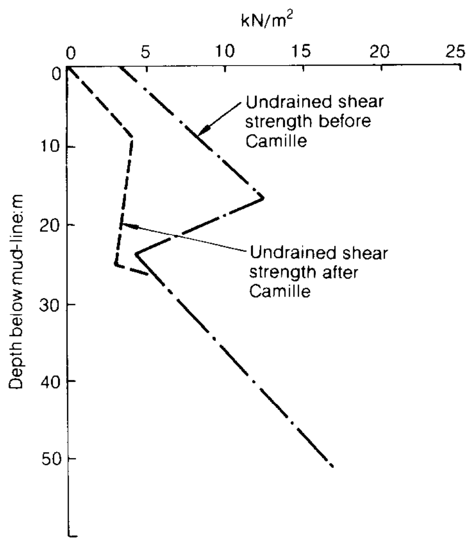


Fig. 15. Changes in shear strength at platform A (Bea & Arnold, 1973)

of organic material is exhausted. If the sediments are disturbed new supplies of organic materials become available to the bacteria and the process of gas generation is renewed. It thus appears (Bea & Arnold, 1973) that the presence of gas in sediment is an indicator that the sediment has been recently disturbed and the field data confirm that the presence of gas correlates well with other evidence of landslide activity. The existence of gassy sediments may be determined by remote sensing because, due to their ability to dissipate acoustic energy, no seismic reflections are obtained from gassy sediments.

The high gas porosities in borehole AM 8 between depths of 12 m and 45 m suggest that underwater landslide movements had extended deep into the recent sediments. The other significant feature in borehole AM 8 was the existence of the stronger crust near the mud-line. A possible explanation of this phenomenon has been supplied by Doyle (1973) as a result of model tests he carried out to investigate the relationship between waves and sediment movement. Doyle also found that, during the consolidation of the sediment in the tank, vertical pore tubes were formed in the soil and that these vertical drains permitted the rapid escape of water from the upper layers of the sediment. Small volcano-like structures were formed at the mud-line as clay particles were ejected from the pore tubes.

When wave loading was initiated the drainage from the pore tubes was reactivated and water and soil spewed out as additional excess pore-water pressures were generated by the wave loading. The wave action combined with the natural vertical drains led to an accelerated consolidation process together with the upward migration of fine particles. The higher shear strengths and Atterberg limits near the mud-line in borehole AM 8 may well be the field expression of this laboratory phenomenon.

Additional field evidence of the effects of waves in Block 70 was provided by the passage of hurricane Camille—the most intense hurricane ever recorded—to the east of the Birdfoot Delta in September 1969. By this time the area had been thoroughly surveyed and production platforms carried on piled foundations were in operation.

The changes in bottom topography which took place during hurricane Camille are shown in Fig. 12 and the positions of production platforms A and B are also shown. An enormous area sunk by up to 2 m and at the south end of the block a massive accumulation of material led to the formation of a mound with a maximum height of 10 m.

The changes on the section line XX in Fig. 12 are shown in Fig. 13. The mound formed is very

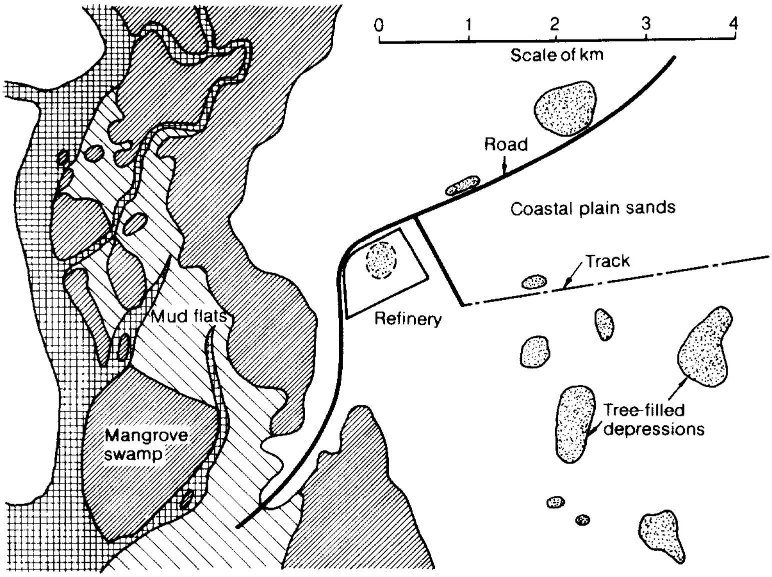


Fig. 16. Plan of refinery area

similar to that seen on the 1940 section, and in the migrating mud waves in the laboratory wave tank. Bea & Audibert (1980) reported that, based on high resolution geophysical data, a nose of soil advanced 1200 m down-slope and that large-scale soil displacements took place to a depth of 30 m.

During the hurricane Camille, platform B disappeared beneath the waves. It was found lying on its side on the sea floor as shown in Fig. 14. The lateral down-slope translation of the platform base was about 30 m. This event provided striking additional evidence in support of the hypothesis that storm waves could lead to massive instability in the weak sediments of the Mexican Gulf.

