Second Rankine Lecture

FIELD MEASUREMENTS IN SOIL MECHANICS

by

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When I was invited by the British National Committee to give this second Rankine Lecture, I must confess that my reactions were of a mixed nature. While I was naturally very gratified at the honour this invitation conferred on me, I was also conscious of the fact that the task of maintaining the standard expected in these lectures was not an easy one and would be a considerable strain on my capacities. However, I was fortified into accepting the honour by the remembrance of the many occasions in the past when this Society had shown great indulgence to honest if somewhat pedestrian endeavour.

On this occasion, I thought it would be of value to review the position in one broad aspect of the subject, to see how far we have travelled, what remains to be done, and in which direction we should go in future development. Such an exercise could usefully be carried out on many aspects of soil mechanics (all of them important), but the one I have chosen for this talk is that of field measurements on full-scale structures and its rôle in the application of soil mechanics to civil engineering problems. I have made this choice for various reasons; first, because I think it is appropriate to a Rankine Lecture, for, although in soil mechanics we tend to regard Rankine as a theorist there is no doubt that he had a full appreciation of practical considerations and the difficulties of applying theory to soil problems. In his *Manual of Civil Engineering*, Rankine wrote: "The properties of earth with respect to adhesion and friction are so variable, that the engineer should never trust to tables or to information obtained from books to guide him in designing earthworks, when he has it in his power to obtain the necessary data either by observation of existing earthworks in the same stratum or by experiment." Later in the same section he wrote: "There is a mathematical theory of the combined action of friction and adhesion in earth; but for want of precise experimental data, its practical utility is doubtful." If we interpret the term "precise experimental data" to include reliable field measurements on actual structures, then my theme is obviously in line with Rankine's thinking. My second reason is that the subject is of considerable importance in its own right for the future development of soil mechanics, and anyone who has made a study of Terzaghi's writings will have been struck by his insistence on the urgent need for taking reliable field observations. My third reason is that my colleagues and I at the Building Research Station have been particularly interested in this aspect of soil mechanics and have, from time to time over the past 25 years, carried out a number of investigations involving field measurements of various types on full-scale structures.

FIELD MEASUREMENTS IN SOIL MECHANICS

INTRODUCTION

The art of dealing with soils in civil engineering works resides largely in the skill, experience, and judgement of the individual engineer and in his knowledge of precedents. This is still perhaps the decisive part of practical design and construction, but as the science of soil mechanics grows the contributions it can make, particularly in adding more precision to design

methods, become more and more important. While it would be generally agreed that substantial advances have been made, it is also necessary to appreciate the limitations of the methods developed and it is in defining these limitations that field measurements are essential.

Many of these limitations arise from the fact that we are dealing with geological deposits, materials which have been laid down by nature. Individual soil strata vary in their properties from point to point and at any given site the geological structure may be more or less complex.

As you know, the current procedure in tackling soil problems is to put down boreholes to procure "undisturbed" samples and to gain some idea of the pattern of subsurface strata; then by field tests or by tests on the samples in the laboratory to obtain the salient soil properties and their degree of variation. These are then used in a design analysis appropriate to the particular problem. Design methods vary a good deal in their degree of reliability, depending on the background of knowledge and on the complexity of the factors governing the soil action involved. In using any design method the actual boring records and test results need to be replaced by a "simplified" profile and "average" values of the soil characteristics. This radical simplification admits a margin for interpretation and the more complex the geological conditions the wider the margin becomes. The nature and importance of these errors can only be learned by observations and measurements on full-scale structures. For this reason field measurements are necessary both from a practical point of view and for the development of design techniques. In his Opening Address to the Rotterdam Conference, Terzaghi stated that "Further progress depends chiefly on the improvement of our methods for measurement in the field, on the scope and quality of the field observations and on the adaptation of our methods of subsoil exploration to practical requirements".

Field work in general is more important in soil mechanics than in other branches of civil engineering; I had, therefore, better define more closely what I mean by field measurement. In my talk this evening I do not propose to deal with field tests to measure the properties of soils "in situ"; nor shall I deal with failures of engineering structures for, while these have been extremely useful in developing design techniques that ensure stability, such studies are of the "post-mortem" type and are of little value for assessing the forces and strains in a stable structure. I shall concern myself with measurements made on full-scale structures which, by giving an insight into the behaviour of soils in practice can further the development of what might be called "diagnostic techniques".

SCOPE AND PURPOSE

Field measurements can yield valuable information on a very wide range of problems and the scope of such measurements needs to cover a number of different types of observation (Cooling, 1945).¹ Among these may be mentioned settlement measurements on structures, lateral movements of earthworks, observations of pore-water pressures, and measurements of loads and pressures on earth-retaining structures.

The purpose of recording full-scale behaviour may vary according to the type of problem and on the complexity of the site conditions. As already mentioned, the degree of reliability of available design methods varies a good deal with the type of problem. For fairly simple site conditions involving a problem for which a well-developed method of analysis exists, the purpose of field measurements may be to check the degree of validity of the theory. In other problems where the present theory is rather crude or very tenuously related to practice, the purpose of field measurements may be to develop a better working hypothesis.

Where geological site conditions are complex, it may not be possible to give, prior to construction, a good quantitative performance forecast. In such cases a knowledge of the behaviour of soils gained from a background of soil mechanics experience may be helpful in determining in advance of construction, the type and location of a potential source of trouble.

¹ The references are given on p. 102.

If the probable mode of failure or the probable movements can be even broadly anticipated, it is often possible to arrange for observations during construction which will reveal at an early stage whether anything untoward is happening and so enable appropriate measures to be taken before it is too late. In such cases field measurements form an essential part of that powerful approach to soil mechanics problems which had been called by Terzaghi (1961) the "observational procedure".

In addition to its use in a "learn as you go" observational procedure and for the purpose of checking and improving existing theories, field measurement is also important in those problems where the behaviour of a structure is mainly determined by varying environmental conditions. They include such problems as the creep of hillsides, the seasonal shrinkage and swelling of clay soils and the effects of industrial processes on the foundations of the structure in which they are housed. In such cases field measurements are essential to discover the nature and extent of the problem, to reveal the important factors involved and so permit the formulation of a rational design approach.

When the field measurements are made for the purpose of establishing a link between theory and practice, it is important that, on the one hand, there should be an adequate exploration of the soil conditions at the site, accompanied by sufficient tests to determine the characteristics of the important soil strata for use in the theory; on the other hand, the programme of field observations must be carefully planned and made appropriate to the particular problem under consideration and the methods adopted must be sufficiently reliable to keep the margin for their interpretation reasonably small.

