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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Use of Ground Strain Measurements in Civil Engineering

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The use of ground strain measurements in civil engineering

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Strains of the ground are of increasing importance in civil engineering for as projects get larger the strains they induce often exceed the natural strains. For the engineer to ensure the safety and stability of a structure and its surroundings he must be able to predict and, if need be, control the strains. Our approach is to measure the deformations in specific cases and to use the information to gain a better understanding of ground behaviour, to determine parameters of the ground to use in prediction and to check the safety and design of the project. It demands simple and sensitive instruments that can be used reliably under rigorous field conditions. Examples of recent studies are given.

Introduction

To ensure the safety and stability of civil engineering projects such as dams, excavations and large buildings the engineer needs to be able to predict, and if necessary, control the local ground strains, in particular those caused by the new construction itself, for they may be quite large and arise generally whenever the surface topography is altered, or from mining, from the loading of the project, or from changing the 'climate' near or in the ground. Our approach is to measure the deformations of the structure and the local ground in specific cases and to use the information: (*a*) to gain a better understanding of ground behaviour; (*b*) to determine parameters for future predictions by the detailed analyses possible with a computer; (*c*) as a check on the design and safety of the project. The traditional method of ground investigation and design relies heavily on laboratory tests carried out on small cores to determine the ground parameters and the use of rather simple theoretical models of ground behaviour to predict strain. This approach has severe limitations. For example, the core tests are not representative of a large ground mass, and simple theoretical models neglect substantial inhomogeneity and anisotropy of the ground.

Our method is illustrated here by means of a few examples of ground deformation measurements associated with constructional loading and excavation, the interpretation of the measurements and their use for prediction.

Equipment, accuracy and duration of measurement

We need in our method simple, reliable and sensitive measuring equipment for wide use under rigorous field conditions. Normal optical surveying methods are not always sufficiently accurate, and use has been made of the Mekometer (Froome 1971) and precise water levels. Reference is made to some specific equipment in the examples that follow.

The local displacements caused by the civil engineering project should be measured with respect to the most stable reference marks in undisturbed ground and an accuracy of better than 1 mm is often necessary. Natural displacements, especially hydrologic and temperature effects, need to be known or avoided in selecting reference points.

Strains must often be measured to 10^{-6} and even 10^{-7} over distances varying from tens of millimetres to tens of metres; tilts are measured to 10^{-7} radians over tens of metres.

Measurements of displacement and strain extend from a few hours to tens of years or more and it is therefore most important that measuring equipment be stable and that recording devices be referred frequently to simple, readily available standards of length and frequency.

Load-deformation properties of a large site in Norfolk for a proposed proton accelerator

The accelerator had very stringent requirements for ground stability and deformation under load, so a site of some 9×5 km was selected on the Chalk – the hardest rock in southeast England, at Mundford, Norfolk. The load-deformation properties of the chalk were assessed entirely in the field (Ward, Burland & Gallois 1968). First the Chalk over the whole site was graded visually into five classes of stiffness, I to V. Secondly, very detailed measurements were made of the deformation properties of the various grades of chalk at one point, using a water-filled tank 18.3 m diameter and 18.3 m high to load the ground up to 200 kN/m^2. Thirdly, plate-loading tests (0.86 m diameter) were made at various depths alongside the tank and elsewhere.

