COMPARISON OF FLAT DILATOMETER IN-SITU TEST RESULTS WITH OBSERVED SETTLEMENT OF STRUCTURES AND EARTHWORK

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ABSTRACT

One of the main objectives of practicing geotechnical engineers is to obtain accurate assessments of soil compressibility below structural foundations or earth works. The flat dilatometer, developed by Marchetti, is an in-situ testing device which can provide quasi-continuous soil compressibility values as part of a conventional site investigation. Compressibility values, obtained from dilatometer tests, are used to estimate settlements at five projects in southern Ontario where actual settlement measurements are available for comparison. The results indicate that reasonably accurate settlement estimates can be obtained quickly and economically for materials ranging from sand and clay to peat.

INTRODUCTION

The use of in-situ testing techniques for estimating and measuring geotechnical soil parameters is now common, even routine, in practice. One of the more recent additions to the arsenal of in-situ testing devices is the Flat Dilatometer, developed and introduced by Marchetti in 1980. Many investigators and practicing engineers have reported on the value of dilatometer testing (DMT) procedures for identifying soil type and estimating various soil parameters. A number of studies have been made to compare DMT-derived parameters with those derived by other in-situ and laboratory test procedures.

For the practicing geotechnical engineer, assessing soil compressibility in order to estimate settlement under load is probably the most common project requirement. The purpose of this study is to illustrate the use of DMT-derived compressibility parameters in estimating settlement and to compare those estimates with actual recorded settlements of structures or embankments. It should be noted that these results were obtained from our normal consulting practice and were not intended to be part of a precise research-oriented study. We have simply been curious to know how accurate the DMT-based predictions would be.

DILATOMETER PROCEDURES

Basic In-Situ Test Methods

The basic dilatometer test is a fairly simple and straightforward procedure. It involves connecting the dilatometer blade to conventional drill rods and feeding a pressure tube through the drill rods from the blade to the control gauge and pressure source. The size and general shape of the DMT blade is illustrated on Figure 1. The rods and dilatometer assembly is then pushed (or driven) into the ground to the desired testing level. After completing a test at that level, the dilatometer blade is advanced to the next test level. A test interval of 200mm is commonly used and provides a nearly-continuous profile.

The procedure at each test interval consists of using a pressure control valve to expand the membrane hoizontally against the soil while noting the pressures at two membrane positions.

(i) At membrane "lift-off" (A-reading).

(ii) After 1.1mm movement of the membrane (B-reading).

As soon as the 1.1mm expansion has been reached, the gas pressure is released under control until the membrane returns to the lift-off position where a third pressure (C-reading) is noted.

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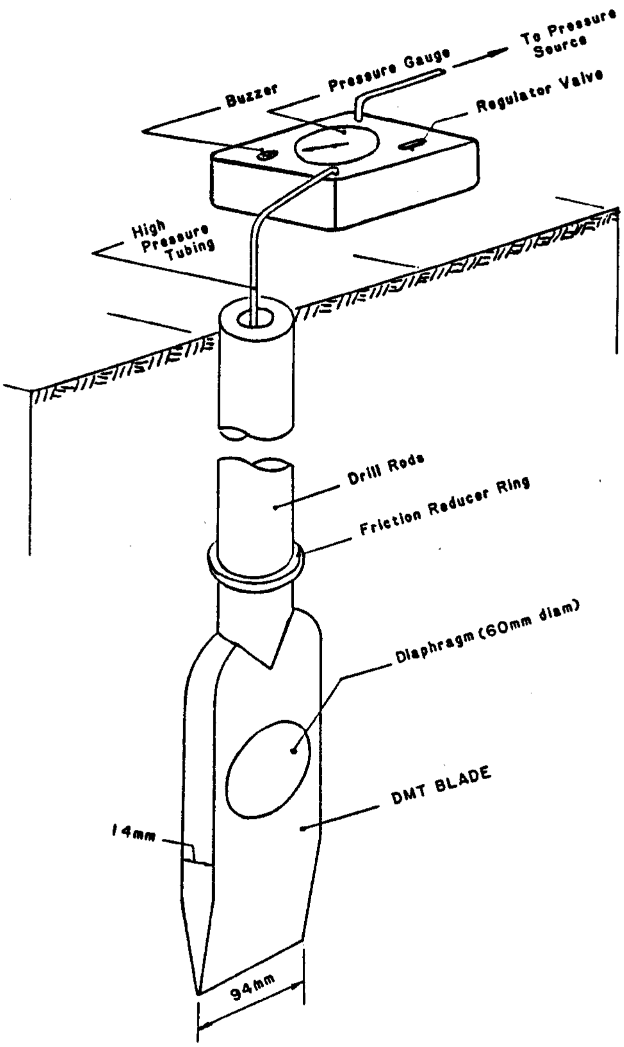