The sediments at the site of platform A were considerably stronger and precision measurements indicated that the structure had been displaced by about one metre down-slope without its operational functions being impaired. Borehole data obtained before and after Camille showed that a considerable reduction of strength had taken place during the storm and provided field evidence of the increase in excess pore-water pressures and loss of strength associated with repeated loading as shown in Fig. 15.

Since these events, and partly as a result of them, an enormous research effort has gone into the problems associated with rapid accumulation of sediments in the Mississippi Delta. The real problems are probably much more complex than I have indicated (Bea & Audibert, 1980). In the enormous area of the Mississippi Delta there are wide variations in the rate of deposition and the types of material being deposited and many geomorphological processes are at work. However, even a simple examination of one problem shows that we need to know what is there and why it has its present form before we can start to understand what is going on.

TROPICAL WEATHERING AND CHEMICAL CHANGE

Very different types of problem are associated with tropical weathering and the stability of soils subject to changes in groundwater chemistry.

A substantial cavity discovered beneath a concrete slab in the main process area of an oil refinery had no obvious cause and so an investigation was made to find out why the cavity had developed.

The site was on the edge of the Niger Delta, close to one of the discharge mouths on the Bonny River. The general geological conditions at the site are Pleistocene coastal plain sands overlying thick sandy and clayey delta deposits.

The details of the surface features in the vicinity of the refinery were examined using aerial photography. The only visible natural feature, on the otherwise flat coastal plain, was well-defined clumps of trees. When stereo pairs of the area were examined all the trees appeared to be growing in hollows. Aerial photographs taken before the refinery was constructed showed that the process area in which the cavity had been found was located where a clump of trees had been growing. If the problems were to be understood the geomorphological significance of the tree-filled hollows needed to be assessed.

A plan of the ground in the vicinity of the oil refinery is shown in Fig. 16. In order to establish the possible significance of the tree-filled depressions, the depression closest to the refinery along the track was visited first. The general appearance of the clump of trees from the track was not spectacular but among the trees there was a dank smell of rotting vegetation and a chaotic mass of plant debris, as well as an army of ferocious ants. The ground level of the clump of trees was about 2 m lower than that of the adjacent ground and the surface soils showed signs of intense leaching.

Although the geological description of the surface soils at the site was coastal plain sands, the processes of weathering had produced a matrix of kaolinite holding together the relatively unweathered sand grains. The explanation for the depressions appears to be that the organic acids produced by the rotting vegetation in the depressions had led to an accelerated rate of breakdown of the coastal plain sands with a consequent decrease in volume.

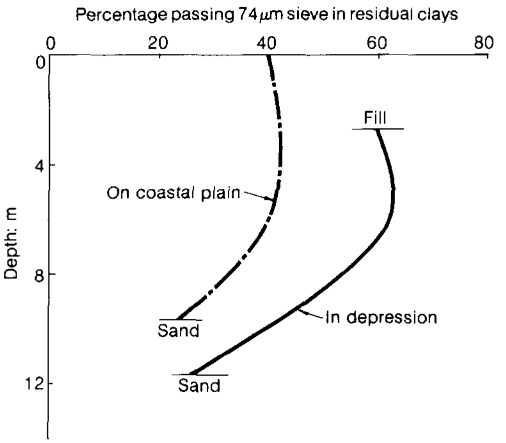


Fig. 17. Comparison of coastal plain and depression soils

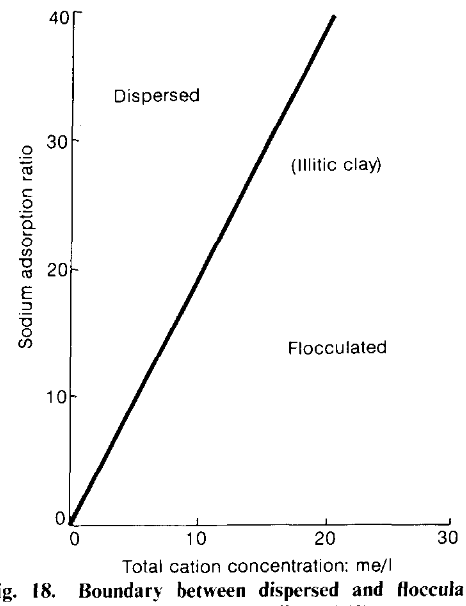


Fig. 18. Boundary between dispersed and flocculated states (after Collis-George & Smiles, 1963)

A simple indicator of the intensity of weathering is the percentage of material passing the 74 μm sieve. In Fig. 17 the soils in the depression and on the flat coastal plains are compared. In the depression the percentage of fine material is much higher and the weathering has proceeded to a greater depth.

In the area of the refinery, a further small cavity in the ground was found in a drain into which water, treated with sodium carbonate, was being discharged. Although there had been some contamination by hydrocarbon wastes it was possible to establish that erosion of the soil along fissures had taken place. The texture of the surface of the natural soil and the fact that the sand grains stood out very clearly suggested that a chemical dispersion process was involved.