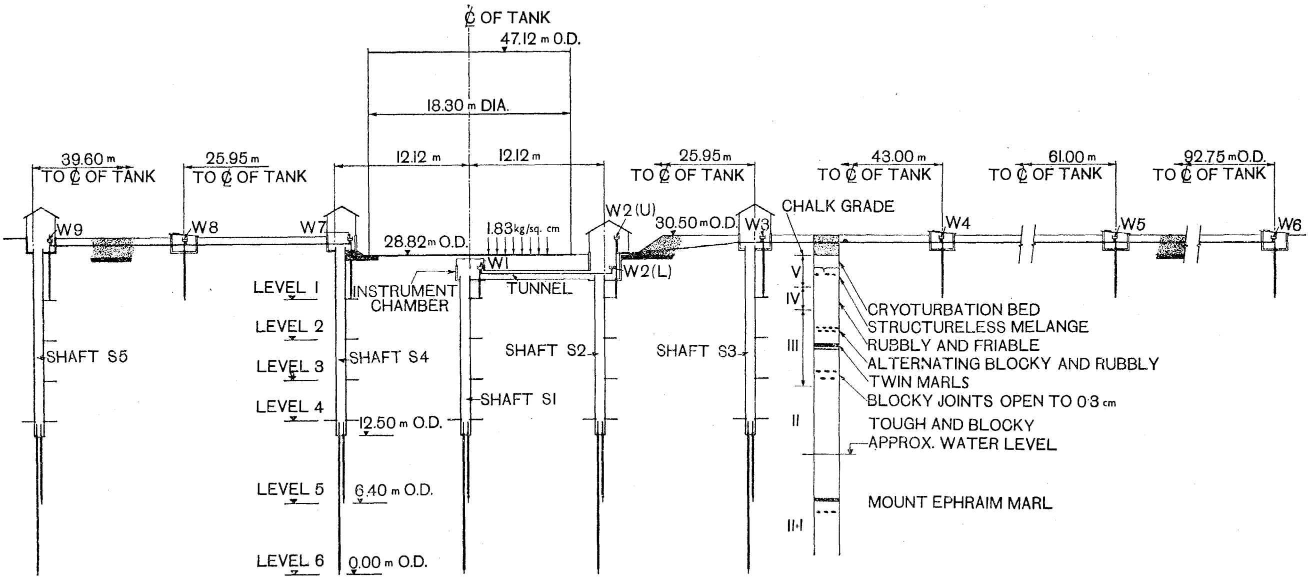

Figure 1. Vertical section through the shafts and water-level gauge positions at the tank site, showing levels of vertical displacement measurements and the grading of the Chalk.

Figure 1 shows a section through the ground under and around the tank. The vertical displacements between each of six levels in five shafts were obtained to 5×10^{-3} mm by comparing the intervals with the lengths of steel tube (below the water table) or invar wires (above the water table) using inductive transducers. The displacements of the uppermost levels were found by comparison with a system of precise water-level gauges consisting of closed interconnected pots each containing a stainless steel float, the position of which was determined to between 0.1 and 0.02 mm with an inductive transducer. The data were recorded automatically and were processed by a computer.

In a short-term loading test the tank was filled in 37 h, remained full for 4.5 days and was emptied in 23 h, and it was found that the vertical deflexions at various levels under and outside the tank were everywhere proportional to the load. The immediate deflexions in all except

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grade V chalk effectively disappeared on unloading. It is a very useful and practical result to find elastic deformation for such a highly jointed rock mass.

A simple Boussinesq calculation for the surface settlement profile considerably overestimates the deflexions outside the tank. Accordingly, a detailed finite element elastic analysis was made, Young's modulus being varied with depth to obtain a best fit to the deflexions at all levels beneath the centre of the tank (Burland, Sills & Gibson 1973), see figure 2. The good agreement with the plate-loading tests should be noted. Realistic stiffness values could then be assigned and the load-deformation characteristics of the whole site were established.