FIG. 1 - FLAT DILATOMETER EQUIPMENT

These pressure readings, after appropriate corrections for membrane stiffness, are then converted using the relationships established by Marchetti (1980), Schmertman (1982) and others to obtain a number of soil properties. A typical DMT sounding provides indications of soil type (Id), preconsolidation stress (Pc), E-modulus, compressibility modulus (M), shear strength in clays and angle of shearing resistance in sands. Needless to say, the computation for these soil parameters at each test level requires a computer or a powerful programmable calculator. A decade ago, the computation requirements of the DMT process would have been a serious drawback for many geotechnical engineers. Now, it is not.

We have found that the DMT method is easily adaptable to conventional SPT-oriented drill rigs. The cost per test is relatively low, the test provides a sensitive indication of soil strata changes, and the procedure is quick (4m to 12m/hr.). An assessment of site characteristics can be done, virtually, in "real" time. This is particularly useful to the geotechncial engineer when potential structural settlements must be determined quickly. The conventional "undisturbed" sampling and laboratory test techniques can be time-consuming and costly if the site has a complex soil profile. Since, in practice, it is usually settlement rather than total shear failure that governs foundation design, we have focused our assessment on DMT methods for predicting settlement.

DMT Compressibility Estimates

The relationship of DMT results to compressibility of the soils is both theoretical and emperical. The membrane expansion can be modelled as the loading of a circular area on the surface of an elastic half-space. A mathematical relationship between the applied loading and modulus of elasticity is available from the analysis of Gravesen (1960) as follows:

$$\Delta p = \frac{\pi W_r}{4R_0\sqrt{1-\left(\frac{r}{R_0}\right)^2}}\left(\frac{E}{1-\mu^2}\right) \qquad (1)$$

where:

Δp = the applied load
W_r = movement normal to the surface of a point at a radius r within the loaded area = 1.1 mm
r = radius to the point of interest=0
R_0 = radius of loaded area = 30mm
E = Young's modulus
μ = Poisson's ratio

The ratio $E/1-\mu^2$ is known as the dilatometer modulus, E_D. For the DMT dimensions, we have:

$$E_D = 34.7\,\Delta p \qquad (2)$$

There is also a theoretical relationship between the tangent constrained modulus (M), Poisson's ratio (μ) and Young's modulus (E). The constrained modulus (M) is defined, as illustrated in Figure 2, as:

$$M = \frac{\Delta\sigma_v'}{\Delta\varepsilon_v} \qquad (3)$$

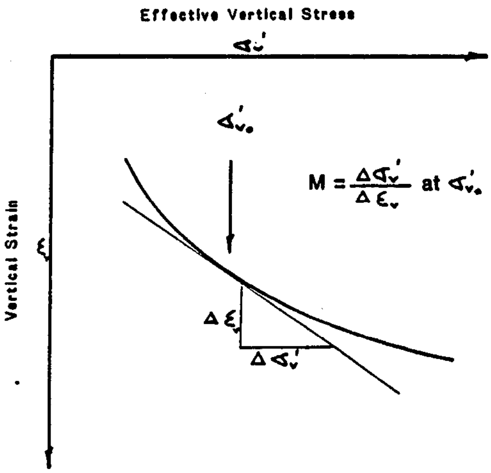

FIG 2 - DEFINITION OF TANGENT CONSTRAINED MODULUS

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The relationship between M, μ and E at a particular stress level is:

$$M = \frac{E\ (1-\mu\ )}{(1+\mu)(1-2\mu)} \qquad (4)$$

Using the definition of the dilatometer modulus:

$$E_D = \frac{E}{1-\mu^2} \qquad (5)$$

Bullock (1983) summarized the relationships for E_D, M and μ as follows:

(a) For E_D as a drained parameter -

$$M = E_D\,\frac{(1-\mu\ )^2}{(1-2\mu)} \qquad (6)$$

(b) For E_D as an undrained parameter -

$$M = E_D\,\frac{(1-\mu\ )}{2(1-2\mu)} \qquad (7)$$

Therefore, as Marchetti deduced, there appears to be some theoretical justification for a relationship between M and E_D which would have the form:

$$M = R_m\ E_D \qquad (8)$$

Marchetti (1980) then used high quality oedometer test results to determine emperical correlations between M and E_D. Schmertman (1986) and others have reported good agreement between DMT and oedometer M values, for a wide range of soil types.