FIELD TECHNIQUES

The wide range of problems calls for a variety of techniques to obtain the required observational data. This has necessitated not only the adaptation of well-known methods but also the development of new techniques and specialized instrumentation. For instance, the settlement of structures can be measured by well-known methods. The measurement of pore-water pressure, though fairly simple in principle, has required the development of new techniques to overcome the difficulties met with in field application. In certain cases electrical instruments have been developed.

To measure earth pressures, both the direct approach by means of soil pressure cells and the indirect approach by measurement of strains and loads in the structure which supports the soil, have required the development of methods which can measure accurately very small strains. A variety of instruments is available for this purpose but most have been designed to function under laboratory conditions. Many do not face up to the stringent conditions met with in field work, so special techniques need to be used.

Field work requires robust, stable instruments which are not easily damaged and which can be conveniently installed and read without interfering with constructional operations. No delicate manipulations should be expected of the operator because he may have to work in awkward positions, exposed to extremes of weather and in bad light. Since repeat tests can rarely be made and a failure or inadequate functioning of the odd instrument is a hazard which must be taken into account, reliance should not be placed on too few instruments. It is often an advantage when using specialized techniques to take check readings by an independent set of observations using another form of instrumentation, even if the second method is rather crude. Such results should at least "give the street you are in" and can lend a good deal of confidence to the more accurate measurements given by the special technique.

The planning of a field programme is most important and much could be written on the subject but I will content myself with a few general comments. First, it is necessary to have clearly in mind the purpose for which the work is being carried out so that the observations can be tailored to the particular problem and purpose in mind. Plan early so that careful consideration can be given to details before the urgency of the construction period is imposed.

Do not attempt too much; an elaborate programme is not necessarily the most rewarding. The reliability of the measurements should be the overriding consideration. Since most field measurements need to be carried out over a period of time, they have to be arranged systematically so that the readings can give a sufficiently connected picture covering any critical periods and continued as long as necessary. In addition, some thought should be given to the protection of instruments exposed to the many hazards on a construction site, and in this connexion it is often an advantage to explain to site personnel the broad object of the work. Finally, the recording of the measurements is most important; they should be clearly set out and the copying of results from the field book into the record book should never be unduly delayed. Field books are apt to become difficult to decipher and their interpretation may become a source of uncertainty.

To discuss field techniques in a little more detail I propose to describe examples of field work involving three types of measurements—settlements, pore-water pressures, and earth pressures. It will only be possible to make brief reference to a few examples of each type but I hope to bring out such considerations as: (a) method; (b) purpose of work; (c) value of the information obtained; (d) the need for future work.

TYPES OF MEASUREMENT

A good deal of field work has been carried out in this country but I hope you will forgive me if I confine myself to examples with which we at the Building Research Station have been concerned; this enables me to speak, if not with first-hand experience of all the details, at least with second-hand experience of having been responsible for the work. In quoting these examples, I am of course vastly indebted to my past and present colleagues and to the many engineers and organizations who have not only afforded facilities for the work but have actively collaborated with the site work.

(a) Settlements of structures

The technique of measuring the settlements of a structure is fairly straightforward and the value of such records both from the theoretical and practical point of view is generally recognized.

The usual method of measuring settlements is by means of a precise telescopic level and it involves determining from time to time the level of observation plugs built into the structure at suitable points in relation to a reference datum. The constancy of the level of the reference datum is, of course, of fundamental importance especially if theories are to be checked. In a few cases an easily accessible datum can be placed on a rock outcrop or on deep piles or shafts. Normally, however, it needs to be specially prepared. In such a case the reference datum should be located as deep as possible away from all possible disturbances. Fig. 1 illustrates the general features of two types of datum point which are commonly used.

Two separate datum points should be installed and observations on their relative levels can then be used to check their stability. Experience has shown that there is a risk of a datum point becoming buried in the course of tidying up the site after construction or during subsequent use of the area. For this reason accurate co-ordinates should be taken of the position of these points, say, with reference to corners of the building, so that it will be possible to find them should they become covered up.

It is sometimes convenient to locate the reference datum beneath the structure and to have observation points on the building in the same vertical line. A screw micrometer or dial gauge can then be used to measure the movements directly and thereby higher accuracy of measurements can be obtained. This was used for observations on Waterloo Bridge (see Fig. 2). The top protecting tube was built into the pier, and the datum rod, the bottom end of which was located at some 40 ft below the pier bottom, came up through a sleeve pipe and the relative movements were measured with a dial micrometer. This method has also been

Fig. 1. Settlement observations—typical datum points

found useful for accurate readings on small houses, when the measuring point can be located in a cavity of the wall and a locked panel will protect it from interference. A disadvantage is that a datum point is needed for each observation point.

The measurements at Waterloo Bridge were taken by the engineers (Buckton and Cuerel, 1943) and Fig. 2 gives the sort of information which was obtained. Apart from the datum, it shows the sequence of soil strata, a time-loading diagram and a time-settlement record. It also shows results of observations on the heave of the clay at formation level as the result of excavation. This is a problem on which few observations have been taken and in view of its importance I should perhaps emphasize the need for many more records of this kind (Serota and Jennings, 1959).

To begin with, it may be of interest to indicate in broad outline important simple relationships which have been demonstrated by settlement observations. One example concerns the Chelmsford Gasholder investigation described by Meyerhof (1951) and illustrated in Figs 3 and 4. This is a good example of a case where under a uniform loading of about 1 ton/sq. ft, serious differential settlements resulted due to the variable thickness of a soft stratum underlying the structure. Another relates to a grain silo at Oxford (Cooling, 1948), illustrated in Fig. 5. Here it will be noticed that the variations in the grain load are closely reflected in the movements of the foundation.