The cavity in the process area, which led to the initial concern on the site, was downstream of an ion exchanger used to condition the boiler feedwater. In order to recondition the ion exchanger 14 kg of 98% sulphuric acid and 80 kg of flake caustic soda were passed through the ion exchanger and flushed into the drainage system every eight hours. It appeared that leaks had developed in the drainage system and that some of the chemical waste materials had found their way into the ground. The natural pH of the groundwater at the site is about 5, but in many places near the drains, the pH had increased to about 9 because of contamination from caustic soda.

For many years dam engineers have been concerned about the possibilities of internal erosion in dam foundations and it has been established that internal erosion can take place when the clay particles are in a dispersed rather than a flocculated array. When flocculated the clay particles cling together but when dispersed they are readily removed by flowing water. Dam engineers and soil scientists have a common interest in this problem because whether the soils are dispersed or flocculated has an important effect on their permeability and also the agricultural yield.

The factors which control the flocculation or dispersion of clays are very complex and there are no adequate theories to explain all the phenomena. However, there is strong pragmatic evidence that the presence of sodium ions is one of the more important factors leading to dispersion. As an example the results obtained by Collis-George & Smiles (1963) are shown in Fig. 18. They indicate that the ratio between the sodium adsorption ratio and the total cation concentration control whether the clays are in a dispersed or flocculated state.

I am a believer in simple field tests, and a sample of the alkaline effluent from the ion exchanger was allowed to flow through a small hole in a sample of the soil from the process area. The hole had an initial diameter of about 3 mm which enlarged rapidly, and very dirty water carrying fine particles in suspension emerged from the hole. It was clear that the caustic soda was causing surface erosion of the clay particles.

The effectiveness of dilute caustic soda in causing dispersion is shown in Figs 19 and 20. In Fig. 19 the surface of a sample of the soil from the oil refinery which had been subjected to a flow of distilled water is shown. Although coarse particles are visible they are obscured by a thin layer of clay-sized materials. The grid consists of 2 mm squares. Fig. 20 shows the soil surface after a weak solution of caustic soda had been allowed to flow across the sample. The surfaces of the coarser particles have been washed clean. Again the grid consists of 2 mm squares.

On a larger scale the effects of the caustic soda in the effluent were examined using a scanning electron microscope. Fig. 21 shows the untreated soil; it has the typical appearance of a weathered kaolinite. Fig. 22 was taken after the surface of the sample had been washed with dilute caustic soda solution. The kaolinite sheets had broken down into a mass of small particles which could easily be eroded by flowing water.

Holes into which the particles can be washed are provided by the many fissures which are formed as the soil volume decreases due to the weathering process. The presence of an extensive network of termite burrows provides further routes for the erosive effluents to carry away the dispersed clay particles.

Experience elsewhere in West Africa has shown that the adverse effects of allowing effluents containing caustic soda to come in contact with the well-drained soils produced by tropical weathering of sandy materials are fairly common.

These examples of the effect of changes in

Fig. 19. Surface of natural soil (2 mm grid)

Fig. 20. Surface of soil washed with dilute caustic soda (2 mm grid)

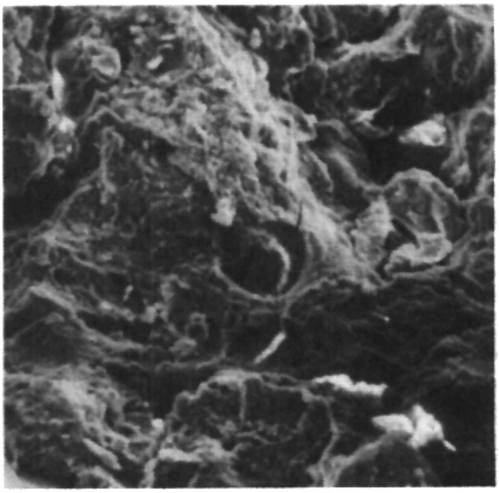


Fig. 21. Electron microscope picture of natural soil; width of sample shown 0·7 mm

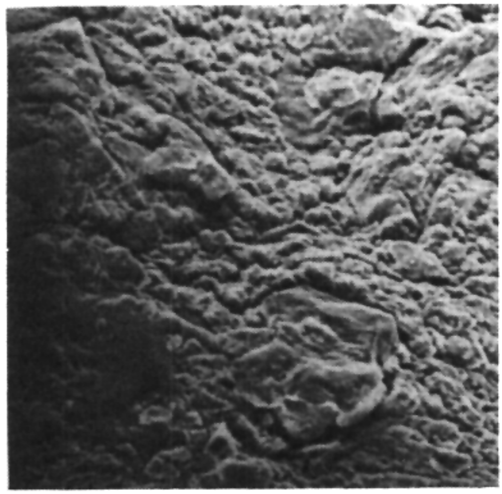


Fig. 22. Electron microscope picture of soil treated with dilute caustic soda; width of sample shown 0·7 mm

chemical environment emphasizes the importance at each site of the three fundamental questions of what is there, why does it have its present form and what will happen if we change anything.