To some geotechnical engineers, the ability of the DMT method to determine vertical soil compressibility is surprising since the DMT test is conducted horizontally in-situ. However, recent studies by Khera & Schulz (1984) indicate that it is better to measure in a horizontal direction if the vertical preconsolidation stress is desired. In any case, a growing body of evidence (Schmertman, 1986) suggests that the DMT method does reliably predict soil compressibility parameters.

SETTLEMENT CALCULATIONS

The tangent modulus (M) is a convenient parameter to use in settlement calculations. Knowing the applied load, P, the vertical stress increase, $\Delta\sigma_v'$, at depth z, is estimated using appropriate stress distribution charts, tables or algorithms. Using M values derived from the DMT (or from any other appropriate test procedure) the settlement for the layer, illustrated in Figure 3, is determined from the following:

$$\text{Settlement, } \Delta S = \frac{\Delta\sigma_v'\,(\Delta z)}{M} \qquad (9)$$

Since there is an M value determined at 200mm intervals in a typical DMT test, the writer has found it convenient to subdivide the strata below a foundation into 200mm layers. A computer is then used to calculate the compression of each 200mm layer. The total settlement is the sum of the individual layer settlements.

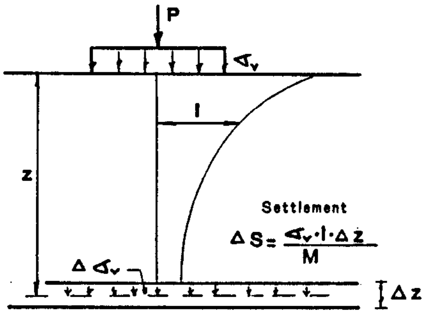

FIG. 3 - CALCULATION OF SINGLE LAYER SETTLEMENT

There are some important precautions which must be taken when using the DMT tangent modulus approach to estimating settlement. The geotechnical practitioner must ensure that M_{DMT} is appropriate for the stress range induced by the foundation loads. If the DMT values were measured in highly over-consolidated (HOC) soils, then M_{DMT} will be appropriate for stresses which do not exceed the preconsolidation pressure (Pc). If the DMT values were measured in normally-consolidated (NC) soils, the M_{DMT} again will be appropriate for stress increases normally encountered in practice. In the case of lightly over-consolidated (LOC) soils, however, the DMT values for M can be misleading, since the increased stress due to loading will probably exceed Pc. In such cases, the appropriate M-value is that for NC conditions.

Where significant layers of LOC soils exist below a proposed structure, it is necessary to revise the DMT value of M to reflect the higher compressibility in the stress ranges exceeding Pc. Schmertman (1986) has developed very useful procedures for estimating revised M-values. His "Special Method" makes use of the modulus number (m) relationships reported by Janbu (1985) and allows reasonable settlement estimates in layers of LOC soils.

Tentatively, the author has used the Id values from the DMT test to estimate Janbu's modulus number, m, using the following relationship:

$$m = 40\ (Id) \qquad (10)$$

where Id = the material index from the DMT.
40 = a trial constant subject to revision.

ACTUAL PERFORMANCE

The monitoring of the actual settlement under load, at four of the projects cited in this paper, was done as part of an "observational" approach. We wanted to ensure that our assumptions were reasonably close to reality. One of the projects (Site 3) required settlement monitoring because of a design failure.

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All of the settlement measurements were made with conventional survey equipment and benchmarks. At two of the sites (#3 & #4), the owner carried out the survey; the author's firm did the monitoring on the remainder.

The actual loads, applied to the subsoils, had to be calculated from available information regarding actual weights of building materials, soil unit weights and weights of stored equipment and supplies. Although the loading estimates are not precise, they are believed to be accurate within a range of ±10%

The following sections provide a brief description of the characteristics of each site:

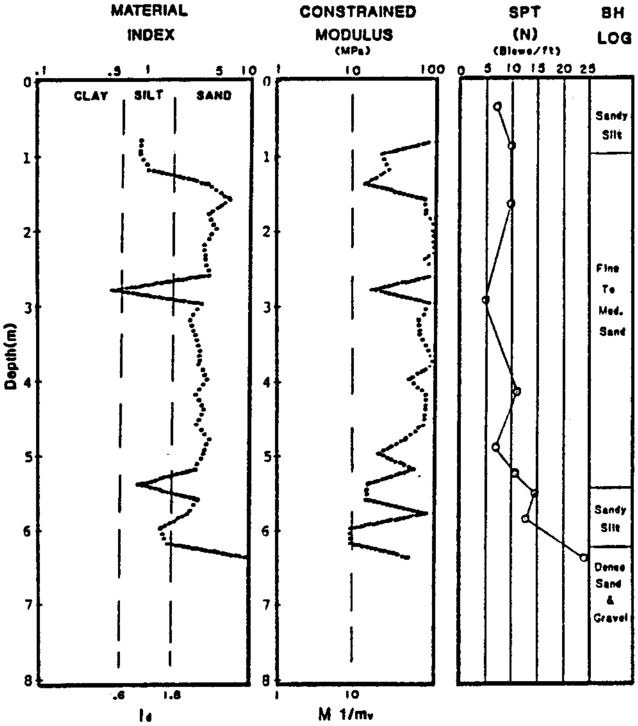

Fig. 4 - DMT RESULTS (SITE #1)

Site #1

This is an industrial plant site at which the structure was placed on a 1.2m thick "pad" of compacted granular fill. The pad is about 30m by 75m in size and carries the structural loads on conventional concrete slabs and footings placed on the granular pad. A combination of fill loads, structural dead loads and "permanent" live loads is reasonably uniformly distributed and produces a net bearing pressure of 100 kPa. Measured settlements ranged from 15 to 20mm over the loaded area, with an average of 18mm. Soil profile and DMT modulus values are shown on Figure 4.

Site #2

To minimize differential settlements, this 6-storey apartment building was designed to rest on a semi-rigid box which served as an underground parking area. The design was intended to provide a reasonably uniform distribution of the structural loading. The average net bearing pressure (taking the weight of soil removed into account) on a 20x65m base was calculated to be 94 kPa. The structural base was located at a depth of 4.1m in relation to the profile data on Figure 5.

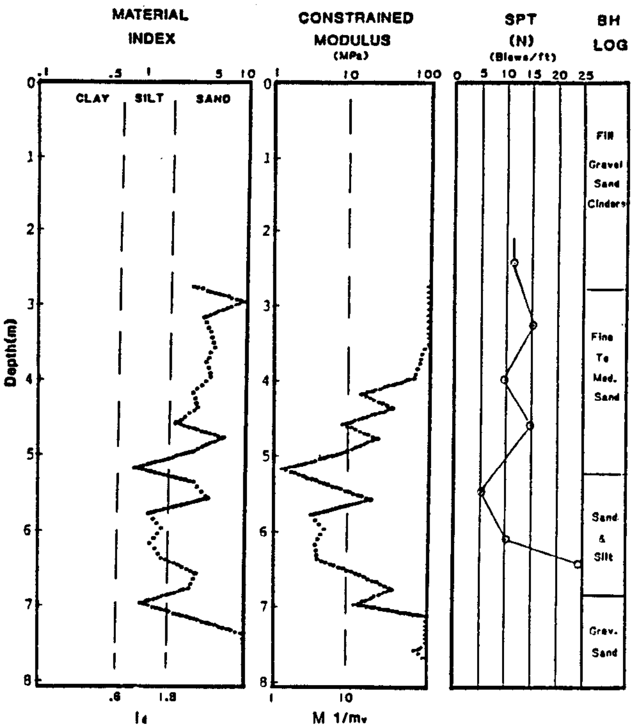

Fig.5 - DMT RESULTS (SITE #2)