The purpose for which a settlement study is carried out will, of course, vary with the site and problem. If site conditions are fairly straightforward, observations of settlement, apart from confirming that the movements are within the limits that the structure can withstand, may have their chief value as a means of checking existing theories and indicating the limits of their application. From the time Terzaghi published his theory of consolidation of clay

Fig. 2. Observations on Waterloo Bridge

and demonstrated that on the basis of this theory and that using the results of tests on soil samples, a quantitative forecast of the settlements of buildings underlain by a clay layer could be made, the value of reliable records of observed settlements on actual buildings had been enhanced. Those case records which permit a valid comparison between computed and observed settlements have played a major part in indicating the degree of applicability of theoretical methods of analysis and in pointing the way to improvements in the theoretical approach. In recent years a number of Papers describing settlement studies on particular structures have been published and a survey of comparisons between calculated and observed settlements of structures on clay was given by MacDonald and Skempton (1955). Fig. 6 is based on results given in this Paper and shows the agreement between calculated and observed net final settlements for eighteen case records, six of which related to measurements with which B.R.S. was concerned, most of them when Skempton was with us. These show that current methods of calculating net final settlements give results of adequate accuracy for engineering purposes. Other conclusions arrived at in the Paper were: (a) the current method of computing immediate settlement was correct in principle although attention needed to be directed towards improved determination of Young's modulus in soft clays; (b) the rate of settlement is usually underestimated and there was a need for further evaluation of three-dimensional consolidation theory. Full-scale observations including pore-pressure measurements as well as settlement records would give valuable information on item (b).

From the point of view of structural damage, it is the differential settlement which is of

Fig. 3. Chelmsford Gasholder

prime importance and consequently the general arrangement of observation points in a structure should be such as to give a fairly clear picture of the pattern and contours of differential settlements. Skempton and MacDonald (1956) gave a comprehensive survey and analysis of existing data on the distortion of some ninety-eight buildings and established tentative values for damage limits in terms of angular distortion and in terms of maximum and differential settlements. This permitted them to suggest allowable distortions as a basis for design for certain types of structure.

In a practical appraisal of the results of a theoretical settlement analysis it is important to be able to indicate the permissible distortion which a structure can withstand. As is well known, the stiffness of a structure determines how, and to what extent, differential settlements can occur and important information which is required is the magnitude of the stresses occurring in the structure. Settlement observations would, therefore, be much more valuable

Fig. 4. Chelmsford Gasholder—relation between settlement and depth to gravel

Fig. 5. Oxford grain silo. Response of settlement to varying grain load

Fig. 6. Comparison of calculated and observed net final settlements

if they were linked with the measurement of stresses and strains in different parts of the structure. One such investigation has been carried out by B.R.S. on the Government office block in Whitehall Gardens (Wood and Mainstone, 1955), but many further comparisons between estimated and observed foundation movements and the corresponding strains and displacements in buildings are required before this difficult problem can begin to be resolved.

Incidentally, a water level system was employed for recording differential settlements in this building. This method was thought to be more convenient within the confines of the basement and although the accuracy of measurement was adequate, certain difficulties were encountered. One important source of error was found to be due to air pressure differences resulting from air conditioning in the building. For instance, near a large meeting hall, differences up to about 5 mm were observed when the doors to the hall were opened. This difficulty can be overcome by having a continuous air line connecting the tops of the wall water gauges and the reservoir.

In addition to the problems concerned with the settlement of buildings as a result of structural load there are problems, especially with clay soils, where the ground can move either as a result of seasonal change in weather conditions or due to industrial processes. A number of investigations carried out by B.R.S. on structures such as boiler houses, brick kilns, etc., founded on clay have shown the extent of settlement due to heat transmitted to the ground and have pointed the way to foundations designs which avoid this trouble (Cooling and Ward, 1948); similarly with the problem of frost-heave under cold storage rooms (Cooling and Ward, 1944). The effect of the seasonal movement of clay soils on shallow foundations is a world-wide problem which manifests itself in different ways according to the climate. Field observations in many parts of the world are helping to solve the problem. In semi-arid regions

swelling of the clay under the foundations has given rise to structural damage whereas in Great Britain most trouble is experienced due to shrinkage. The seasonal movements of both roads and houses due to the drying effect of nearby trees and vegetation has also been the subject of study at B.R.S. and at the Road Research Laboratory, and a number of Papers have been written on this subject (Ward, 1948; Croney and Ward, 1948). However, B.R.S. have recently had occasion to make observations on two structures which exhibited long-term heave of the foundations due to wetting of desiccated clays. These sites had previously supported the growth of large forest trees, and the time required to reach a new equilibrium has proved to be much longer than anticipated.

One was the case of a terrace block of cottages, single-storey, brick-built of 11-in. cavity wall construction. It was built at Windsor on London Clay in 1952 and cracks had appeared after 2 years and continued to increase in size over the subsequent 4 years. In 1958 we at the Station were asked to investigate what the architect thought was a stubborn case of settlement. A study of the site plan and aerial photographs taken before construction showed that two large elm trees had existed on the site near one end of the cottages. Reference points were then fixed in the building and observations of movement made with reference to two datums 20 ft deep and about 50 ft from the building. In the course of a year the observations showed that points near where the trees had been, had risen 1 cm, while points at the far end of the terrace remote from the trees had scarcely moved (Fig. 7).

The second structure was a larger one, a three-storey block 140 ft long and 37 ft wide built on a shrinkable boulder clay at Garston. Several well-established oak trees, about 8 ft in girth, were felled and removed in November 1958. The building was completed in July 1959 and levels have been taken since the start of the construction. These have shown that while in other parts of the building slight settlement has occurred, in the region where the trees had been there was a rise of about 1.25 cm; this area is still rising and the movement is continuing at a rate of about 1 mm every 2 months.

In considering future work in the broad field of settlement of structures a number of problems come to mind where more full-scale observations are still urgently needed to aid their solution. I should like to mention a few.

In the case of structures founded on deep layers of sand, reliable settlement theory is lacking and there is a need for a systematic semi-empirical approach. To give opportunities

Fig. 7. Rise of foundations due to wetting of desiccated clay

Fig. 9. Loading tests on a bored cast-in-place pile. The total load on the pile, the load on the base, and by difference the load carried by the shaft in skin friction plotted against the downward movement of the pile head in two successive loading tests

Fig. 10. Typical standpipe systems

for improvement of the design hypotheses more settlement observations on heavily loaded structures founded over sand need to be obtained.

Another problem is that of building on reclaimed land and on fills such as those resulting from open-cast mining. If measurements were taken over a period of time to record the progress of "self-consolidation" of made-ground after placing, the problem of how long it should be left before building is undertaken and the design of the proposed structures could be more confidently tackled. Mention may also be made of problems due to mining subsidence. Systematic observations of the movements of both ground and structures in mining areas are needed and the possibilities presented by the use of light flexible structures (Lacey and Swain, 1957) could be further investigated.