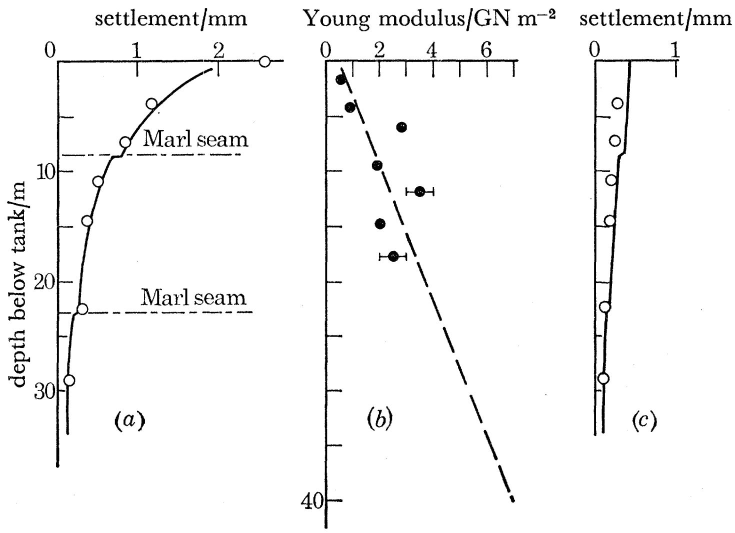

FIGURE 2. Measured and calculated settlements at various depths: (*a*) Beneath the tank centre, and (*c*) at shafts 2 and 4 just outside the tank. (*b*) Distribution of the Young modulus with depth. ○, Measured settlement; ●, plate-loading tests; — —, ——, finite element analysis.

A second cycle of loading lasting a year was carried out to assess the creep properties of the various grades of chalk. Settlement occurred only between levels 1 and 3 beneath the tank, whereas between levels 3 and 6 beneath the tank, and at all levels outside the tank, very small vertical extensions were measured, the strain outside the tank in a period of 4 months being 4×10^{-5}. The cause was the steady seasonal rise in ground water of about 3 m during this period reducing the effective vertical stress in the ground. This result was used to estimate the stiffness of the ground for small long-term changes in stress.

It appears that chalk is a very much better foundation material than had been supposed hitherto on the basis of laboratory tests on small cores.

Deformation of the ground and tunnels beneath the Shell Centre, London

One of the large buildings to be constructed in London soon after the war was the Shell Centre (Measor & Williams 1962). An area of some 210 m × 110 m was excavated to 12 m and a tower 28 storeys high with 12 storey wings was built. The Bakerloo Line tunnels traverse the site from north to south between the deep pile foundations for the buildings and only about 1 m beneath the basement (see figure 3).

Observations of strains and displacements have been made in the tunnel (Ward 1961) to assist London Transport in maintaining the safety of the tunnels, to measure the distortions of the 57-year-old segmental cast-iron tunnel linings when unloaded, and to obtain design data on ground movements associated with excavation and construction of future large building foundations in London Clay.

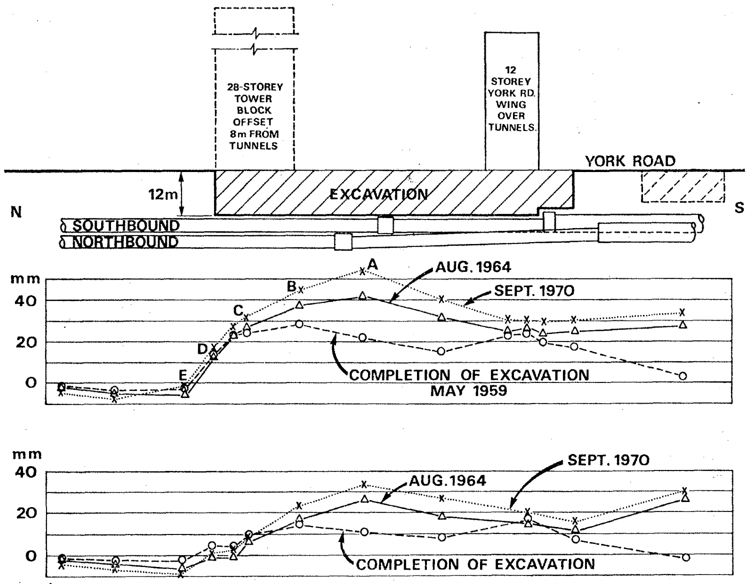

FIGURE 3. Section across excavation along Bakerloo Line tunnels, showing short and long-term vertical displacements of the crowns of the south-bound (upper graph) and north-bound (lower graph) tunnels.

The strains across horizontal and vertical diameters and over a succession of lengths parallel to the side of the tunnel have been measured with micrometer rods to about $\pm 1.5 \times 10^{-5}$, local circumferential strains in the linings at about 220 locations have been measured with vibrating-wire strain gauges to about $\pm 2 \times 10^{-6}$ strain and the vertical displacements of the crowns of the tunnels have been measured by precision levelling to about ± 0.5 mm.

