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Use of a Penetrometer for Site Investigation and Compaction Control at Perth, W.A.

BY

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Summary.—This paper describes the development and calibration of a falling weight penetrometer of suitable size for easy use in the field.

The usefulness of such an instrument for *in-situ* testing of sandy soils in Perth, Western Australia, areas is discussed both in relation to obtaining data for design purposes and for the control of compaction in accordance with specified requirements.

1.—Introduction.

Sounding rods or penetrometers have been used for many years as an aid in site investigations mainly to give some indication of density and consistency of the various soils. Much has been published on this subject. Refs. 4, 6, 9 and 11 provide a brief introduction to the subject.

As a result of the very considerable amount of field work it has been established that there is, for sand and gravels a clearly defined relationship between driving resistance and relative density for a particular size and type of rod and method of driving. The standard Penetration Test using the 140-lb. weight falling 30 in. on the 1⅜ in. I.D. 2 in. O.D. Split Spoon Sampler has been correlated with Relative Density (Refs. 3, 6). Many attempts have been made to relate the driving resistance of some other form of penetrometer to the so called "Standard" (Ref. 5).

Perusal of the literature shows that penetrometers have been assembled in many forms to suit the particular job in hand. There is in fact no such thing as a truly "standard penetrometer" and it is difficult to imagine that such an instrument could be devised for general use. Many factors have to be considered, such as whether deep or shallow sounding is required, the grain size of the material and the driving equipment available.

The Perth areas of Western Australia, and the Swan Coastal Plain is predominantly sand for some considerable depth below the surface (Ref. 1). As a result many structures are founded on sand and most projects include sand compaction. In recent years the latter type of work has become increasingly important and large scale levelling and compacting of sand is now carried out frequently using vibrating rollers. All this has led to the need for a rapid method of assessing the in-place density. A sounding rod is the obvious choice as a rapid, convenient, inexpensive control device. This paper describes the development of an instrument for use in the Perth area together with its calibration and some experiences with it in the field. An extension of its use to the estimate of bearing capacity and settlement of foundations is illustrated in the Appendix.

2.—Penetrometer Selected and its Calibration.

The sounding rod selected for use in Perth sands is a modification of the Country Roads Board of Victoria penetrometer (Ref. 7). The conical tip has been replaced by a blunt end, either as a removable tip, or the rod cut off square. Basically the instrument consists of a 33-in. length of ⅝ in. diameter rod driven with a 20-lb. weight falling 2 ft. For convenience it is made in two sections and the weight is shaped for easier lifting. The use of longer rods with the same driving attachment is also possible. Details of the instrument are given in Fig. 1. The model marketed in Perth is constructed of cadmium plated mild steel and may be considered the "consultants' model". Simpler, less refined versions are obviously possible.

Having selected this device as being the most convenient for the purpose in mind, laboratory experiments were undertaken to observe the effect of the main variables, density and moisture content, on the driving resistance. Other minor variables such as height of drop and type of tips, and the effect of surcharge were also considered. The sand chosen then for these experiments is what may be considered as an "average Perth sand". It has angular quartz particles well graded as shown in Fig. 2. Its sphericity number is 0.78 and roundness 0.46 (Ref. 2).

The sand was compacted to selected densities and moisture contents in a 2 ft. by 2 ft. by 3 ft. high box made of steel forms as used for concrete work. Densities ranged from 0 per cent to 80 per cent relative density and moisture contents from 0 to 12.5 per cent. The compaction was carried out in layers, after care-