Another occasion when reliable full-scale measurements of settlement are likely to be useful is when a new form of foundation design is adopted; for example, the use of large

Fig. 11. Variation of ground-water pressure in underlying gravel alongside the Thames Estuary

cylinder bored piles for the foundations of new tall buildings in London introduces many new problems. When the foundation comprises a combination of bored piles and basement raft, it is not possible to assess how much is carried by the bored piles and how much by the raft. There is, at present, no sound basis for the theoretical estimation of the probable settlement of such buildings. It is therefore very encouraging to note that in a number of these cases settlement observations have been put in train. We shall all look forward to seeing these results put on record and published. In particular I think measurements of the tilting of tall buildings would be very useful.

In this connexion I should like to mention some further work which is being carried out by the B.R.S. in conjunction with the Institution's Committee on Deep Bored Cylinder Foundations. It does not involve field measurements on a full-scale structure but is concerned with the field study of an element of the structural foundation, namely, the bored cylinder with an enlarged base. Special full-scale loading tests are to be carried out in an attempt to

find what part of the load is carried by the shaft and what by the enlarged base and how the proportion varies with the settlement. Laboratory small-scale model tests have given an indication of the mechanism involved and these are being followed up by full-scale tests. A special load cell has been developed for interposing between the foot of the shaft and the base of the pile to measure the load coming on to the base. The total load is measured either by a proving ring or by special jacks. Fig. 8 shows a small prototype load cell consisting of two stiff end plates between which are placed eight small steel cylinders fitted with resistance wire gauges. These are read in groups of four to assess eccentricity of loading and the results are added arithmetically to give the aggregate load on the base of the pile. For the full-scale tests larger diameter load cells are being constructed. So far only preliminary tests for the purpose of trying out the prototype load cell have been completed and these related to a bored pile 15 in. dia., 26 ft long, with a base of the same diameter as the shaft, but it may be of interest to indicate the results obtained (Fig. 9). These show that a large proportion of the load was carried by the shaft especially at small settlements. The first part of the test was performed by incremental loading, the pile being allowed to come to virtual equilibrium before, increasing the load. At a penetration of 1.7 in. the adhesion factor α for the shaft load was 0.34 of the average shear strength and the end bearing $N_c = 7.7$. The load was removed and the pile was then pushed in at a constant rate of penetration for a further 0.6 in. giving a final value for $\alpha = 0.38$ and $N_c = 9.2$.

(b) *Pore-water pressures*

One of the principal features of modern soil mechanics is the significance attached to the influence of pore-water pressure on the mechanical behaviour of soils. The recent Pore Pressure Conference held here in 1960 (Conference on pore pressure and suction in soils), in addition to discussions of a theoretical nature, included many Papers describing field measurements of pore pressure and clearly showed that many engineers appreciated the practical importance of measurements of this kind. However, a brief review of the problem may help to emphasize the value of this kind of work.

The measurement of pore-water pressures may be required for a number of purposes. First it should be emphasized that such measurements form an essential part of a site investigation since a knowledge of the pore-water pressures in the natural ground prior to construction may point to the need for special action in design or construction. This is particularly the case in relation to the excavation and installation of deep foundations when ground-water pressures are likely to be high. Appropriate measures to deal with water inflow and the avoidance of buoyancy effects and "blows" in the excavation can then be arranged. A critical situation may also arise if an impermeable stratum covers more permeable beds below holding water under artesian pressure. In such cases "relief" wells penetrating into the permeable layer to reduce the pressure have proved useful on numerous occasions (McHaffie, 1938; Ward, 1957).

Pore pressure measurements are a valuable guide in seepage problems. While theoretical flow-nets for steady flow conditions may be drawn, conditions in the practical case may be difficult to assess since these may be affected by even minor geological features and hence it is often necessary to check values of pore-water pressure by field measurements at selected points. The First Rankine Lecture, Casagrande (1961) gave many examples of the value of pore-pressure readings in seepage problems connected with dams and made a point of emphasizing the need for more observations of this type. Observations during a controlled draw-down test at Glen Shira dam were described in a Paper by Paton and Semple (1960).

Perhaps the most important use that has been made of pore-pressure measurements is in connexion with fine-pored soils, silts and clays, where they have been applied as a means of control during construction. With such soils, economic design may demand that the stability of the structure shall be dependent upon an increase in shear strength during the construction

period. The most convenient way of inferring how the shear strength is increasing with consolidation is to measure the pore-water pressure at critical positions in the job and to follow systematically the way the pore pressure dissipates with time.

Pore-water pressures may be determined by measuring the hydrostatic height of water in a lined borehole or standpipe which is open at the top to the atmosphere, or by various types of piezometer and hydrostatic pressure cells (Cooling, 1955). The vertical standpipe is the simplest method and three variants of the system are illustrated in Fig. 10. In order to ensure that a correct reading is being obtained, it is essential to stop seepage along the outside of the pipe and the space between the standpipe and the wall of the hole must be adequately sealed above the point. Practical techniques using puddle clay, bentonite mixtures, or sometimes cement mixtures have been developed for this purpose. The hole is then back-filled to the surface. The level of the water inside the polythene tube is measured by the means of a flexible electric cable which is lowered inside the tube until contact with the water surface is registered by means of an ohmmeter (Casagrande, 1949). In certain cases it is found more convenient to push a porous cylinder into soft ground by means of a small steel tube surrounding a polythene tube. In some cases the open standpipe is converted into a closed system by connecting the upper end of the polythene tube to a Bourdon gauge or mercury manometer. This is convenient when pore pressures are high and would need a tube reaching well above ground surface to act as an open standpipe. The air purge system illustrated in Fig. 10 has also been used and is convenient for obtaining continuous records of standpipe levels as required, for instance, in sites adjacent to tidal waters.

A typical example of results obtained is illustrated in Fig. 11 which relates to a site in the marshland adjoining the Thames Estuary (Cooling and Marsland, 1953). The marsh clay was underlain by a layer of sandy gravel and measurements were taken to see how the pore pressure in this layer responded to variations in the tidal level. Points to be noted are that the tidal response decreases with the distance inland; that there is a measurable response even at $\frac{1}{2}$ mile inland; and that the time lag in the peak value of the response increases slightly with the distance inland.

While the vertical standpipe is the simplest method to use, it is only appropriate under conditions which permit easy access to the top of the pipe for taking observations and where sufficient time is available for equilibrium to be established.

