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Individual foundation design for column loads

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ABSTRACT: Structural column loads are supported by either shallow spread footings or deep foundations. While design analyses should always avoid a catastrophic or bearing capacity failure, it is usually the unsatisfactory performance due to excessive settlement that controls the design. Column loads and subsurface conditions can vary across the project's site. Often engineers recommend a general bearing pressure for spread footings or a constant tip elevation for deep foundations based on what they consider to be the worst-case scenario. Ironically, while they think that they are being safe, the over designed foundations will have minimal settlement, while the "worst case scenario" foundations may settle the amount predicted by the engineers. With this design approach, differential settlement occurs. Over designed foundations provide poorer performance and cost more. The approach presented here requires that the foundations for each column be individually designed based on the load and subsurface conditions.

1 INTRODUCTION

By designing all foundations at a site for the worst possible load and soil support conditions, the engineer may increase the magnitude of undesired differential settlement and the cost of the foundations. Designing each individual foundation for the load and support appropriate to its location helps achieve a more balanced design. However, for this method to succeed an accurate delineation of the geologic conditions and soil properties is required.

For shallow foundation design, soil tests should measure both the deformation and strength properties of the soil beneath the foundations. For deep foundation design, the engineer must perform tests to accurately determine the pile capacity. The engineer can then prepare contour maps showing total predicted settlement for spread footings or pile tip elevations for required capacity. These contours provide a means by which to adjust and balance the overall design. Because the foundations for each column load are individually designed, the error due to spatial or subsurface variability is minimized and satisfactory performance of the foundation will occur.

2 SHALLOW FOUNDATION DESIGN

As shown in Figure 1, the Marchetti dilatometer test (DMT) is a calibrated deformation test and can be used to accurately predict settlement (Schmertmann, 1986 and Hayes, 1986). The ratio of predicted to measured settlement from their case studies was 1.15 with a coefficient of variation of 0.29. If one ignores the data from driving the DMT blade and quick silts, the average reduces to 1.06 with a coefficient of variation of 0.18. From each DMT the constrained deformation modulus is computed based on correlations developed by Marchetti (1980). Tests are typically performed at 20-cm intervals.

Wickremesinghe (1989) found that the random error for dilatometer tests was only 5.5%. The error inherent in the method used to calculate settlement should be similar across a site with the same subsurface geologic formations. For the differential settlement between adjacent soundings at a site, this error should tend to cancel itself out and approach the random error value of 5.5%.
Because the constrained modulus is in the denominator of the settlement prediction equation, low values have a much greater impact on settlement than

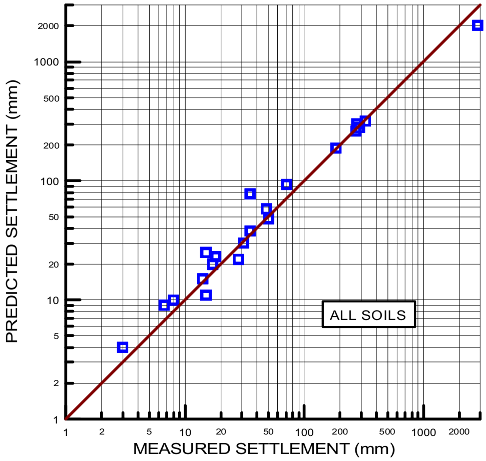

Figure 1: Dilatometer Predicted Settlements after Schmertmann (1986) and Hayes (1986)

high values. By performing dilatometer tests at a close vertical interval spacing, the engineer can detect thin soft layers, which often control design. In very soft zones, tests at 10-cm intervals provide better layer definition and a more precise settlement estimate.

For accurate readings, the pressurization rate should be relatively slow near the “A” and “B” readings so that the pressure in the blade is the same as that shown on the control unit’s gauges. Thrust measurements from a load cell or pressure transducer may also provide a warning of potential shifts in the “A” and “B” readings by comparison with the previous thrust measurement. Low thrust measurements also alert the engineer of soft soils.

At each sounding location, a settlement prediction from DMT data is made using Schmertmann’s (1986) design method. While the engineer can define the soil layers and assign M-values to them, we found that it easier to use each test as a “mini-layer”, either 10 or 20 centimeters thick. A spreadsheet, including an elastic estimate of the stress increase beneath a given footing size and load, provides quick settlement computations. The output file from the DMT data processing program provides for direct import of the sounding data into the settlement spreadsheet. (The spreadsheet has too many columns to be shown in this paper, but a copy may be obtained if you email us.)