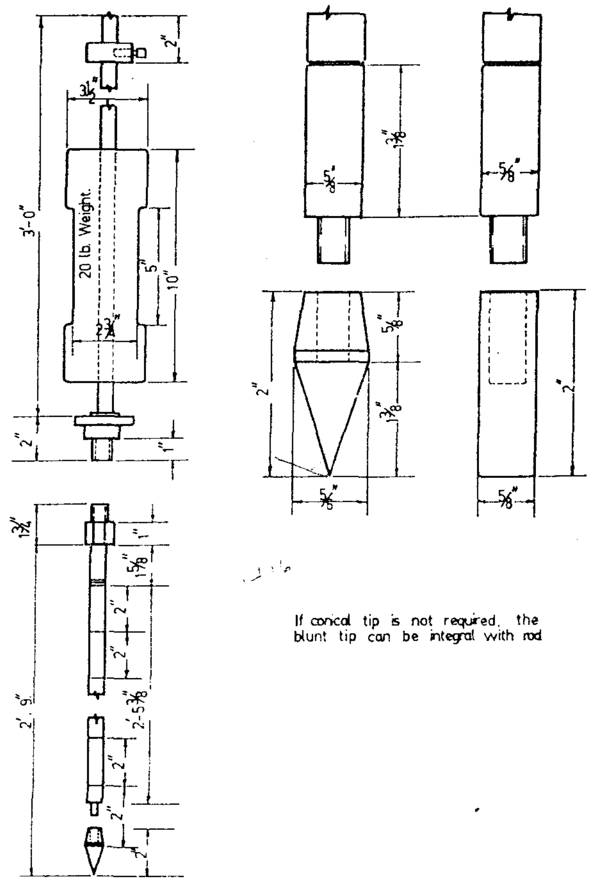

Fig. 1.—*Detailed Dimensions of the Falling Weight Penetrometer.*

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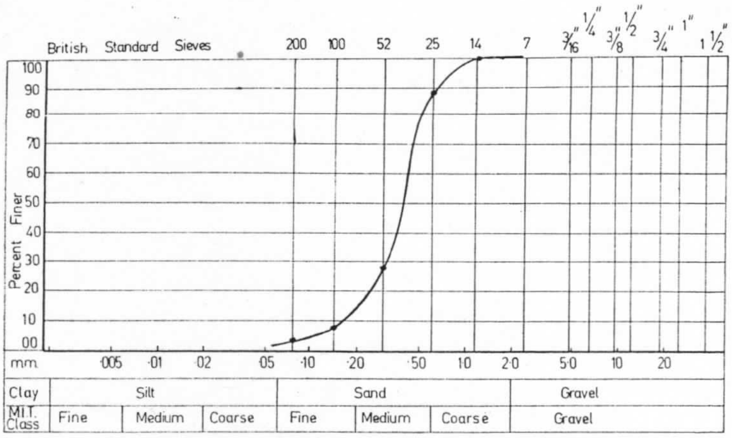

Fig. 2.—Grading Curve of a Typical Perth Sand.

fully weighing the batches which were mixed in a concrete mixer. Despite the care taken it was found that tests in the centre of the box always gave driving resistances greater than at the corners. This was found to be due to lower density in the corners. Despite the fact that the variations were in the order of only 1 per cent of the unit weight being aimed at the variation was magnified in the relative density and hence the driving resistance. Five determinations were made with each sample prepared, keeping a minimum of 4 in. between test positions. Fig. 3 shows a test in progress.

Fig. 3.—A Calibration Test in Progress.

The maximum and minimum void ratios for the relative density determinations were established in simple laboratory tests. For the loose state the dry sand was gently poured into a 4 in. dia. by 5 in. high container through a funnel. This gave 92.8 lb./cu. ft. For the dense state the sand was poured into water in layers, rodding each layer and tapping the mold. This produced a dry density of 114.6 lb./cu. ft. Continuous vibrating of the mold over a long period produced slightly higher maximum density but for practical reasons the simpler procedure was preferred.

In order to assess the effect of high water table the box was sealed and the voids filled with water from the bottom. The driving resistance for this submerged case at 80 per cent relative density was found to be between one third and half that at the maximum moisture content for the same density under free drainage conditions.

Typical results of the tests are presented in Figs. 4 to 6. Fig. 4 shows the effect of height of drop for relative densities of 20 per cent and 40 per cent and indicates that driving resistance is more or less proportional to height of drop except at the lower densities with greater drop, where the penetration exceeds one foot per blow.