The excavation temporarily reduced the total vertical stress on the underlying 30 m of London Clay by some 200 kN/m². The load of the building is much less and only under the tower, which lay some 8 m to one side of the tunnels, was the effective vertical stress increased above its original value. Over the tunnels, there was a final net reduction in effective vertical stress of some 150 kN/m², except for a short length under the 12-storey York Road wing where the nominal net change in stress was zero.

The deformation of the ground shown in figure 3 comprises short-term 'elastic' movements which take place as the excavation is made and do not involve volume change or drainage of the relatively impervious clays, and long-term movements associated with volume change and readjustment of the pore water pressures. Thus, on completion of the excavation in May 1959, the crown of the south-bound tunnel had risen by up to 28 mm and the north-bound by 16 mm, while vertical long-term displacements of the crowns of the tunnels have continued beneath the excavated area and in 1970 amounted to as much as 53 mm at point A in the crown of the south-bound tunnel.

Outside the excavation the tunnels settled initially and were compressed vertically, but long-term swelling is spreading gradually outside the excavated area.

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Deformations of the ground around Britannic House, London

In the previous case and in an earlier one (Serota & Jennings 1959) vertical movements across a horizontal plane were measured as the ground was unloaded and calculations could only be made of the average vertical stiffness of the underlying ground. But it is necessary to be able to predict horizontal as well as vertical strains of the ground around building excavations, particularly as neighbouring buildings are not normally designed to resist horizontal strains.

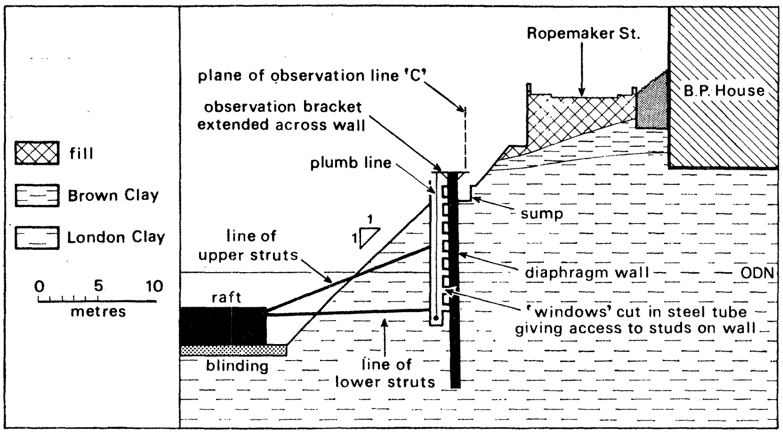

Figure 4. Section through north wall of basement excavation at Britannic House.

The basement excavation for Britannic House (Cole & Burland 1972) was some 110 m × 65 m in area and up to 18 m deep. After the upper 4 m had been removed, the ground yet to be excavated was surrounded by a reinforced concrete wall constructed by a fairly new method known as the bentonite-mud trenching process whereby a steady hydrostatic pressure is maintained on the ground during construction and in consequence very little ground movement is caused in London Clay.

The horizontal movement of the top of the north wall was measured by theodolite with respect to targets remote from the site and the inward tilt was measured with respect to a fine steel plumb line suspended in a lined borehole just in front of the wall (see figure 4). All horizontal displacements were measured to an accuracy of about 1 mm.

The inward movement of the wall and the settlement of the neighbouring street were slow in the early stages of excavation, accelerated rapidly as excavation approached full depth, but slowed down before the upper struts were placed, by which time a 20 mm wide crack had appeared between the ground and the top rear face of the wall.

A finite element analysis was carried out assuming the ground to behave as a linear elastic material having a stiffness varying with depth. The initial total vertical stress in the ground was assumed to be proportional to depth and the initial total horizontal stress was taken to be

$$\sigma_h = K_0\,(\sigma_v - u) + u,$$

where σ_v is the total vertical stress, u is the pore water pressure, and K_0 is the coefficient of earth pressure at rest.