The engineer can easily change the size of the footing to equalize the predicted settlement for each combination of DMT sounding and column load. The footings must always be large enough to avoid bearing capacity failure.

Where there are varying thicknesses of structural fill to be placed beneath the footprint of the structure, the weight of the fill may have a significant influence on the amount of settlement that will occur. (The engineer may not be able to adjust for this condition.)

To confirm the validity of the DMT M-value correlations, we made some comparisons with laboratory consolidation tests. As shown in Figure 2, the DMT M-values and laboratory M-values fall closely to the 1:1 line for various soil types and soil origins. The sites were mainly located in Virginia of the United States.

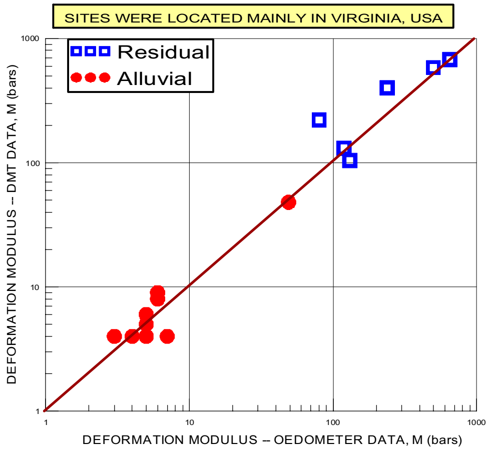

Figure 2: Comparison of DMT M values and Laboratory M values

2.1 *Numeric Settlement Example*

For the building foundation plan shown in Figure 3, eight (8) dilatometer soundings were performed along the perimeter wall footings (i.e.: D-1 to D-8) and nine (9) dilatometer soundings were performed for the interior columns (i.e.: D-9 to D-17). The wall footings supported a load of 12 kips/ft (175 kN/m) and the column loads were 200 kips (890 kN). The dimensions of the footings were adjusted until the resulting settlement was approximately 0.5 inches (12.7 mm). Figure 3 shows the foundation plan with the DMT sounding locations and the predicted settlements superimposed. Figure 4 presents a contour map of the resulting settlements predicted across the building foundation.

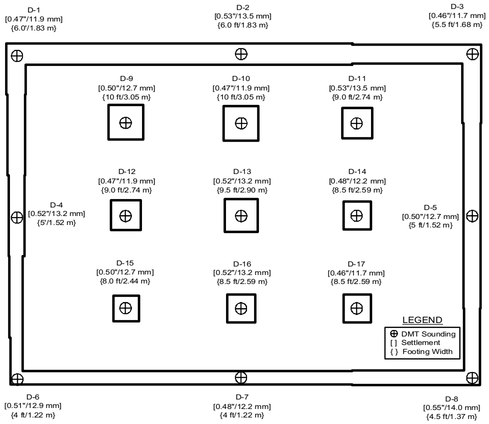

Figure 3: Foundation Plan for Individually Designed Footings

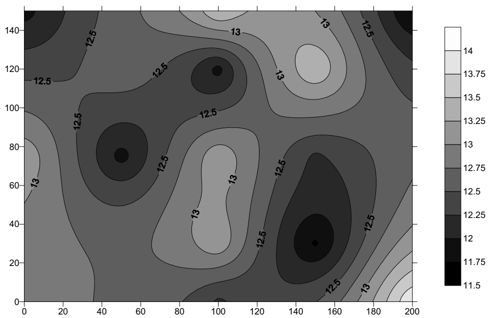

Figure 4: Contour Map Showing Predicted Total Settlement (mm)

3 DEEP FOUNDATION DESIGN

While it is often difficult to predict settlement of a piled foundation, it is much easier to predict the pile capacity. If all of the piles have a similar capacity and similar stratigraphy, any differences in settlement will mostly be a function of differences in pile compression, a relatively minor magnitude. For each column, the length and number of piles is adjusted so that a constant allowable capacity is provided. By maintaining a constant capacity over the site, the settlement of the structure will also be approximately constant.