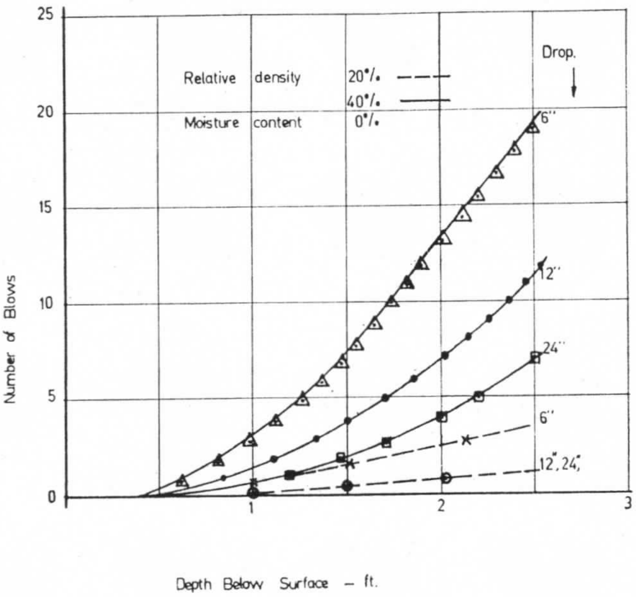

Fig. 4.—The Effect of Height of Drop.

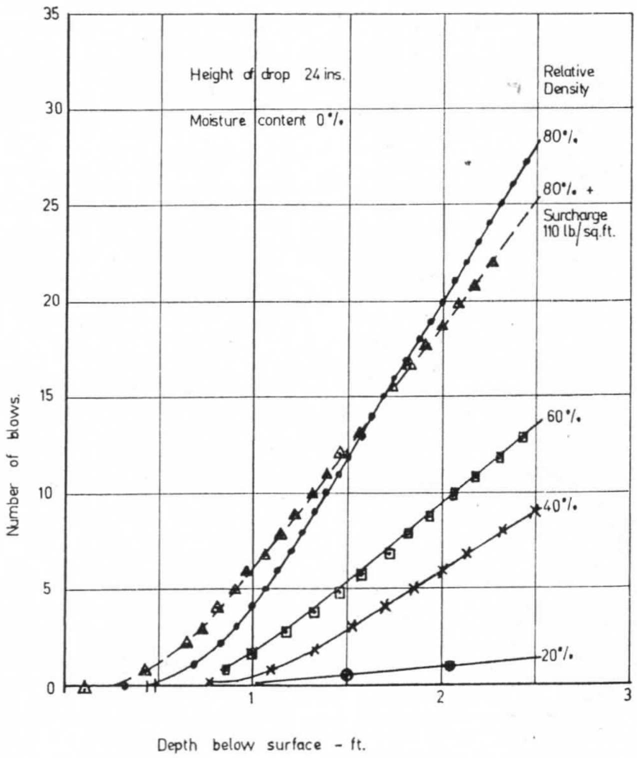

Fig. 5.—The Depth-Blows Relationship for Different Relative Densities.

Fig. 5 illustrates relationships between relative density, depth of penetration, and the number of blows. It can be seen that there is an almost linear relationship between blows and depth below surface for depths beyond about 6 in. A typical test result for surcharge weights on the surface surrounding the penetrometer is plotted on this figure and shows that surcharge does not change the number of blows but tends to make the resistance assume a constant value nearer to the surface. A typical result of plotting of blows per foot against relative density for a constant moisture content is shown in Fig. 6. Driving resistances with blunt and conical tips were substantially the same. Assuming a linear relationship between blows per foot and depth commencing at a depth of 6 in. below the surface for the densities generally encountered (40 per cent relative density and over) the calibration graph in Fig. 7 was derived.