Weathering plays an extremely important role in determining the engineering behaviour of materials and I think that engineering geologists could provide a valuable service to the civil engineering profession by giving more information on the geomorphological consequences of weathering in a variety of climatic and geological circumstances.

In the high rain-fall areas of the Western Ghats in India, where 10 m of rain fall every year, all the silica in the residual soils is dissolved and very porous soils of high permeability are produced. By squeezing the soil in the hand it is possible to squeeze out water as from a sponge.

Weathering processes are very sensitive to the micro-climate at any point and modest changes in surface can produce significant differences in weathering rates and hence soil properties. As an example, Fig. 23 shows a cutting in weathered basalt.

Over the past few years there has been a series of massive construction projects in Hong Kong where many of the engineering problems are associated with the weathering of volcanic or granitic rocks to form residual soils. Provided the in situ weathered rock is not disturbed, the original structure of the granite is retained. The retention of the original coarse-grained structure in spite of intense weathering produces a soil with high permeability and high compressibility. This means that in excavations or in diaphragm wall construction significant swelling can take place during the short period that the stresses on the ground are reduced. Unless large excess bentonite heads are maintained large settlements take place during the construction of diaphragm walls.

EFFECTS OF GROUNDWATER CHANGES

The effects of groundwater lowering in causing settlement are well known from experience in Venice, Mexico City, Long Beach California and London. In most cases groundwater lowering does not lead to sharp discontinuities in the ground surface but in certain geological circumstances the results can be catastrophic.

A massive groundwater lowering operation was carried out in Far West Rand in South Africa, where the land surface is old, the most recent rocks being the Karroo system, which corresponds to the Carboniferous of the Northern Hemisphere.

A plan of the Bank Compartment is shown in Fig. 24. The term compartment is used because of the syenite and diabase dykes which divide the water-bearing dolomite into a number of virtually watertight compartments. Some of these dykes are shown on the plan. Associated with each dyke was a spring which carried the groundwater over the dyke from one compartment to another.

The West Driefontein Gold Mine is situated in the Oberholzer Compartment, immediately to the west of the Bank Compartment, and in October 1968 an unprecedented and unexpected inflow of water occurred in a stope in the eastern part of the mine near the dyke between the Oberholzer and Bank Compartments (Taute & Tress, 1971).

The water inflow was in excess of

Fig. 23. Weathered basalt

360 000 m^3/day or 250 m^3/min and it became apparent that a fissure connecting the two compartments had opened up. Part of the mine became flooded. The only practical way to reinstate the West Driefontein Mine was to drain the Bank Compartment, and permission to do this was obtained from the Department of Water Affairs. The depth of groundwater lowering required was about 1000 m and in the Bank Compartment water levels were lowered during 1969, 1970 and 1971.

A section through the Bank Compartment along the line XX in Fig. 24 is shown in Fig. 25. The Witwatersrand system, which contains the important gold-bearing conglomerates, lies