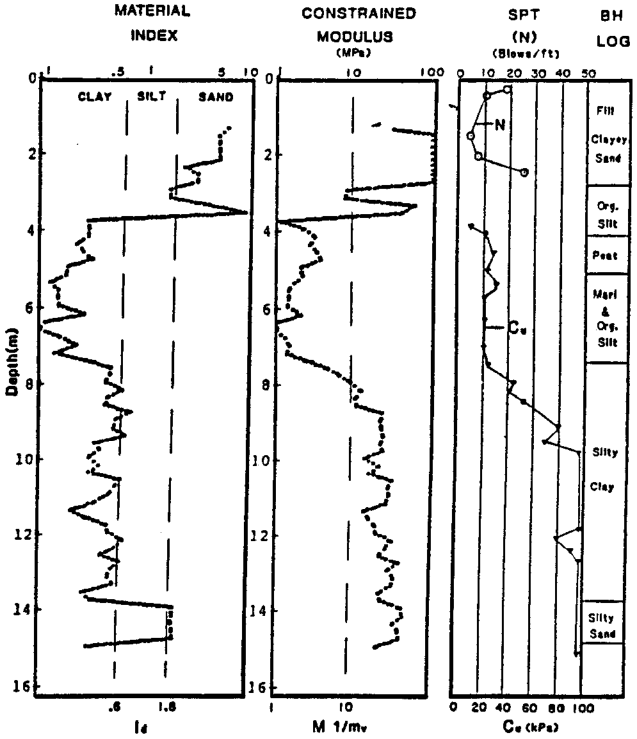

Fig. 6 - DMT RESULTS (SITE #3)

Site #3

The steel frame industrial building at this site was located, through a design error, over a very compressible, buried peat and marl deposit. The net added bearing pressure, due to earthfill, structural loads and stored materials, was about 90 to 100 kPa on an area 15x30m in size. A settlement of 270mm was measured in the vicinity of the DMT location, 3 years after construction was completed. The soil profile and DMT compressibility values are noted on Figure 6.

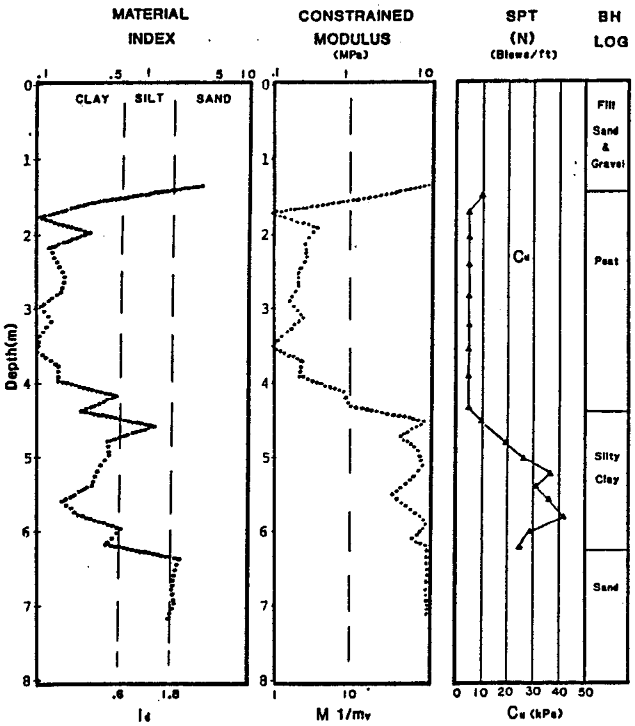

Fig. 7 - DMT RESULTS (SITE #4)

Site #4

This project required a 1.2m increase in embankment height over a 900m long swamp crossing. The embankment is about 15m wide and is underlain by a 3 to 4m layer of peat. Elevations were measured, before, during and after construction, by the owners. The monitoring of road settlement is continuing. Based on the data available to date, the projected long term (20 year) total settlement will be 250 to 300mm. The soil profile and DMT modulus values are shown on Figure 7.

Site #5

A concrete and compacted granular pad was constructed to support three large liquid storage tanks at this site. The storage tanks were originally designed for a location at the site where DMT analyses indicated up to 150mm of settlement. The tank farm location was changed to another location on the site where the underlying materials were less compressible and settlements would be tolerable. The conditions, at the final location, are indicated on Figure 8. A net bearing pressure of 175 kPa includes the weight of granular fill, concrete and steel containing-structure and the stored liquid. The pressure is exerted over an area 7.6x30.5 metres in size. Settlement monitoring indicates that a settlement of 23mm occurred after the initial loading of the tanks. Consolidation of the clayey materials at a depth of 9 to 13m is continuing and the projected total settlement is 30 to 35mm.