The variation of u with depth was measured on the site. No direct measurements of K_0 are available, but from laboratory tests on London Clay (Skempton 1961; Bishop, Webb & Lewin

1965) a value of K_0 varying linearly from about 3.5 to 2.5 between the top and bottom of the London Clay was adopted. The analysis revealed a strong increase in stiffness with depth in the London Clay with values much greater than obtained from laboratory tests on cores.

Figure 5 shows the predicted displacement vectors outside and beneath the wall on 21 July 1963; it can be seen that the horizontal displacements at the surface outside the excavation are two to three times as large as the vertical displacements.

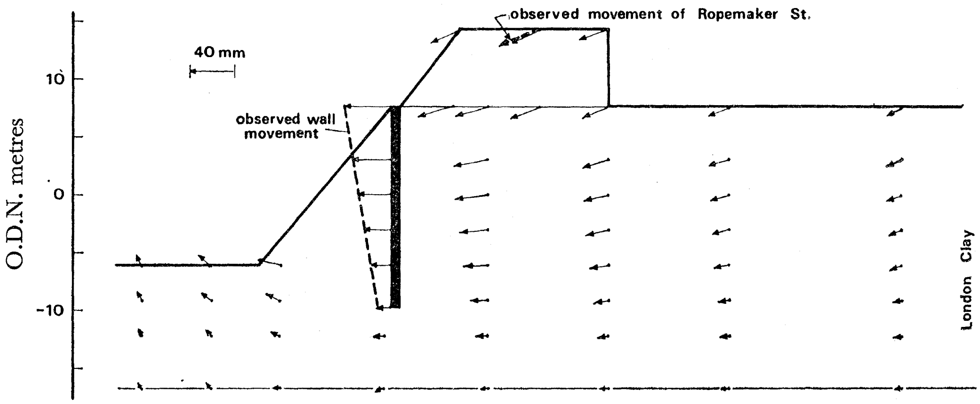

Figure 5. Predicted displacements associated with the observed wall movement on 21 July. Note comparison between observed and predicted movement of the street.

Prediction of ground deformations for other large basement excavations in London Clay

The field deformation data on the London Clay are steadily being added to, but even with the few yet available it is possible to start predicting the deformations of the ground for new large basement excavations in the London Clay, and that has been done in the last two years for the new Barbican Arts Centre in the City of London which is surrounded by three tower blocks, for the new central Y.M.C.A. building and for an underground car park at Westminster (figure 6) close to several important buildings. The retaining wall of the car park is first built around the site by the bentonite-mud trenching method. At the same time the columns which later support the floors are founded on bored piles below the bottom of the future excavation. The upper floor is constructed on the ground surface and provides the uppermost lateral support for the walls; excavation then proceeds in five stages, a floor being built at the end of each stage.

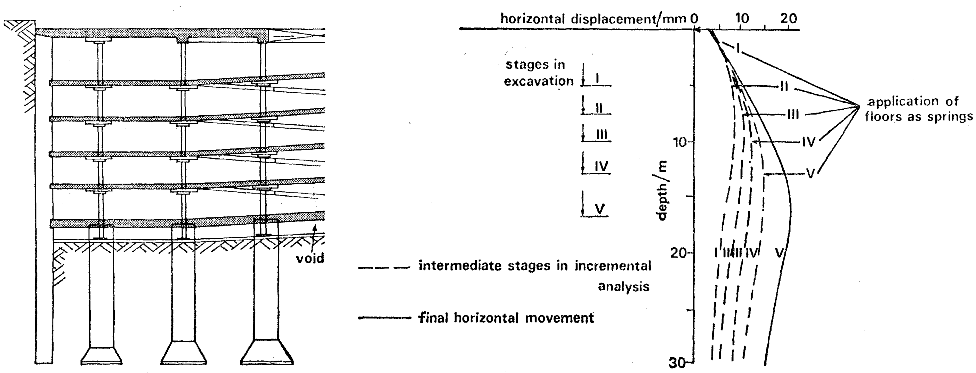

Figure 6. Car park at Westminster showing construction stages of excavation and corresponding horizontal displacements of the retaining wall.