A closed system using twin tube piezometers is particularly useful for observations in connexion with the construction of earth dams. One of the first investigations in which B.R.S. used this system was in connexion with the construction of the earth dam for the Usk Reservoir (Sheppard and Ayles, 1957). When the fill had reached the required level, shallow trenches were dug across the surface and piezometers (type A, Fig. 15) placed at selected points. The connecting tubes were carried along the trench to a gauge house at the toe of the dam. One Bourdon gauge was used for each piezometer point. This investigation was initiated as a research project but the results turned out to be of considerable practical significance. During the first season's construction 40 ft of boulder clay fill was placed and it was observed that very high pore pressures were recorded. During the winter months, the placing of fill was stopped and although some dissipation of pore pressure occurred it was very slow (Fig. 12). These high pore pressures gave cause for concern. Consideration was therefore given to the need to modify the design of the dam, and Professor Skempton and Dr Bishop were called in to advise. A number of open-ended pipes were installed in other parts of the bank, and these confirmed the gauge measurements. However, it was interesting to note that this simple direct method of measurement brought home the picture much more vividly to the engineers who were most impressed to see the water rise in the pipes to a level well above the top of the fill. As a result of these measurements, together with laboratory tests and analyses, a modification was made to the design by placing filter blankets consisting of a layer of crushed rock sandwiched between two layers of sandy clay. This enabled the rate of

Fig. 12. Usk Dam. Pore-pressure observations in partly completed bank

dissipation of the pore pressure to be accelerated and the dam was safely completed in 1954. This investigation for the Usk Dam represents as important an example of the use of the "diagnostic technique" as the investigation for the Chingford Dam (Cooling and Golder, 1942) does of the "post-mortem" technique.

Another form of twin-tubed piezometer (type B, Fig. 15) was used in a foundation problem relating to oil tanks to be built on a deep layer of soft alluvial clay in Kent. To study this problem a number of pore-pressure measuring points were installed at selected points in the foundation soil beneath the area on which the tank was to be built (see Fig. 13). The piezometer in this case consisted of a fine-pored hollow cylindrical pot sealed with a rubber bung through which passed two polythene tubes. These were jacked into position by means of a steel tube, which was later withdrawn, and the hole filled with bentonite slurry. The tubes connecting the points were all led *via* a horizontal trench to a gauge house nearby. The tank, 144 ft dia., was constructed over the area and test loaded by filling with water in stages. Both pore-pressure and settlement readings were taken and the results have been discussed in detail in Papers by Cooling and Gibson (1955) and by Gibson and Marsland (1960). Fig. 14 gives an indication of the results and shows rapid response of the piezometer to changes in loading. From the rate of dissipation of pore pressure it was possible to assess the rate of increase in strength of the soil under the tank load.

Oil tanks are often built over soils which have a low bearing capacity and in these cases field measurements of pore pressure not only serve a useful purpose as a control but in addition can yield data which may have a wider value for design purposes.

Many installations using the twin-tube piezometer have been placed in earth dams in Great Britain, and at the recent Pore Pressure Conference examples were given and reference also made to developments using finer pored pots and nylon tubing (Fig. 15, type C) (Bishop, Kennard and Penman, 1960). A disadvantage of the system is that gas is apt to collect, especially when the pressure at any point falls below atmospheric, and de-airing becomes necessary. Also the response time of the system may not be short enough in certain cases. For these and other reasons, electrical instruments have been developed to follow changes in water pressure by measuring the distortion of a diaphragm which can be recorded remotely. Electric resistance strain gauges have been used in many models (Boiten and Platema, 1948; U.S. Waterways Experimental Station, 1944). At B.R.S. the vibrating-wire strain gauge has been used to measure the diaphragm deflexion. A study of the response time of various types of piezometers (see Fig. 15) has been made by Penman (1960). The advantages of the diaphragm cell type are that the volume change required to measure the pressure difference can be made extremely small so that its response is rapid; there are no connecting tubes and no trouble due to air bubbles within the system. An air tube fitted to keep the pressure on the inside of the diaphragm at atmospheric pressure (Fig. 15, type E) can also be used to calibrate the instrument when installed. The cost of the electrical equipment is higher but it has been found useful for quick spot observations for exploratory purposes to check readings given by a group of simpler type piezometers.

A new type of vibrating wire piezometer developed by my colleague, W. H. Ward, is shown in Fig. 16. This uses the distortion of a curved tube, like part of a Bourdon gauge, to actuate the vibrating wire gauge and it has been found to be very sensitive and convenient to use.

Finally, mention should also be made of work which is being carried out by Croney (Croney and Coleman, 1960) and others at the Road Research Laboratory to measure the capillary potential (negative pore pressures) of foundation soils under road slabs and to record the long-term changes that take place.

Fig. 13. Position of pore-pressure points under oil tank

Fig. 14. Results of pore-pressure measurements during full-scale loading tests on oil tank

As to the future, pore-pressure measurements represent such an obviously powerful new technique that there seems no doubt that all these methods will be fully exploited and developed further.

(c) *Earth pressure and related problems*

The measurement of earth pressures and the related measurements of deformation and displacement of earth-retaining structures represents a field of endeavour in which a great deal remains to be done.

Considering first the question of deformation of earth-retaining structures, much useful information can be obtained from fairly simple measurements.

It is interesting to note that Terzaghi and Peck (1948, p. 327) in considering the design of retaining walls emphasized the need for long-term observations on the movements of walls and periodic measurements of the pore-water pressure at several suitably located points in the

Fig. 15. Types of field piezometers

backfill as well as tests on the backfill prior to construction. They concluded with the comment: "Measurements of earth pressure against the back of the wall are desirable but not essential."

There have been very few observations of the movements of mass retaining walls, but mention may be made of the long-term observations of the old retaining wall at Kensal Green made by the London, Midland and Scottish Railway, which show the value of such measurements (Barbey, 1944).

The problem of the measurement of distortion of sheet-pile walls has received attention, mainly in the U.S.A. and in Germany, but there is still need for further full-scale observations. The Building Research Station is, at the moment, engaged in carrying out measurements on a sheet-pile wall at Avonmouth which will be referred to later.