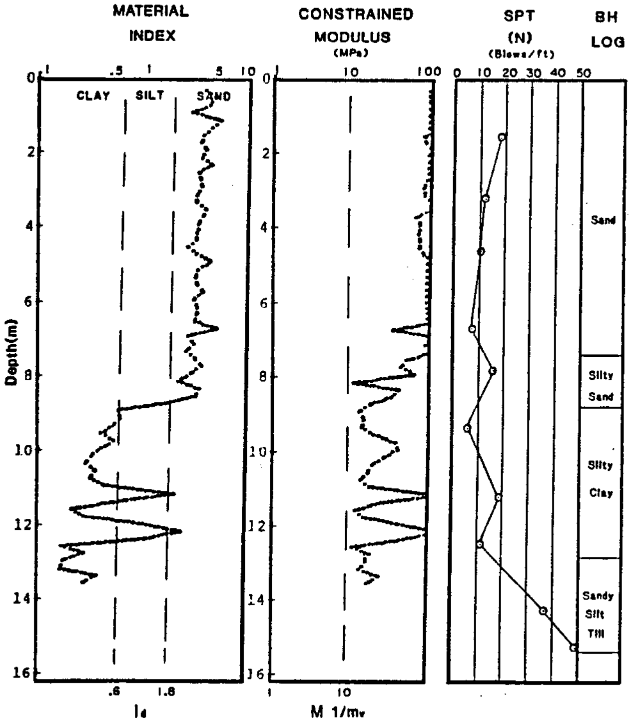

Fig.8 - DMT RESULTS (SITE #5)

Calculated vs. Measured Settlements

The settlements which were calculated using DMT procedures are compared to the actual measured values on Figure 9. The calculated values were initially determined by the so-called "ordinary method" using the constrained modulus M-values directly from the DMT test. Subsequently, the calculated values were determined by a variation of the "special method" suggested by Schmertmann (1986).

The range of computed values, for both the ordinary and special method, appears to be reasonably close to the actual measured values. It has been noted by others that the ordinary DMT analysis tends to overpredict settlement (slightly) in sands and silts while tending to underpredict settlement in very soft organic soils and peat. Based on the limited information from the projects cited in this study, the special method, proposed by Schmertmann, tends to do just the opposite (i.e. to underpredict in the sands and silts of Site #2 and overpredict in the organic soils of Sites #3 and #4). In any case, the use of both the ordinary and the special methods, appears to provide a meaningful range of settlement to which engineering judgment can be applied.

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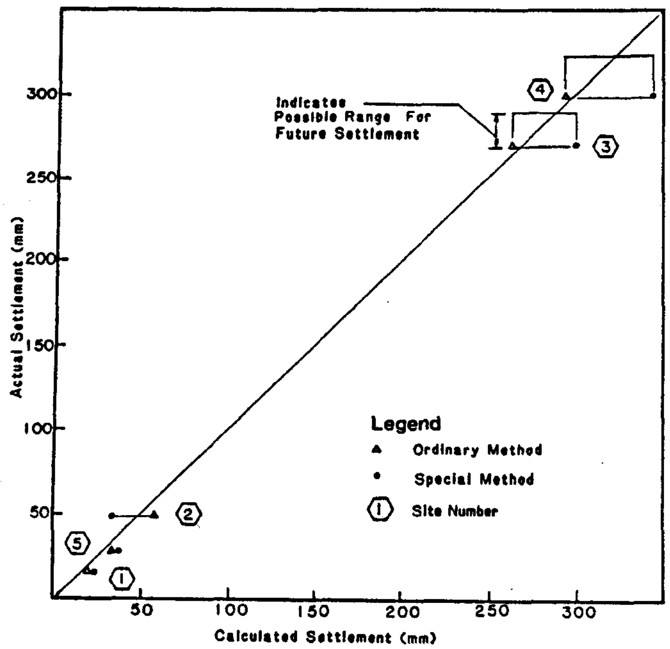

FIG. 9 - COMPARISON OF OBSERVED AND CALCULATED SETTLEMENTS

SUMMARY AND CONCLUSIONS

The flat dilatometer (DMT) in-situ testing method, developed by Marchetti, is a useful addition to the geotechnical engineers' procedures for assessing foundation soil characteristics.

Based on our experience, the DMT method is particularly good for estimating compressibility and predicting settlement. The estimated settlements, using both the ordinary method and Schmertmann's "special" method, appear to bracket the actual settlement range with a reasonable degree of accuracy. The method works in a wide variety of materials from very dense sands to very soft organic soils.

As with any geotechnical testing method, engineering judgment is required when using the DMT method. In lightly overconsolidated materials, for example, the in-situ DMT constrained modulus, M, could be misleading if used without regard to the actual stress level imposed by foundation loads. When used in conjunction with conventional sampling and testing procedures, however, these limitations can be overcome. In our practice, the DMT is used along with the SPT, thin wall tube sampling and conventional laboratory tests to provide complementary soils information.

For the practicing geotechnical engineer, the speed with which fairly complex soil formations can be tested and analyzed with the DMT is a definite asset.

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