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DIVISION OF BUILDING RESEARCH

INSTRUMENTATION FOR A CONSOLIDATION STUDY OF A
CLAY DEPOSIT BENEATH AN EMBANKMENT

BY

K. N. BURN

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BY
K. N. BURN, B.Eng., M.Sc.

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INSTRUMENTATION FOR A CONSOLIDATION STUDY OF A CLAY DEPOSIT BENEATH AN EMBANKMENT

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SYNOPSIS

In order to instrument a deep clay deposit for measurements of consolidation beneath a 23-ft-high embankment, it was necessary to develop a settlement gauge which could be installed just below the natural ground surface before the embankment was constructed.

The Paper presents the considerations involved in the design of such a gauge and describes the one finally adopted. Measurements of settlements between the natural ground surface and reference elevations within the clay deposit are made by determining electrical resistances which are proportional to vertical displacements. This is accomplished by the simple gearing of a chain and sprocket to the shaft of a spirally wound potentiometer. By a judicious choice of potentiometer and sprocket pitch diameter it is possible to determine displacements to an accuracy of 0.05 in. or 1.3 mm.

The field installation is described in detail and, finally, time-settlement curves for four gauges are shown.

Afin de mesurer scientifiquement le tassement d'un profond dépôt d'argile situé sous un remblai mesurant 23 pieds de haut il a fallu concevoir une jauge spéciale qu'on pourrait installer sous la surface du terrain naturel avant de faire le remblai.

On passe en revue les considérations dont on a tenu compte dans la mise au point de ce type d'instrument et on décrit la jauge qu'on a finalement adoptée. La mesure des tassements produits entre la surface du sol naturel et les points de référence choisis à différentes hauteurs dans le dépôt s'est effectuée en déterminant les résistances électriques lesquelles sont proportionnelles aux déplacements verticaux. On a réalisé cette mesure en engrenant simplement une galle à l'axe d'un potentiomètre hélicoïde. En choisissant comme il faut le diamètre du pas on a pu déterminer les déplacements à 0.05 pouce ou 1.3 mm près.

L'installation utilisée pour la mesure est décrite en détails et l'étude est complétée par des courbes de tassement établies en fonction du temps.

INTRODUCTION

One of the most common problems faced by foundation engineers is that of determining the maximum allowable foundation load that may be applied to the soil without producing detrimental settlements. To compute this allowable load, the results of laboratory tests on samples of the subsoil are used. Because it is necessary in many cases to make some simplifying assumptions in computing settlements, a comparison with observed settlements often shows a discrepancy. It is only by making such comparisons, however, that the theory can be improved.

Settlement studies of this type have been conducted by the Division of Building Research of the National Research Council, Canada. With one exception, the comparison of computed and measured settlements has been of limited value because the foundation loads, and therefore the resulting settlements have been small and the possibility of observational errors relatively large. In the one case where foundation loads were heavy and the settlements large, the comparison has been obscured by an incomplete history of settlement and complicated by footing loads which varied considerably in magnitude from one part of the building to another (Crawford, 1953).¹ One other important factor influencing the validity of such a study is the effect of sample disturbance on the results of laboratory testing.

Possibly the most suitable conditions for a study of this nature are those produced by the construction of an earth embankment. Such a uniform load, applied over a large area probably comes as close to theoretical load assumptions as may ever be encountered in actual construction. A high embankment implies a heavy load, the possibility of large settlements if the soil is fairly compressible, and, therefore, relatively small experimental errors.

The opportunity to make this study presented itself when plans were completed for the building of a limited access east-west highway through the city of Ottawa, Canada. Two miles beyond the eastern limits of the city the proposed "throughway" crosses the present provincial highway to Montreal. Here, a high-level crossing was planned by the Ontario

¹ See Reference on p. 142

Department of Highways, which required the placing of wide approach embankments with a finished grade as much as 23 ft above the natural ground surface. The deep underlying soil was known to be part of the local widespread glacial marine deposit known as Leda clay. Because of its unusual physical properties this soil is currently the object of intensive engineering studies.

Permission to install instruments to measure settlements was obtained from the Department of Highways with the stipulation that there would be no interference with the contractors' operations. This complicated the design of the installation required to measure consolidation, but it did reduce the chances of damage which were inherent in attempting to place vertical rods in the embankment as it was being constructed.