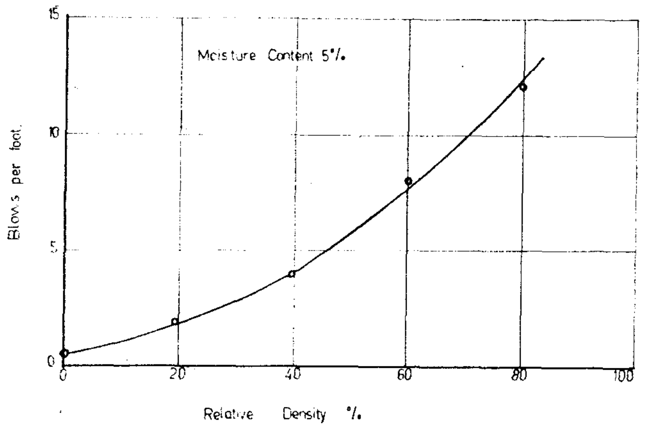

Fig. 6.—*Driving Resistance-Relative Density Relationship for Constant Moisture Content.*

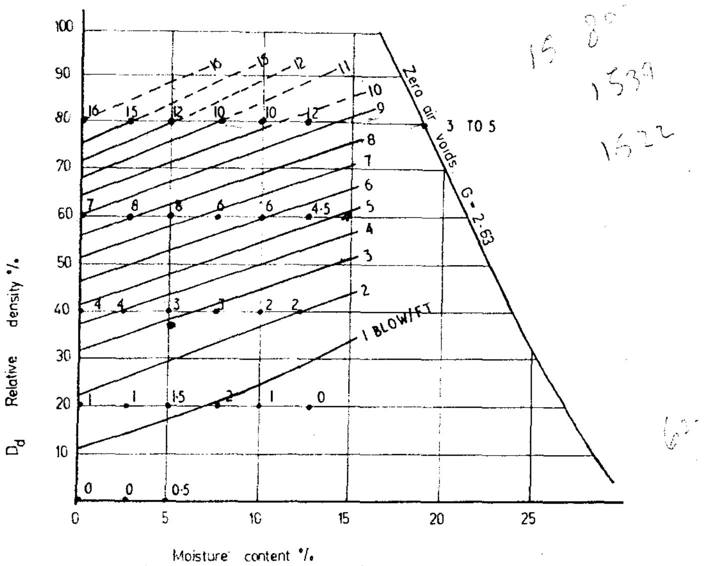

Fig. 7.—*Calibration Chart.*

Fig. 8 shows the relationship between relative density, density ratio and dry density for the "average Perth sand" used in the calibration.

The density in terms of lb./cu. ft. has little significance except for the particular sand used in the calibration and either relative density or density ratio (Ref. 8) is to be preferred for general application.

Since void ratio is not commonly used in the field of earthwork compaction, the term density ratio, which is very similar to relative density, is to be preferred in specification writing and in discussions with contractors. In technical discussions and research work in foundation engineering, the use of relative density is more applicable.

$$D_d\% = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100 \qquad D_\gamma = \frac{\gamma - \gamma_{min}}{\gamma_{max} - \gamma_{min}}$$

e = void ratio γ = dry density

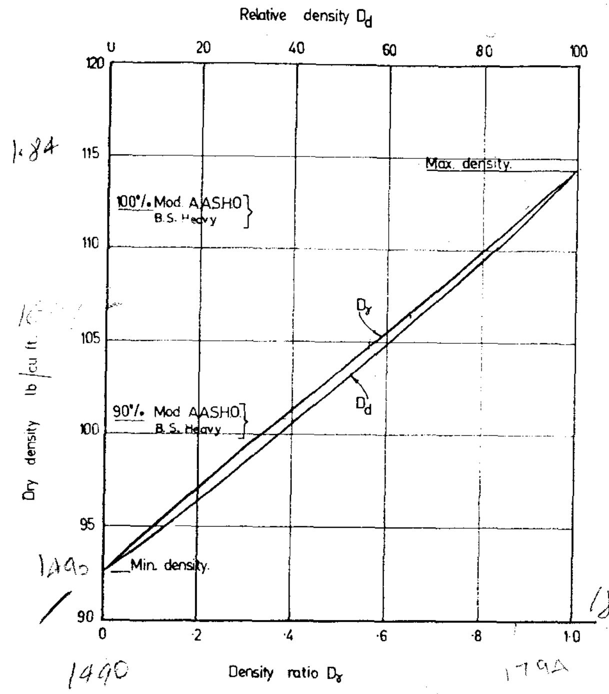

Fig. 8.—*The Relationship Between Relative Density, Density Ratio, and Dry Density.*

3.—Application to Site Investigation.