A special case in which a small deformation assumes large importance is that of the lined tunnel. In tunnels up to about 15 ft dia. changes in distances between opposite walls can be measured by means of a metal rod or tube with a screw micrometer or dial gauge fixed at one end (Fig. 17). Thermometers must be fitted both to the measuring rod and to the reference bar and temperature corrections made in the usual way. Typical results are given in Fig. 18 which show measurements made in a small Post Office railway tunnel. The tunnel was 7 ft dia., located at a depth of 55 ft in London Clay and built of cast-iron segments which were grouted in the usual way. It will be noted that after construction the shape of the tunnel changed slowly with time, the vertical diameter decreasing slightly and the horizontal diameter increasing slightly. Similar results have also been obtained with observations on 12-ft-6-in.-dia. tunnels for the new Victoria Line and indeed all observations on tunnels in clay have shown a similar behaviour.

Brief mention may also be made of measurements to follow the distortion of the Bakerloo

Line tunnels as the result of construction work at South Bank for the new Shell building which was immediately over the tunnels. Here the removal of load by excavation caused a distortion of the tunnels in the opposite sense, the vertical diameters increasing slightly, about 0.2 in. in 12 ft, and the horizontal diameters decreasing slightly. A detailed description of this work and a discussion of the findings have been given in a recent Paper by Ward (1961).

In special cases, instruments have been constructed to measure the changes in diameter of a water tunnel when it was full with water under pressure. Such an instrument was developed at the Building Research Station in co-operation with the Metropolitan Water Board and is described in a Paper by Tattersall, Wakeling, and Ward (1955). The results of these measurements will be mentioned later.

When it comes to measuring earth pressure the question of instruments looms large. A great deal of work has been carried out in different parts of the world on the development of a suitable soil pressure cell and on the study of the important fundamental problem of the measurement of stress within a soil mass under various loading conditions. This problem is of such wide scope that I do not propose to include it.

At the B.R.S. we have been mainly concerned with the measurement of loads and pressures against earth retaining structures, or counter pressures on foundations.

As indicated by Ward (1961) the determination of loads and pressures on earth retaining structures has been based on one or other of two principles: "Advantage may be taken of the elastic nature of the structure itself and from measurements of its deformation under load, the forces causing that deformation may be arrived at by calculation. Alternatively, appropriate parts of the structure are interrupted by the insertion of load or earth pressure gauges so that the forces received by the members pass through the gauges and are measured."

The appropriate method depends on the circumstances but in most cases measurements require the use of specially designed instruments of a type not normally employed in civil engineering practice. Simple methods were tried originally. Golder (1948) carried out an investigation to measure the loads in the timber struts of an

Fig. 16. Diagram of B.R.S. vibrating-wire piezometer

DIAMETER CHANGES IN 7' DIAM. C.I. TUNNEL

Fig. 18. Typical measurements of diameter changes in newly constructed tunnel in London Clay

Fig. 19. Sectional view of vibrating wire-load gauge

Fig. 8. Prototype load cell (14 in. dia.)

Fig. 17. Measurement of changes in tunnel diameter with micrometer tube

Fig. 22. New type of vibrating-wire strain gauge. Two vibrating wires fixed to a pair of posts to measure both direct and bending stresses

Fig. 24. Instrumentation of new type of cast-iron tunnel lining before installation in experimental length of tunnel

Fig. 25. Vibrating-wire strain gauge recessed into surface of a precast tunnel segment

Fig. 26. Avonmouth. Vibrating-wire strain gauges fitted on either side of tie-rod to measure load in the rod

Fig. 27. A steel sheet pile, 65 ft long, being equipped with twelve twin wire strain gauges in laboratory before transport and installation in dock wall

Fig. 28. Diaphragm type of earth-pressure gauge with a vibrating-wire anchored across the diaphragm for bolting to the surface of a steel pile

excavation in clay behind a wall at Park Village East, near Euston. A simple direct method was employed by using the strut itself as the elastic member and measuring the strain by means of a gauge rod fitted with a screw micrometer; the accuracy was not high and the method was superseded. Next a mechanical beam gauge was used as a load measuring unit placed at the end of a strut in a timbered excavation. While this type of gauge proved reliable, the accuracy was not very high and the method still had the disadvantage that it was necessary to get down to the place where the unit was fixed before a reading could be taken. While hydraulic gauges and proving rings have been used for short-term work, they have not been seriously considered for long-term observations owing to the possibility of breakdown due to leakage or other reasons.

A later development which has proved much more useful is that of the vibrating wire load gauge which need not be larger than 5 in. dia. and about 5 in. long and with little variation in overall size can be made to measure loads from about 1 to 100 tons. Fig. 19 shows many features of the design of the instrument which is now being used extensively with very satisfactory results. The stability of the gauge has proved to be very good even after being in use for a number of years and the change in zero load readings has been negligible.

The load gauge has been used in a variety of problems and a few examples will be given. An early investigation related to a deep cofferdam in soft alluvial clay at Shellhaven in the Thames Estuary. Load gauges were used to measure the thrust transmitted from sheet piling to the walings. A section of the sheeting comprising eleven contiguous sheet piles on one side of the cofferdam was supported against the walings at the level of each of the three frames solely by load-gauges. Fig. 20 shows typical results of measurements on the top frame of the three: it shows the individual load gauge reading and the changes that took place as the result of various constructional operations. A detailed account of the work has been published in a Paper by Skempton and Ward (1952) which gives the results of both soil tests and observations and also outlines an interpretation of the results in the light of the calculated earth pressures.

Another investigation which was carried out in collaboration with the Metropolitan Water Board concerned a small 9-ft-dia. water tunnel with its axis 90 ft below ground in London Clay, in which a new technique of lining was used. The tunnel was lined with wedge-shaped concrete segments which were jacked into place. Special segments were made to accommodate a number of radial pressure gauges comprising a load gauge bearing against a steel face plate which formed part of the earth face of the segment. In addition, in four of the rings load gauges were installed to measure the circumferential load in the ring. The tunnel was later filled with water under a head of about 140 ft and most of the load gauges continued to function giving results such as those indicated in Fig. 21. These results showed that the net earth pressure on the tunnel lining decreased with increasing internal water pressure and increased again as the water pressure was reduced. Since the net radial pressure decreased by only about two-thirds of the applied internal water pressure, none of the test rings ever became completely unstressed; also the changes in diameter of the tunnel were small. These results provided invaluable information for the design and helped the engineers in arriving at a decision to omit a steel pipe lining, thus saving considerable cost. A detailed account of this work is given in a Paper by Tattersall, Wakeling, and Ward (1955).

Load gauges have also been used for foundation problems. For instance, H. B. Sutherland of Glasgow University used B.R.S. vibrating wire load gauges to measure foundation pressure distribution under two adjacent column footings in a large building (Sutherland and Lindsay, 1961). This work enabled the pattern of load distribution found to be compared with the theoretical pattern for rigid footings on a cohesive soil.