PLANNING

The selection of the exact site for the installation was primarily influenced by the desirability of having a maximum increase in load over a fairly large area. A 75-ft section was chosen between stations 183 + 75 and 184 + 50, where the embankment was to be 23 ft high and about 210 ft wide at the base with side slopes at 2:1. It was decided to measure the total consolidation of the clay deposit, and the rate of consolidation with depth in three or four layers.

Before a method of measuring consolidation could be adopted it was necessary to estimate the magnitude of total consolidation to be expected. Based on estimates for the weight of the fill and the depth and compressibility of the deposit, with certain simplifying assumptions about the uniformity of stress distribution beneath the load, an approximate total settlement of about 1.5 ft was predicted. A margin of 50% was added to this to allow for difficulties in vertical adjustment during installation. The instrument to measure the consolidation of the deposit was finally designed for a vertical displacement of 27 in. Instruments to measure the consolidation of layers within the deposit were designed for vertical displacements proportional to the thickness of each particular layer.

DEVELOPMENT, DESIGN, AND CONSTRUCTION

A commercial firm became interested in the instrument-design problem. It had recently developed a small electronic disk capable of measuring angular displacements with considerable accuracy. It was thought that if the vertical movements could be linked to angular displacements by using such a unit, readings of satisfactory accuracy could be obtained. The difficulties involved in machining and mounting, however, soon cancelled this idea.

The principle of measuring change in conductance of a solenoid with displacement of a core was discarded because of the possible changes in magnetic fields around the instruments in the ground. Autosyn motors were considered unsuitable because of the difficulty of determining the number of revolutions through which they had turned. Hydraulic systems were considered to be susceptible to a number of difficulties which made their successful use very questionable. If a leak or break in the line occurred, a complete and irreparable breakdown of the system would result.

The use of micro-switches running in a series of parallel coded tracks was considered in some detail, but this method was eventually discarded for the following reasons. The fineness of adjustment required for the micro-switches to function properly was considered too difficult a task to perform in the field during installation. Once installed, there was no assurance that accurate alignment could be maintained under unknown conditions of lateral pressures. Eight separate tracks with a micro-switch running in each would have been necessary to measure the estimated settlement in increments of $\frac{1}{8}$ in. Each micro-switch requires three electrical leads which would involve a tedious job of splicing in the field. Any mistakes in connexions would lead to an incorrect transcription from the code and would be difficult errors to trace. The failure of one micro-switch could also cause a breakdown of the measuring system.

A design incorporating the measurement of displacement by means of proportional electrical resistances was finally adopted and used. Settlement of the entire deposit is being measured by determining the relative movement between a floating plate at the natural ground surface and the upper end of a rod extending to the surface from a point of reference at the bottom of the deposit. Similarly, the consolidation of a number of layers is being obtained by making measurements between the natural ground surface and various reference points within the deposit.

The principle of the instrumentation design is simple in that it utilizes a chain-and-sprocket system to translate vertical displacements to rotational movements. By gearing one of the sprockets to a spirally wound variable electrical resistance, readings in ohms can be converted to total vertical displacement (Figs 1 and 2).

The proper choice of sprocket-pitch diameter and number of turns in the spirally wound resistance permits full use of the electrical resistance and maximum accuracy of the system. Because the chain is quite flexible, there is no need to make and maintain precise adjustments in alignment. To avoid the development of stresses on the spindles of the sprockets, the method of attaching the chain at the top of the reference rod was arranged so that there could be no horizontal thrust. This was done by using long pins which could pass snugly through links of the chain and permit a minimum amount of vertical play but comparatively free movement in a horizontal direction.

With the instruments being used to measure resistance, it is thought that readings can be repeated well within $\pm 5 \Omega$ or ± 0.016 in. The accuracy of linearity of each variable resistance is within 0.05%, or $\pm 5 \Omega$ or ± 0.016 in. The error then may be ± 0.032 in. or $\frac{1}{32}$ in. If the play in gears and linkage is further considered the accuracy may be reduced to an error perhaps 50% higher, making the total error ± 0.05 in. Under a constant stress or pull from one direction this error may be assumed smaller since the slack would be taken up at the beginning of consolidation but, thereafter, would be considerably reduced.