Large areas around Perth are endowed with a sandy soil which is very suitable for foundation construction. Such sand is free draining and not subject to volume change with varying moisture change. As a result footings (especially for smaller buildings) are usually placed very close to the surface. With the rapid growth in recent years of larger domestic dwellings, suburban offices, shops and industrial buildings more attention has been focussed on footing design and consequently more interest shown in the bearing capacity and resistance to settlement of the top sand layers.

Perth sands may be very broadly divided into 3 classes (Ref. 1).—

(*a*) Coastal dune sand (calcareous). Cottesloe Association.
(*b*) Yellow quartz sand (usually containing some clay content). Karrakatta Association. Taken as "average Perth sand" for calibration purposes.
(*c*) White quartz sand (usually containing very little clay content). Bassendean Association.

Each of these sands may exist naturally within the range of very loose to well compacted, especially within 5 ft. of the surface.—

Very loose—relative density below 30 per cent.
Well compacted—relative density above 70 per cent.

However, it is commonly believed that once the top soil (18 in.) is removed, the natural soil exposed is always of good capacity. Tests carried out by one of the authors over the past 3 years have shown this to be far from the case. Natural sands giving readings as low as two blows per foot have been encountered in locations well above the water table. In such cases the decision has to be made whether to deepen the excavations or try to compact the top layers of soil.

In this regard the penetrometer is very useful. With the aid of an extendible rod it is always possible to test to a depth of 10 ft. Immediately, one has an assessment of the variation of density with depth. Should it be decided to try to compact the soil in the excavation (usually with some form of mechnical tamping or vibrating machine) it is an easy matter to test with the penetrometer the effectiveness of the operation, both in density increase and depth influenced. Most forms of compacting machines of size that can be operated in a hole or trench can influence soil only to a depth of 18 in. Local soft patches can very easily be traced with the penetrometer which would not otherwise be found by conventional density testing.

Another useful purpose of the penetrometer is the assessment of density of soil under an existing footing or floor without disturbing the structure. This necessitates driving the rod at an angle using the falling weight as a hammer. With experience the engineer can assess very closely the density of the soil and ascertain if soft patches or hollows are present.

In conjunction with a post hole digger the penetrometer makes a useful tool for quickly mapping a building site. Penetration readings are taken alongside two or three auger holes spaced at the extremities of the area. The type of material is seen from the bores and the penetrometer can be used to probe the areas between the bores and interpret the type of soil over the whole area.

4.—Application to Control of Compaction.

Perth sands are well suited for filling material. They can be suitably compacted in the wet or dry state. Being free draining, winter conditions do not hinder earth moving procedures.

Many low lying sites have been raised up to 10 ft. by sand filling. If such filling is systematically compacted the resultant sand bed provides a foundation which is more uniform and dense than natural soil. Compaction may be carried out with any type of roller, but for small sites and especially for working in confined spaces the smaller 7- to 14-cwt. vibrating roller is the most effective. For larger areas the tractor-drawn 1- to 4-tons vibrating roller or multi-tyred roller is more effective.

Filling and compaction are best carried out in layers 6 in. to 12 in. deep and testing of each successive layer carried out before the next layer is added. Field density testing by core cutting or sand replacement methods is slow and cumbersome and requires some sort of laboratory facilities. Fairly large holes need to be dug, to allow an operator to test lower layers. The authors' experience has shown that density tests should not be taken in the top 6 in. and in the white clay free quartz sand preferably 12 in. Only a limited number of field density tests can be taken at one time and the results of tests are not known until some hours later. The penetrometer overcomes many of these limitations.