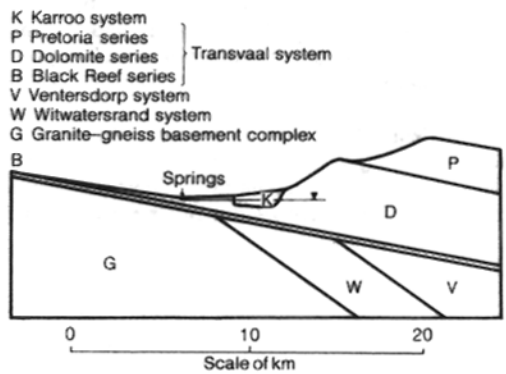


Fig. 25. Section XX through Bank Compartment

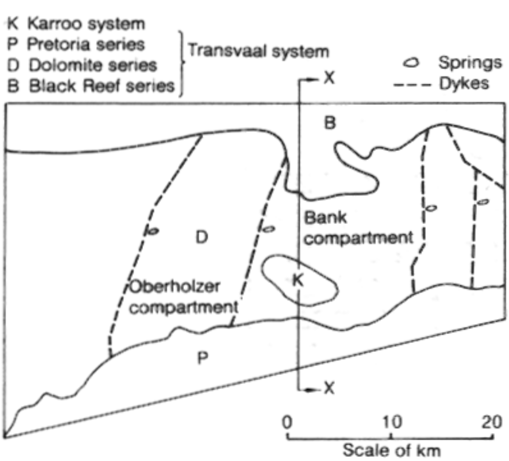


Fig. 24. Plan of Bank Compartment

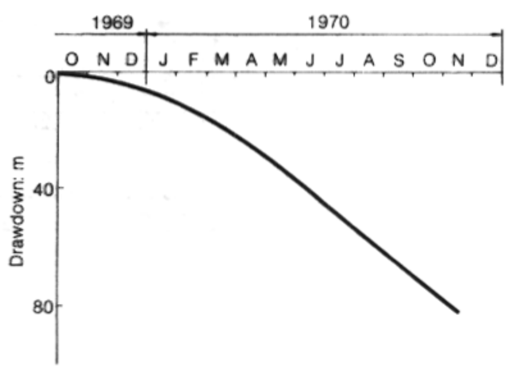


Fig. 26. Water levels in borehole near Brickor

directly on the granite–gneiss basement complex. The Transvaal system, which includes the water-bearing dolomite, rests uncomfortably on an erosion surface which cuts across the older rocks. An isolated pocket of the Karroo system is laid down on the weathered and glaciated surface of the dolomite. The weathered shales of the Karroo system provided admirable raw material for the manufacture of bricks and the Driefontein brick-works, known as Brickor, were established on this outlier.

Water levels recorded in a borehole near the Brickor site are shown in Fig. 26. The readings were ceased in October 1970 because the water level had sunk below the bottom of the borehole.

As the water levels in the Bank Compartment were lowered problems were encountered with the continuous kiln process being used. The cars carrying the bricks became jammed in the kilns and it was decided to measure the settlements of the kilns and adjacent areas. The settlements which took place between July 1970 and April 1972, when movements had effectively stopped, are shown in Fig. 27. During this period the settlements amounted to 180 mm and it had become impossible to operate the kilns which required very tight tolerance on level for their successful working.

The detailed geology of the area was investigated thoroughly by Brink (1979); a section through the area of maximum settlement is shown in Fig. 28. The Karroo sediments were laid down in a solution channel in the dolomite and the settlement profile approximates to the relative thickness of the Karroo sediments which had been dewatered in the pumping operation. The reduction in the hydrostatic uplift led to consolidation of the sediments.

A more alarming aspect of the geological investigations was the discovery of a substantial zone of material known as 'wad'. This is an insoluble and highly compressible material left after the dolomite has been dissolved by percolating waters containing carbonic acid. The solution of the dolomite took place after the deposition of the Karroo sediments. It was fortunate that, at the site of the brickworks, the Karroo sediments, which had infilled a solution feature in the dolomite at the time of their deposition, were able to arch across the very weak and compressible wad produced by additional solution and thus prevent a catastrophic collapse.

Catastrophic collapses had occurred in a number of places adjacent to the brickworks and in a short helicopter trip a number of surface features associated with the collapse of wad were seen. These are shown in Figs 29–31. Fig. 29 shows an early stage in the development of a hole with deformation and cracking of the ground surface. Fig. 30 shows a situation in which most of the disturbed area has collapsed and Fig. 31 shows a view of this hole seen from the ground.

The catastrophic settlements that can result from groundwater lowering in dolomitic or lime-

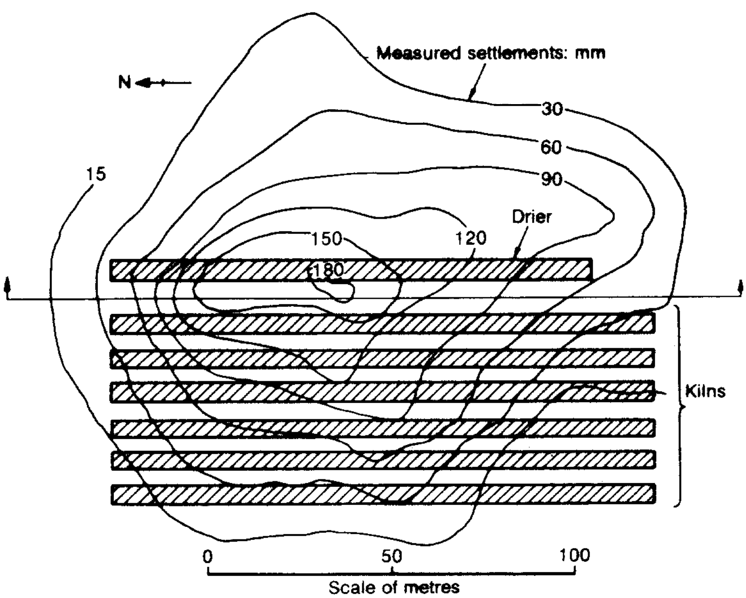


Fig. 27. Settlements at Brickor from July 1970 to April 1972

stone rocks show how important it is for geology and engineering to work together so that situations in which this hazard exists can be identified. It is also clear that where geological unconformities exist it is necessary to examine not only the surface geomorphology but also the geomorphology of the underlying surface.

The solution of limestones and dolomites is continuing in many parts of the world and in order to appreciate the scale of the features that contribute to the problem it is useful to look at areas where the rocks are at the surface. A view of tropical karst in Malaysia is shown in Fig. 32 and the details of its complex, nearly vertical pinnacles are shown in Fig. 33. Where such features exist the difficulties of predicting overall engineering behaviour are formidable and can only be attempted if the processes which led to the formation of the buried topography are understood.