Fig. 1. Schematic drawing of the settlement gauge showing its components

Fig. 2. Measuring system of the settlement gauge, showing the linkage of the reference rod to the spiral wound electrical resistance

Fig. 3. Settlement gauge showing the installation of the measuring system above the guide chamber

Fig. 4. The measuring system encased in the upper chamber with electrical cables attached

Fig. 5. Top of the completed settlement gauge showing the yoke and bearing plates

Fig. 6. Spiral earth anchor of the type used as reference points within the clay deposit

Three separate chambers were used to enclose the completed settlement gauge; an upper one containing two separate and independent measuring systems; a centre chamber required only for alignment of the measuring systems on the reference rod; and a lower chamber to keep the upper section of the reference rod, which is to move into the gauge as consolidation progresses, free of particles and rust which might cause jamming of the instrument (Fig. 1).

The size of the upper chamber was governed by the space required for the measuring systems which fitted comfortably into a 6-in.-dia. pipe. The centre chamber maintained this diameter for ease of construction and rigidity, and the lower chamber was designed to provide only a small annular space for grease around the reference rod.

Standard-size pipe fittings were used throughout, to minimize workshop operations, and bolted together using gaskets to make the chambers watertight. As a further precaution against the seepage of water into the gauges, subsequent rusting and possible failure of the electrical system, all the chambers were filled with oil insoluble in water.

The question of performance of the resistances when submerged in oil was also considered. Experience had shown that they would certainly function properly for a few months in transformer oil, but it was not known whether their lifetime under such conditions would extend throughout the desired 5 or 6 years. Tests had shown that the casing for the variable resistance was insoluble in transformer oil, but the long-term effect of the oil on contact resistances is still unknown. It is considered, however, that if the presence of oil over a period of 4 or 5 months does not noticeably alter the readings of resistance, then the effect at the end of 5 or 6 years will probably also be negligible. (To check this effect, a variable resistance of this type is being kept submerged in transformer oil in the laboratory.)

If the system were tightly sealed, a hydraulic pressure would develop on the top of the reference rod as consolidation occurred. To prevent this a flexible neoprene seal was provided at the lower end of the instrument, which would permit only a small pressure to build up before releasing some oil or grease.

The bearing plates (Fig. 5), which transmit the vertical movement from the soil to the casing of the instrument, were designed to prevent the development of lateral pressure on the settlement gauge which might lead to jamming of the instrument on the centre rod. The yoke which straddles the construction trench is free to rotate in a vertical plane through its axis; the bearing plates are free to rotate in vertical planes at right angles to the first plane, so that any slight differences in consolidation would be averaged out and could be transmitted only in a vertical direction to the settlement gauge. These bearing plates were located about 1 ft below the surface to protect them from heavy concentrated wheel loads at the beginning of construction of the embankment.

The lower end of the longest centre rod (the one designed to measure consolidation in the full depth of the deposit) was provided with a small foot to rest on the underlying material. The lower ends of the other centre rods (those instruments designed to measure consolidation to intermediate depths) were comprised of spiral earth anchors turned into place down pilot holes.

The centre rods were kept to a minimum size to reduce the weight on the earth anchors and to reduce load transfer from the consolidating layers to the rods by keeping the surface area to a minimum. Casing could have been used to free the centre rods of any vertical loads, but this would have meant a larger surface area causing a reduction in consolidation in the immediate vicinity of the gauges. It is thought that the pilot holes will remain open but even if the soil closes in around the rods the exposed surface area is too small to develop significant loads.

SAMPLING AND FIELD VANE TESTING

Two test holes were made at the site chosen for the installation of the consolidation gauges. The first was used for determining the undrained shear strength by vane tests in connexion

with a more general study of the properties of the post-glacial marine soil (Leda clay). The results of these tests show that the material was deposited under fairly uniform conditions; the shear strengths were found to increase linearly with depth. The purpose of the second borehole was to procure samples for laboratory testing for comparison with field test results and a more intensive study of the compressibility of the soil.