Similar developments have occurred with strain gauges. In 1942 the first measurements by B.R.S. were made on cast-iron linings in a tunnel being constructed at Belsize Park. For these, Skempton used a detachable gauge of the Whittemore type, the punch marks being

Fig. 20. Typical load gauge readings in top frame of steel sheet-pile cofferdam at Shellhaven

Fig. 21. Typical results of changes in radial earth pressure and in tunnel diameter with head of water in a tunnel lined with concrete segments. (Taken from Paper by Tattersall, Wakeling, and Ward, 1955)

made as soon as the segments were erected with subsequent readings taken at intervals to show the increase of stress with time (Groves, 1943). While gauges of this type can be very handy, their accuracy is not very high when used under field conditions. Attention was therefore directed to permanently attached strain gauges which would be fixed to a structure. Two types were investigated, the stick-on electrical resistance gauge and the vibrating wire gauge. The resistance type is very convenient to use under laboratory conditions where the zero drift can be checked and leads can be kept intact; however, when used in the field the method was found to be very vulnerable except when used in special field instruments where adequate protection could be provided. With the vibrating-wire gauge, a fine steel wire is clamped to two rigid posts which are screwed directly into the structure. This type of strain gauge has been used extensively for field work by B.R.S. It is fairly cheap and convenient to install and experience has proved it to be not only robust but also very stable and reliable over a period of several years. It has also been found particularly suitable for remote reading because long electrical cables can be used without difficulty, although it is necessary to ensure that there is not too much inductance between leads to different instruments; in some cases it has been found better and cheaper to use a small cable which can be switched by electro-magnetic selectors placed near the group of gauges. In fact, a very small telephone exchange is installed adjacent to each group and in this way, 200 gauges have been read using a six-core cable.

Recent developments have added to the value of the method. An electronic oscillator has been developed as a source of known frequency (Ward and Cheney, 1960) which added greatly to the accuracy and rapidity of measurement. It has also enabled shorter gauge lengths to be used as, for instance, in the pore-pressure gauge mentioned earlier. In addition, a new type of gauge has been developed using two wires mounted in the same posts and spaced one above the other (Fig. 22). From the readings of this gauge it is possible to estimate both direct and bending stress. Results from this gauge will be mentioned later.

For many years now a programme of field investigation has been in progress by B.R.S. to study stresses in linings of tunnels constructed in the London Clay. The research has required to take advantage of any constructional work that has been proceeding and much useful data have been obtained. It will not be possible to deal with this work comprehensively but a few cases will be quoted. In some cases measurements have been made of the increase in stress and the change in shape of the linings in a newly constructed grouted tunnel. Fig. 23 shows the build-up with time of the average stress at axis level of the small 7-ft-dia. tunnel for which the deformation measurements were given in Fig. 18. The shape of this curve is again typical of the behaviour of a tunnel in London Clay lined with cast-iron segments and grouted up. Measurements have also been made of the load in segmental linings which were jacked into place against the clay without the use of grout. These observations showed that the initial loads were primarily a function of the jacking pressure and that there is a slow build-up of pressure afterwards gradually approaching the full overburden pressure. In other cases, gauges have been fitted to the linings of existing tunnels, some of them 50 years old, and the stresses in them were estimated by means of strain gauges which recorded changes on the release of load when the linings were dismantled (Ward and Chaplin, 1957). Strains were measured during the process of excavating the clay around the lining and finally when the lining had been dismantled. In general, the results indicated that when the tunnel is well separated from a neighbouring tunnel, the final stresses are those attributable to the full overburden acting hydrostatically. When tunnels are spaced less than 1 diameter apart, significant bending stresses are produced in the earlier constructed tunnel by the operation involved in building another tunnel nearby.

At the present time, work is being carried out in co-operation with the Chief Civil Engineer's Department of London Transport on an experimental length of tunnel recently completed. Measurements are being made to follow the structural performance of two new types of tunnel

AVERAGE STRESS IN 7' DIAM. C.I. TUNNEL AT AXIS LEVEL

Fig. 23. Increase of average stress with time after construction of tunnel in London Clay

linings which are jacked into place directly against the clay without the use of grout. One segmental lining is made of cast-iron, and to measure stress changes an experimental ring has been equipped by fitting two of the new twin wire strain gauges mentioned above, to each of the six segments. Fig. 24 is a photograph showing the segments being instrumented and the gauges read before being built into the tunnel. The other segmental lining is made of concrete and has fourteen segments to a ring. To measure the stress changes, a series of pairs of vibrating-wire strain gauges of another new type has been cast into inner and outer faces of these segments (Fig. 25). In the concrete lining, a good proportion of the strain experienced is expected to be due to moisture movements and creep of the concrete and the experimental tunnel ring will be unloaded at some suitable time after construction in order to measure the structural stresses. Progressive changes in stress and distortion are being observed but it is too early to comment on the results.

This kind of field work is, of course, of a long-term nature and it cannot be expected to have more than a very gradual influence on design and construction methods.

Finally, a brief indication may be given of the instrumentation being used for an investigation which is at present being carried out in collaboration with the Port of Bristol Authority. A series of measurements are being made of earth pressures, forces, stresses, and displacements in a large anchored sheet-pile dock wall. The measurements are being made on a section 35 ft long anchored with six tie rods, the load in each rod being measured by vibrating-wire strain gauges (Fig. 26). The sheet piles of this wall are 65 ft long and three of them have been instrumented. The fitting of the instruments was carried out in the laboratory and the sheet piles were later transported to the site and driven into the construction (Fig. 27). Two of the piles carry a series of diaphragm-type earth pressure cells on the outside of the pile. The general features of the earth pressure cell, which is based on the vibrating-wire principle, is shown in Fig. 28. An instrument of this type was developed by the Norwegian Geotechnical Institute, after discussion with B.R.S., and its use in measurements on a sheet pile structure for the Oslo Subway was described in Papers at the Brussels Conference (Kjell, 1958). The third pile is fitted with a number of the new twin wire strain gauges. These three piles and four others have lengths of square tube welded to one side, and a remote reading inclinometer which slides inside the tubes is used to measure the deflected form of the piles. Observations

To sum up the following points may be made. Fully documented case records which permit a comparison between forecast and performance are invaluable for the purpose of indicating the direction in which design procedure can be improved. Even without a quantitative forecast, field measurements are of considerable practical value in their own right, since

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Fig. 29. Avonmouth. Typical results after first stage of dredging. Bending moments obtained from readings of twin wire strain gauges

every problem presents its own special features and quantitative data can give a sharper edge to experience. When used as part of the "observational procedure" they form the most powerful tool which soil mechanics has produced for resolving difficult soil problems.