ALTERATIONS IN DRAINAGE

It is not often that in the course of a single job one is able to see the interaction between geology, man and geomorphology. I had this opportunity some years ago while working on the Beas Dam in India. At the site of the dam the river cuts through a plunging anticline. The Siwalik rocks are a sequence of weak sand rocks and shales which have been folded as part of the Himalayan uplift. The surface of one of the sand rock layers on the flank of the anticline is shown in Fig. 34 in which the regional jointing pattern, associated with the folding, can be seen.

The alteration of the surface topography by the construction of access roads and drainage ditches led to a concentrated flow of stormwater over the surface of the rock. The effect on the rock exposure was spectacular as is shown in Fig. 35. The water pressure associated with the surface flooding caused the joints to open up and horizontal displacement of about 13 m took place. Fig. 36 shows the area after the movement had occurred.

This experience was a lesson on the delicate

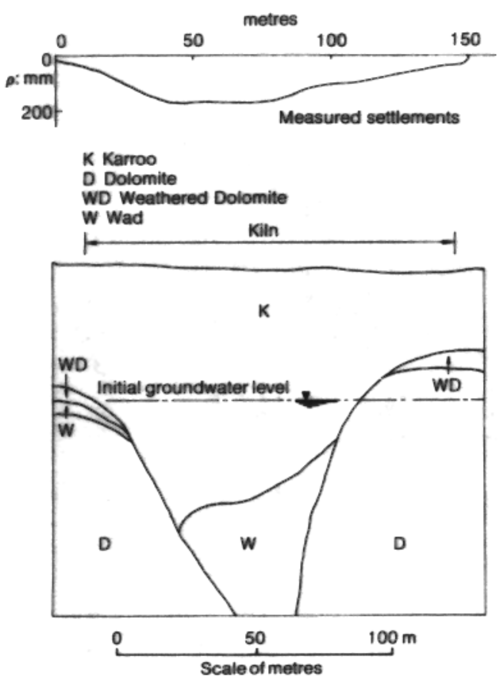


Fig. 28. Detailed geology at Brickor

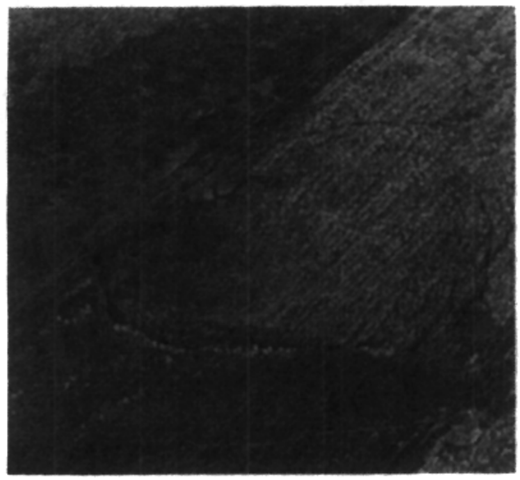


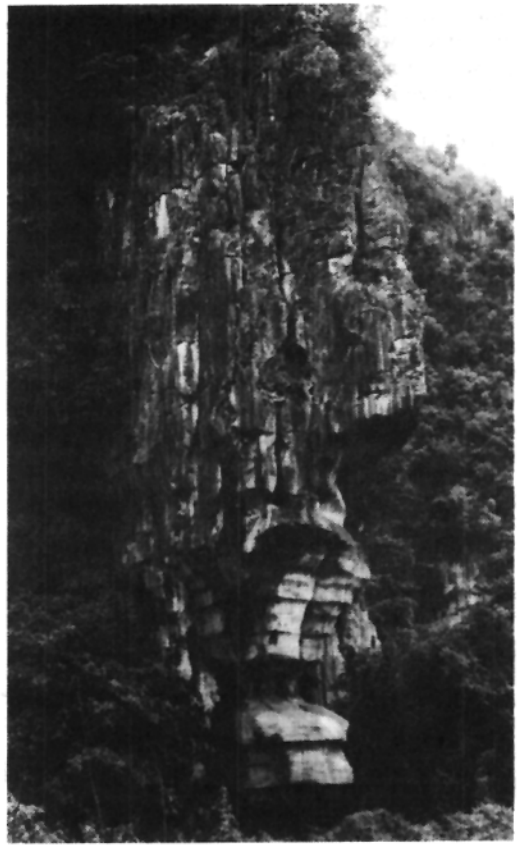
Fig. 29. Early stage of hole development