Once a suitable penetration rate has been established with the Contractor for the particular fill material being used, tests are carried out on the spot and witnessed by the Contractor. As many tests as desirable can be carried out in a very short time. By using a 5 ft. long rod, the lower layers are retested without any inconvenience. Usually the lower layers increase in density with added surcharge and rolling. The psychological effect of seeing the *in-situ* test performed with immediate results and knowing that uncompacted areas covered up before testing can be easily discovered at a later date keeps the Contractor more alert and consequently results in a better job.

For the past two years, one of the authors has incorporated the penetrometer test in all specifications calling for compaction. A minimum number of blows per foot commencing at, say, 6 in. depth is called for. This requirement must always be checked on site at the commencement of the contract since it may have to be adjusted for the soil actually being used. Generally, however, the results are very consistent and no disputes have ever been encountered with contractors over the use of the penetrometer test and in agreeing on a minimum test figure. The penetrometer is a robust and inexpensive instrument and it is known that over 20 such instruments are in use within the metropolitan area.

Most earthmoving contractors are not familiar with terms such as "modified A.A.S.H.O.", "void ratio", and "relative density", etc., but they do understand the language of "8 blows per foot using a 20-lb. weight falling 2 ft. on a $\frac{5}{8}$ in. dia. rod". Even the smallest contractor can "knock up" a rough penetrometer for his own guidance and control.

Until recently no sewer was allowed to be constructed on made up ground in Perth area without supporting the pipes on timber piles or bearers. It has now been accepted that properly compacted ground tested with a penetrometer is suitable for bedding of pipes without the need for extra support.

5.—Conclusions.

Testing is always an expensive and time consuming requirement of modern engineering practice. Any piece of equipment or procedure which is developed to reduce the expense, minimise the time of testing and produce direct reading should be encouraged. The authors feel that the penetrometer described above lies in such a category. It has been shown that this instrument can be calibrated for an average Perth sand, the driving resistance depending mainly on density, but also to some degree on moisture content.

The accuracy of the readings and co-relation to other forms of testing have been open to criticism, but soil is a natural and very variable material and provided any tests carried out indicate a trend or uniformity of results such tests must be accepted as useful guides to design or control. Used together with a reasonable amount of engineering judgment the penetrometer is a convenient, reliable, site investigation and compaction control instrument.

Acknowledgment.

The authors gratefully acknowledge the careful, painstaking work of Mr. Olaf Pihu who carried out the calibration while a student at the University of Western Australia.

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APPENDIX.

Estimate of Theoretical Bearing Capacity and Settlements.

The usefulness of the penetrometer in the field of foundation engineering is illustrated in Fig. A1. This shows the ultimate bearing capacities of 10 ft. square and 5 ft. square footings related to the blows per foot. This ultimate bearing capacity was obtained using Terzaghi's Bearing Capacity Co-efficients and assuming the footing at ground surface with appropriate friction angles (Ref. 2). In arriving at the allowable bearing capacity such other factors as differential settlement and its effect on the particular type of structure have to be considered. This is difficult to assess but in the first instance it requires an estimate of settlement of individual footings at the design load. Assuming a design load of 1/3 of the ultimate bearing capacity the relationship between settlement and blows per foot was obtained as also shown in Fig. A1.

It should be clearly understood that this Figure is based on theoretical relationships for particular assumed conditions. Its use in practice should be tempered with considerable care and judgment. Similar development of bearing capacity from penetration tests is presented by Meyerhof (Refs. 4 and 6).