Techniques need not be over-elaborate but the programme of field work should be carefully planned and systematically carried out. In many cases such work could be readily arranged and should become a more common feature in engineering practice. It is admitted that in some problems special equipment and techniques may be needed as, for instance, for the measurement of earth pressure. In such cases consideration should be given to providing facilities for such work when suitable opportunities come along and it is desirable that the engineer should undertake this task. He should explain to the client that while designs are based on the best advice available, it is only common prudence to provide for measurements which will confirm that the structure is behaving as expected. The words of Terzaghi when addressing the 1957 Conference should be remembered: "I have become more and more impressed by the importance of never missing an opportunity to find out by direct observation the difference between forecasts and the real developments."

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Proposing a vote of thanks to Dr Cooling, **Professor K. L. Nash** said that when the British National Committee heard that Dr Cooling had accepted their invitation to give the Lecture they were truly delighted, and it was quite obvious from the reception Dr Cooling had received that all those present were very grateful. The Lecture would be extremely valuable, not only to those who had listened to it, but also to the very much wider audience it would reach in *Géotechnique*.

Mr Glossop, seconding the vote of thanks, said that, as all must realize, the history of Dr Cooling's career was linked closely with the history of soil mechanics in Great Britain. Dr Cooling had devoted himself to the subject and had been associated with it almost from the start.

About 1925 the British Association for the Advancement of Science had formed an Earth Pressure Committee, of which the Chairman was that fine engineer, the late Mr F. E. Wentworth-Shields. As a result of his influence, research on earth pressure was started at Oxford University, where Professor C. F. Jenkin was then Professor of Engineering. When Professor Jenkin retired from that Chair in 1931, he was provided with a laboratory at the Building Research Station, where he continued his work, which was on strictly classical lines, and consisted of small-scale experiments, and took into account the effect of dilatency. His results² were published in the Proceedings of the Institution of Civil Engineers.

In 1933 Professor Jenkin retired from the Building Research Station, and Dr. Cooling took over the laboratory. His terms of reference included certain extra-mural studies for the Ministry of Transport.

By that time, of course, Terzaghi's *Erdbaumechanik* had been published, as well as several of his Papers in American journals. Dr Cooling was almost certainly the first person in Great Britain to react to that powerful stimulus. He had started work on the study of the physical properties of soils, as they actually occurred in nature; he had introduced the use of Atterberg's Limits, and the other Index Property Tests; and he had initiated work on the measurement of shear strength of soils.

The first International Conference on Soil Mechanics was held at Harvard University in 1936, and Dr Cooling had been one of the only two Englishmen to attend. On his return he wrote a report on the Conference, which had drawn attention to the importance of the new subject. His Department was enlarged, and he was joined by two young men not long out of their universities—A. W. Skempton in 1936, and H. Q. Golder in 1937. They had made an effective and happy team, and under the guidance of Dr Cooling research was started on several lines, all of which had proved of value to the engineering profession.

Those, indeed, were the heroic days of soil mechanics in Great Britain—with high thinking,

² C. F. Jenkin, 1932. "The pressure on retaining walls." *Min. Proc. Instn civ. Engrs*, 234 : 103-233 (inc. discussion and correspondence).

low living, and great enthusiasm! Since they had not been provided with a laboratory assistant, the first task each morning, for the two junior members of the staff, was to wash and dry the weighing bottles which had been used for moisture content determinations on the previous day.

During the next few years Dr Cooling and his team not only mastered a new subject, and initiated research into it, but also laid the foundation of the English school of Soil Mechanics, which was one of which they could all be proud. Although during that early period their work was little known in the industry, Dr Cooling's laboratory soon became a rallying point for a generation of young engineers who were attracted by the subject.

It was fair to say that nearly every engineer who was interested in, or was practising, soil mechanics up to the time of the war, had either received training in Dr Cooling's laboratory or had visited it for discussion.

Mr Glossop, himself, had many happy memories of days spent there and he was glad to have the opportunity of thanking Dr Cooling for the help and advice which he had given to him at that time, and which certainly had had a decisive effect on his career.

During the next few years a number of Papers were published, all of value and of interest to civil engineers, which showed a balance of advanced theory and of engineering practice which had characterized all the work that had come from Dr Cooling's laboratory.

The value of his organization became apparent to practising engineers in 1937, when a slip occurred on the bank of the William Girling Reservoir at Chingford. Sir George Burt, who was then Chairman of the Building Research Board, consulted Dr Cooling, and he, with his two assistants, investigated the failure and demonstrated its cause.

For that time this was an advanced piece of work, and included considerations of effective stress. Mr Glossop added that the opinion of three little-known young men from a Government laboratory was not at once accepted, but shortly afterwards Professor Terzaghi arrived from Vienna to advise on the problem, and his report showed their analysis to be correct.

That was a turning point in the history of soil mechanics in Great Britain. Professor Terzaghi's outstanding knowledge, experience, and personality impressed all who met him with the importance of the subject which will always be associated with his name, and it soon became known that a highly competent laboratory, devoted to soil mechanics, existed in Great Britain.

Dr Cooling had remained in charge of the Soil Mechanics Section of the Building Research Station, and under his direction it had continued to carry out investigations in the field, and to publish useful Papers. Indeed, its activities had always been marked by practical approach and close contact with the civil engineering industry.

In addition to running his own Department, Dr Cooling had carried out a great deal of public work, and there was no phase of the subject in which he had not given valuable service to their profession.

Dr L. F. Cooling, in a brief reply, thanked Mr Glossop for his very kind remarks. He said that it was true that soil mechanics in Great Britain had travelled a long way since the early days. He recalled a reply which was given by his colleague at that time, Dr Skempton, at the end of the second of the Lectures on "Principles and Applications of Soil Mechanics," in which Dr Skempton had remarked that the progress in the subject had been in no small measure due to the sympathetic reception from the civil engineering profession in Great Britain and from the Institution of Civil Engineers in particular. He reiterated that sentiment.

In thanking all present for the appreciative way in which his Lecture had been received, Dr Cooling said that he wished also to acknowledge the help that he had received from his colleagues, particularly Dr W. H. Ward.