Fig. 30. Collapse of disturbed area

Fig. 31. Hole from ground

Fig. 32. General view of Malaysian karst

Fig. 33. (right). Vertical limestone pinnacle



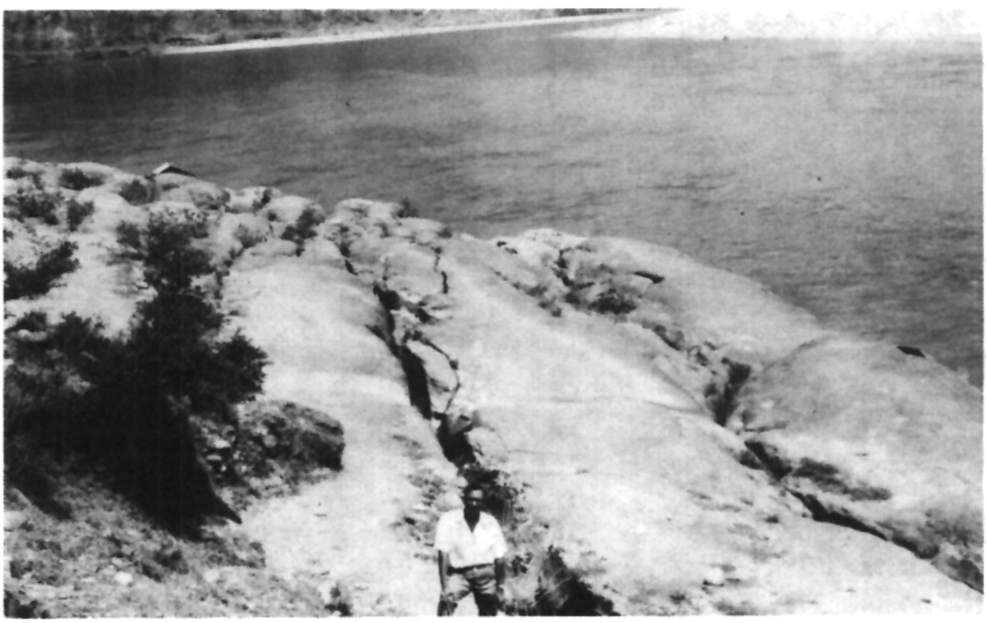


Fig. 34. Rock surface on Beas River

equilibrium that exists in many natural situations, and unless we ask ourselves why the land has its present form and why it is in equilibrium we may not realize what we are doing.

GLACIAL MATERIALS

I cannot leave my subject without a few words about the difficulties of working in some of the glacial material we encounter. The Pleistocene glaciation involved many advances and retreats of the ice and, in the process, complex variations in local erosion and infilling occurred. The one lesson we must learn from experience in glacial materials is that the unexpected should always be expected. In spite of site investigations we will, in many cases, not know what is there until we have opened up the foundation or other excavations. The cliffs in Norfolk near Overstrand (Fig. 37) illustrate the complexity of ice marginal glacial materials. It would be a brave man who would hazard a guess, based on a series of even closely spaced borings, of what could be expected.

An important point emerging from the consideration of the inherent variability of many glacial materials and the variability associated with other geological processes is that in some circumstances it will not be possible to understand what is going on. We must recognize this fact and make it clear at an early stage in the design process so that everyone is aware of the risks involved. However, we should try to define the limiting conditions that might be encountered so that construction strategies to cope with the possible limiting conditions can be developed.