The electric piezocone test (CPTU) is a calibrated quasi-static penetration test and is an ideal model of a pile. Robertson et al. (1988) compared the predicted pile capacity with the measured capacity of driven steel pipes of varying diameters. They predicted the pile capacity using direct methods based on empirical correlations with the corrected CPTU tip bearing, q_T. They also predicted capacity using indirect methods based on correlations with the angle of internal friction and cohesion, and then used those values of shear strength for pile capacity prediction. They concluded that the direct pile prediction methods were much more accurate than the indirect methods. The LCPC method had the lowest coefficient of variation (0.15) of the methods evaluated.

Wickremesinghe (1989) found that the random error for cone penetration tests was only 5.1%. That error is likely to be even lower with today's digital cones. The error of how well the CPT method predicts pile capacity will likely be similar for the same subsurface geologic formations. For pile capacity between adjacent soundings at a site, this error should tend to cancel itself out and approach the random error value of 5.1% or less.

Modern pile drilling and driving equipment have electronic sensors that measure drilling or driving energy and help predict pile capacity. By monitoring these sensors, the contractor can install piles to the same energy levels. The engineer and inspector can use these data to confirm the predicted pile capacity. In pile groups the contractor must start installing piles in the center and work his way outwards.

3.1 *Numeric Pile Example*

For the building foundation plan shown in Figure 3, eight (8) electric cone penetration soundings were performed along the perimeter wall footings and nine (9) CPT soundings were performed for the interior columns. The pile loads were assigned a value of 100 kips (445 kN). From each sounding the tip elevation was computed for the allowable capacity using the LCPC method. Figure 5 is a contour map of the predicted pile tip elevation across the building.

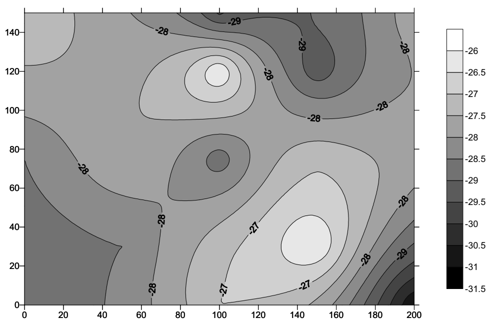

Figure 5: Contour Map Showing Predicted Pile Tip Elevations

4 CONTOURING

Because explorations are performed at a finite number of locations, the engineer must interpret what will likely occur between test locations. Contouring allows numeric interpretation through a variety of mathematical algorithms. They include inverse distance to a power, kriging, minimum curvature, modified Shepard's method, natural neighbor, nearest neighbor, polynomial regression, radial basis function and triangulation with linear interpolation. Contour maps may show peaks, holes, valleys or ridges from the data. At these anomalous areas, additional testing may be required for better definition and more accurate design.

5 BRIDGE/EMBANKMENT DESIGN

From a cost viewpoint it is best to design a bridge with the shortest span possible. Bridges have higher construction costs (approximately $100/square foot versus $10/square foot for roadways) (Kaulfers, 2003). They also have higher maintenance costs because it is difficult to repair any structural defects. From a performance view, bridges are less safe for the motorist than roadways. Bridge spans will freeze before roadways and they often do not have wide enough shoulders.

The fill placed in an approach embankment may cause significant settlement of the underlying soils and the engineer needs to determine how long and high the embankment can be without causing detrimental settlement. This limit can be defined from DMT soundings and contour mapping. From the contour map the engineer may identify a zone where ground improvement should be used and decide to make the embankment longer. Construction costs for ground improvement are approximately $40/square foot (Kaulfers, 2003). To minimize settlement between pile cap locations the engineer should use the individualized deep foundation design approach and contour mapping described above.

6 CONCLUSIONS

When the engineer designs each footing and pile to have the same load carrying capacity as the other footings or piles on the project, the differential settlement of the structure will be minimized.

The dilatometer test has a low random error and can accurately predict settlement of shallow foundations. Footings can be sized to settle the same amount provided that uneven amounts of structural fill are not placed in the structure's footprint.

The electric cone penetrometer test has a low random error and can be used to accurately predict pile capacity. The structural loads can be supported by piles with the same load carrying capacity and differential settlements will be minimized.

The contour map is a useful tool for the designer, contractor, and inspector and helps assure that the project is built as designed.

Bridges can be designed using this approach to improve performance and reduce life-cycle costs.

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