The incremental unloading of the clay and the elastic support of the walls by the floors were modelled in the finite element analysis. The predicted horizontal displacements of the wall at each stage of excavation (figure 6) shows that significant yielding occurs beneath the level of excavation.

A comprehensive set of displacement and strain measurements to be made in the neighbourhood should increase our understanding of ground behaviour in the London area, and will enable a check to be kept on the design and safety of the project. A new magnetic borehole extensometer (Burland, Moore & Smith 1972) will be used to measure the vertical displacements beneath the car park as it is excavated, and the horizontal displacements of the walls will be measured by a remote-reading borehole inclinometer.

Deformation of Scammonden Dam during construction

Scammonden Dam, 70 m high, is of rockfill construction with a clay core and at the time of completion in 1969 was the highest in Britain.

The displacements of the rockfill downstream of the clay core were measured (Penman, Burland & Charles 1971) at some 47 positions at four elevations on the central cross-section during its construction. At each elevation a plastic pipe, passing through steel plates at each measurement position, was laid in the dam. The elevation (to 3 mm) and horizontal position (to 2 mm) of each metal plate was determined relative to gauge houses on the downstream slope of the dam as construction proceeded, by means of a compressed-air motor which towed a measuring tape, an inductive steel-plate detector, and the overflow end of a water-filled U-tube up the pipe when readings were required.

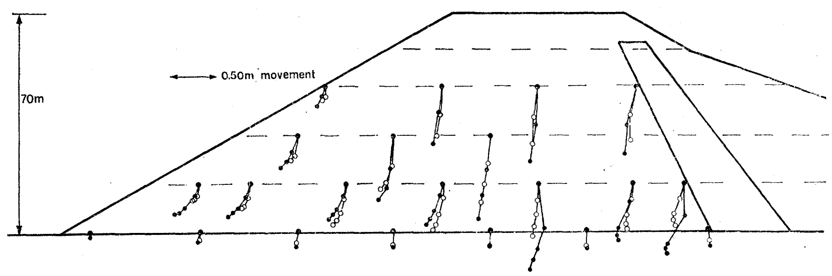

Figure 7. Comparison of observed (–●–) and predicted (–○–) displacements of Scammonden Dam during construction. Each vector corresponds to the movement associated with the placement of a higher layer except on the dam base where the total movement is shown.

The displacement of each gauge house was measured to 2 mm relative to a reference pillar founded on hard rock well downstream of the dam, using a Mekometer for horizontal displacements and precise levelling for vertical displacements.

A simple linear-elastic finite element analysis has been made which models the construction in successive layers, each layer adding load to the underlying material as well as stiffness to the structure as a whole (Penman *et al.* 1971).

Although most materials seldom respond linearly and reversibly to loading, satisfactory predictions can often be made by elastic theory provided suitable elastic parameters are chosen (Penman *et al.* 1971). Some of the predicted and observed displacements are plotted as vectors in figure 7. Considering the simplifications and assumptions made in the analysis it can be seen that the overall agreement is very satisfactory. The fact that the deformations are not symmetrical about the centreline of the dam is due to the presence of the clay core of weaker material and its position.

Conclusions

Most of the deformations we have presented will be regarded by geophysicists as 'noise'. It will be evident that the deformations and strains caused in the ground by civil engineers are of considerable magnitude and duration, even when the projects are safe and stable for most practical purposes. At the same time, however, they can be predicted with some success even though the site conditions are often complex. In order to reduce 'noise' problems geophysicists probably need to pay more attention to the location of their sensitive instruments for detecting natural strains of the Earth. When mounted within and for considerable distances from apparently stable structures, such as tunnels, they will need to be monitored.

From the engineering point of view the measurement of ground strains followed by analysis using modern numerical techniques provides a reliable method of obtaining the properties of the ground in the mass. The examples demonstrate that the stiffness of the ground usually increases significantly with depth and that this has a profound influence on the ground displacements induced by engineering structures.

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