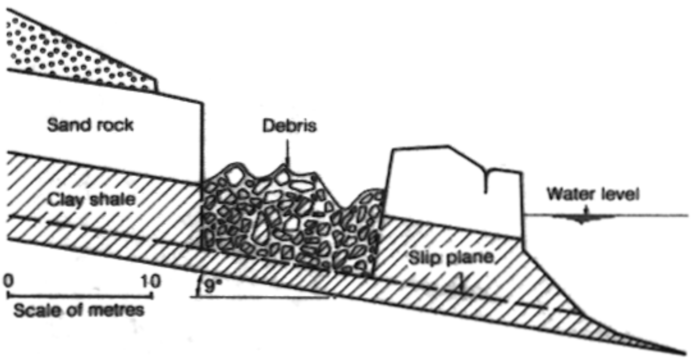


Fig. 35. Section through slip

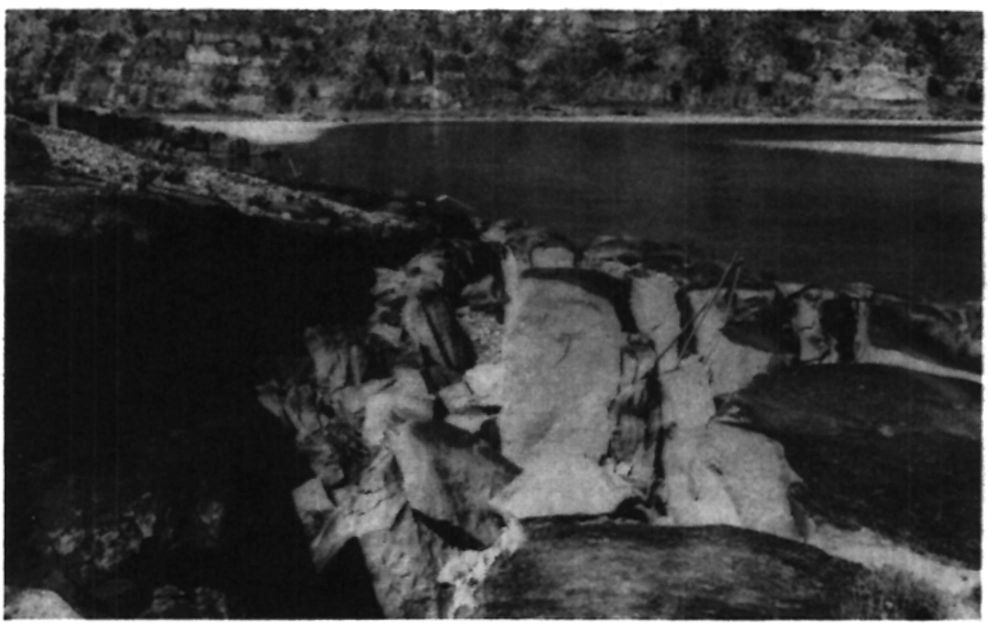


Fig. 36. Rock surface after slip

Fig. 37. Glacial deposits at Overstrand

CONCLUSION

Over the past few decades we have developed sophisticated analytical and numerical methods for the solution of almost any problem provided we are able to make the correct fundamental assumptions. My message is that, in order to define the fundamental assumptions, there is no substitute for painstaking study in the field of geology and geomorphology. We still need something of the Victorian virtue known as 'an eye for the ground'.

The geological environmental is complex with so many facets that control its behaviour that the only way to achieve a fuller understanding is for there to be an interdisciplinary approach in which engineers and geologists work much more closely together. The meeting ground can, I believe, be found by both the professions concentrating on understanding the geomorphology of construction sites.

The birds and fishes in Fig. 1 remind us that in order to understand our problems we have to approach them from two sides—geology and engineering.

ACKNOWLEDGEMENT

The electron microscope photographs reproduced in Figs 21 and 22 were taken by Dr Tovey.

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VOTE OF THANKS

In proposing a vote of thanks to Dr Henkel, Professor J. N. Hutchinson said:

'In his introductory remarks, Professor Wroth highlighted the distinguished and wide-ranging nature of Dr Henkel's career. The lecture which we have just heard has truly reflected these qualities, moving expertly from consideration of soft Holocene deposits in the Gulf of Mexico to the deep geology of ancient rocks in the Transvaal; from the subtle manifestations of tropical weathering in the Niger Delta to the complexities of glacial deposits in East Anglia. With his soundly based, all-round knowledge and his enviable ability, noted by Professor Wroth, to cut through a maze of inessentials to reach the heart of a problem, Dr Henkel bids fair to be a rare exception to Terzaghi's dictum concerning the supposed impossibility of combining, in one person, equal competence in engineering and geology. Whether he achieves this in the form of a flying fish or a diving bird is perhaps less clear.

'I found Dr Henkel's account of his, now classic, work on the generation of submarine landslides in soft clays by differential wave loading to be particularly elegant and satisfying. In this connection, it is interesting to note that, on the bed of the North Sea, similar cyclic wave loading seems to have had the beneficial effect of densifying the widespread sand deposists there, which otherwise may well have been prone to liquefaction.

'Dr Henkel's eminence in both the professional and academic spheres of our subject makes him unusually well equipped to comment on current teaching practices. In the lecture, his views on these were uncharacteristically restrained, but three important points emerge. First, that engineering geology should become more distinct than at present from geotechnical engineering, so that the two disciplines may be truly complementary. Second, that in this context, geomorphology has been seriously neglected and that there is now a pressing need to give this discipline its proper place in the geotechnical spectrum. The claim of neglect is indeed supported by the fact that the term geomorphology has not been mentioned in any of the previous twenty-one Rankine Lectures. Third, Dr Henkel suggests that the discipline of geomorphology can act as a long-needed catalyst to bring about a more effective combination between geology and geotechnics. I believe that these views deserve our serious consideration.

'During his time in the Civil Engineering Department at Imperial College, Dr Henkel was able to put into effect some of his teaching ideas. In particular, he organized and led the first geotechnical field excursion for postgraduate soil mechanics students. Indeed, such was his belief in the educative value of the Norfolk Pleistocene cliffs that we were taken through a field of anti-tank mines to see them! I have never been quite sure how to interpret the fact that this was done with the agreement of the Rector! I would suggest that this episode is symbolic of Dr Henkel's subsequent professional career. In this, he has continued to enter engineering and geological minefields from which, however, because so well armed with the geotechnical virtues, he manages to emerge unscathed.

'There is one matter for which, I believe, there is cause for regret. That is, because of Dr Henkel's intense professional activity over the past decade, he has had little time to record the fruits of this in the technical literature. Tonight's lecture has shown vividly what we have been missing. I hope that, in the future, Dr Henkel will make time to enlarge on, and add to, the wisdom that he has shared with us tonight.

'In conclusion, it gives me great pleasure to propose a warm vote of thanks to Dr Henkel for his outstanding and thought-provoking address'.

The vote of thanks was accorded with acclamation.