INSTALLATION AND INSTRUMENTATION

To install the instruments, four 3-in.-dia. holes were bored at 20-ft spacing, 12 ft from the centre line of the road and in a line parallel with it. The hole bored for field vane testing was used for placing the reference rod of the instrument which was to measure consolidation of the full depth of the deposit. The 1½-in.-dia. rod was lowered down the hole in 20-ft sections and tapped to ensure good seating.

The other three holes acted as pilot holes into which 9-in.-dia. spiral earth anchors were turned (Figs 1 and 6). These were coupled to lengths of 1½-in.-dia. pipe locked together by bolts through the couplings. This was necessary because the upper section of pipe had to be turned off later to be replaced by a special section which fitted into the settlement gauge.

Next, 2-ft-wide trenches were dug at right angles to the centre-line of the road by a tractor back-hoe working away from the centre rods on both sides. These trenches were dug to various depths depending upon the length of the instrument to be installed. Ground-water conditions made some pumping necessary and the trenches were shored to enable men to work in them safely.

The upper sections of the reference rods were removed and replaced by specially machined and cadmium-plated rods which fitted into the gauges. The lower two sections of the gauges were pre-assembled, slipped over the rods and blocked to the correct elevation. The lower chambers were then filled with oil and capped with specially machined blind flanges. Next the working parts of the gauges were mounted on these flanges and the chains carefully positioned with respect to contact on the variable resistances before being attached to the centre rods. This was necessary to assure adequate range in resistance for the expected vertical displacement (Fig. 3).

Before installing the casing for the upper section of each gauge, the electrical cables were threaded through two separate holes, each fitted with a hose-type connector (Fig. 4). They were then slipped into place and gasketed and bolted to the lower sections. After the electrical connexions had been made and insulated the upper sections were filled with transformer oil and the caps bolted into place.

Shallow cuts were made at either side of the trench adjacent to the gauges to recess the yokes and bearing plates, ensuring that these would rest entirely on undisturbed material (Fig. 5). In some places, however, it was necessary to tamp a thin layer of damp sand on the bottom of the shallow cuts in order to ensure a good seating surface. (The yokes were designed to span the width of the trench made by the back-hoe, but during the installation of the gauges small amounts of soil fell away from the edges of the trenches reducing the area of undisturbed soil on which the reference plates rested. This could have been avoided by designing the yokes for a wider span.)

The gauges were then hung temporarily by the yokes until backfilling was completed (Fig. 5). Unfortunately a pneumatic tamper was not available for compaction. Instead of replacing the clay soil and tamping by hand which could have resulted in low densities, hand-compacted sand was used. The result was a fairly dense fill which would resist lateral pressures from the walls of the trenches and reduce to a minimum settlement of the reference pads caused by plastic flow in the soil. The sand backfill will affect the drainage path for the consolidating soil and, therefore, the rate of settlement, but it should have little effect on the total settlement.

A fifth settlement gauge was installed just beneath the toe of the embankment. This may

be retrieved later for examination if the gauges cease to function satisfactorily. The cables from each of these instruments were led to the toe of the fill and connected to a switch box. Readings of resistance are taken periodically to determine the displacements which have taken place.

It was also considered desirable to obtain records of total settlement transversely across the embankment at the site. Before construction began, therefore, concrete pads 4 ft square and about 8 in. thick were cast flush with the ground surface and spaced so that drilling from the edge of the pavement at the top of the completed embankment would permit the lowering of rods of measured length to these reference levels. The dishing effect of settlement of the ground surface could be obtained by observing the elevations at the tops of these rods with an engineer's level.

RESULTS TO DATE

The embankment as it now stands was constructed in two stages because of weather conditions. After a height of about 10 ft was reached, work was suspended because of rain until the first heavy frost (in December) enabled the resumption of construction and the embankment was brought quickly up to subgrade level. The full load of embankment will not be attained, however, until it is advanced another 100 ft to the abutments of an overpass structure, and a further 3 or 4 ft of material are added to bring it up to finished grade. The results so far are justified in that they indicate satisfactory operation of the gauges. By the subtraction of readings the amounts of consolidation in the four layers between the reference anchors and the natural ground surface are obtained. This shows that the amount of consolidation decreases with depth according to the usual pattern.

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Fig. 7. Time-settlement curves

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