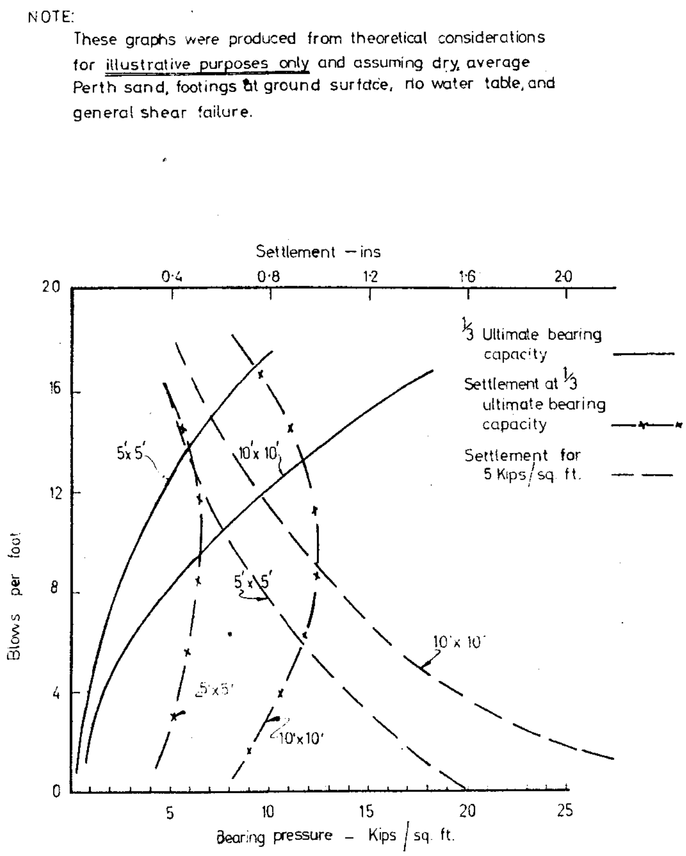

Fig. A1.—An Estimate of Bearing Capacity and Settlement in Terms Driving Resistance.

Discussion.

Mr. R. Lilly (Associate Member, Perth Division).—The Metropolitan Water Supply Board of Perth used one of these penetrometers in 1963 to help in the compaction control of the sand embankment at Bold Park service reservoir. The embankment has a maximum height of 60 ft., with inner and outer sideslopes of $\frac{1}{4} = 1$ and $2 = 1$ respectively. A dry density of 102 lb./cu. ft., equivalent to 70 per cent relative density, was specified.

The penetrometer was calibrated in a 3-ft. square box at the Board's laboratory.

Penetrometer readings and core samples were taken at similar spots in the bank as construction proceeded. It was found that the penetrometer and core sample usually gave values of relative density within 5 per cent of one another. After some experience had been gained, the penetrometer was used to test the compaction of an area initially. When compaction was sufficient to give satisfactory penetrometer readings, core samples were taken at random. It was convenient in this case to take a fair number of core samples, as there was a field laboratory on the site. Normally, however, only a few samples would have been necessary once routine testing started.

The sand at Bold Park is different from the ordinary Perth yellow sand of the paper. The Bold Park sand is a dune sand with a much lower percentage of fines than the Perth sand. This caused lower densities for the Bold Park sand for any given relative density. For example, for a relative density of 70 per cent, the Perth sand density is 108 lb./cu. ft. compared with the Bold Park density of 102 lb./cu. ft. For a given relative density, the number of blows was higher for the Bold Park sand than for the Perth sand. Thus a reading of 10 blows at 4 per cent moisture content indicates a relative density of about 71 per cent for the Perth sand, and about 60 per cent for the Bold Park sand. This difference shows the desirability of a separate calibration before using the penetrometer to control a new major job. It is also interesting to note that between different types of sands, the sand with the higher density at a given relative density will not necessarily give a higher penetrometer reading.

Despite this variation between sands, it is probable that the penetrometer would be accurate enough without specil calibration for many small jobs, and is in any case better than nothing, which is often the alternative. The Board is investigating the use of the penetrometer to determine the condition of sand on which it is intended to lay pipelines. The comparison of one section of the pipeline with another should be quite accurate so long as the sand types are the same. Some idea could also be obtained of the relative density. The amount of foundation improvement necessary to prevent excessive settlement could then be estimated.

The Authors in Reply:

The information presented by *Mr. Lilly* of the Metropolitan Water Supply, Sewerage and Drainage Board, Perth, is very interesting and his comments are appreciated. There does appear to be enough variation between the different sands in the Perth area to require re-calibration for the more important jobs. This is not at all difficult to do either in the laboratory as described in the paper or by comparison with field density determinations made at the beginning of the job. Undoubtedly the instrument has considerable value when good uniform density conditions are required, such as with the sewer trenches as mentioned by Mr. Lilly.
