CPT based settlement prediction over California soft rock

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ABSTRACT: Settlement is a critical parameter for designing shallow foundations. Geotechnical engineers routinely overestimate settlement of shallow foundations bearing on soft rock due to sample disturbance, resulting in unnecessary conservatism and, in some cases, deep foundations. Several methods were evaluated to estimate the settlement of a mat foundation supporting a 20-story class A office tower in southern California. These methods included: i) using finite element analysis based on the Winkler foundation model and subgrade modulus based on elastic properties of the bedrock, ii) Terzaghi's traditional one-dimensional consolidation theory using laboratory tests, and iii) Terzaghi's one-dimensional consolidation theory based on constrained modulus using CPT results. These analyses were compared with actual survey results taken during the building construction to determine the most suitable method for estimating soft rock settlement.

1 INTRODUCTION

Bearing capacity and settlement are two parameters considered in foundation design. However, foundation settlement is usually the limiting factor for the design foundation bearing pressure. Compression of soils and soft rocks are affected by a number of different mechanisms including void reduction, bending and distortion of solids, fracture of solids especially at the contact points, etc. (Sowers, 1979). In 1925, Terzaghi published his "Erdbaunmechanik on Soil Physical Basis" explaining the fundamentals of consolidation and modern soil mechanics. Terzaghi's one-dimensional (1-D) consolidation theory is regularly used by engineers to evaluate settlement of soils and soft rock under foundation loads.

One of the major issues for evaluating consolidation parameters based on laboratory testing is sample disturbance. Sample disturbance can affect the gradient of the virgin compression and unloading curves in addition to the preconsolidation pressure. Soil disturbance during sampling may be reduced by using thin walled samplers or other advanced sampling methods. Ladd and Foott (1974) and Ladd and DeGroot (2004) recommended procedures to reduce sampling disturbance effects on soft soil settlement calculations, resulting in a more accurate estimate of the consolidation parameters. Although these methods may work for soft soils, they are very difficult to implement for very stiff soils and soft rocks.

Evaluation of soil compression using in-situ testing, whenever possible, can minimize the errors introduced by sampling and laboratory testing procedures.

2 PROJECT DESCRIPTION

A mat foundation was considered for a new 20-story class-A office tower in southern California. The project was investigated by excavating seven bucket auger borings to depths ranging from 16.2 to 22.3m below ground surface (bgs), three hollow-stem auger borings to a depth of 33.5m bgs, and advancing four Cone Penetration Tests (CPTs) to depths ranging from 13.7 to 20.4m bgs. A total of 26 consolidation tests were performed as part of this and earlier investigations. The tower has an approximate footprint of 1,858 m^2. Column dead loads ranged between 2.5 MN (562 kips) and 15 MN (3375 kips) and dead plus live loads varied between 3 MN (674 kips) and 23.5 MN (5,283 kips) for an average dead load mat footing pressure of 250 kPa (5.2 ksf).

The project area is within the northwestern portion of the Peninsular Ranges Province and at the southeastern extremity of the Los Angeles Basin. The site lies within a series of uplifted terraces between Newport Bay to the north and the San Joaquin Hills to the south. The Monterey Formation, which is Miocene in age, was encountered below a thin layer of Terrace Deposits in all borings. The Monterey Formation consisted predominantly of low to moderate plasticity siltstone and claystone interbedded with thin sandstone beds. High plasticity intervals and shear zones (MH & CH) were also present within the formation.

Two CPTs (one of which included shear wave velocity measurements) and a boring were excavated within the tower footprint. Prior to construction, the building site was underlain by approximately 4.5m of granular Terrace Deposits overlaying Monterey Formation bedrock. The Monterey Formation is a California soft rock with Standard Penetration Test (SPT) blowcounts between 23 to 80 blows per 0.3m of penetration measured to a maximum depth of 33m.

Figure 1 presents a representative CPT profile of the site with the measured and estimated shear wave velocities of the site. The CPTs had average tip resistance values of 6 MPa (125 ksf) and 10 MPa (209 ksf) in the Terrace Deposits, and the upper 15m of the Monterey Formation, respectively, with some lenses of high tip resistances (q_t >30 MPa or 626 ksf). The estimated shear wave velocities were estimated using procedures recommended by Robertson (2009), which correlated well with the measured values reflecting the slight cementation in the soft rock.

The tower was supported on a variable thickness mat foundation. The mat foundation was founded on 1.5m of on-site select granular engineered fill derived from the Terrace Deposits compacted to a minimum relative compaction of 95% per ASTM D1557. Monterey Formation soft rock material approximately 6m below the original ground surface underlies the thin zone of engineered fill. The following sections discuss the procedures used for evaluation of the mat foundation settlements, which are compared with the survey values measured during different stages of construction.

3 SETTLEMENT EVALUATION

Mat (raft) foundations are generally used where the total and/or especially differential settlement of the spread footings is an issue. Mat foundations result in less settlement by spreading the column loads over a larger area and bridging soft lenses of compressible soils. In addition, the rigidity of a mat foundation can connect the columns and prevent differential movement of individual columns, thus allowing a larger tolerance for total settlements. Settlement of the mat foundation was evaluated using three different methods: i) Finite Element Analysis (FEA) using the Winkler foundation model over an elastic subgrade and measured shear wave velocity, ii) the one-dimensional (1-D) Terzaghi's consolidation theory using consolidation laboratory test results, and iii) the 1-D Terzaghi's consolidation theory using the constrained modulus from CPT data.

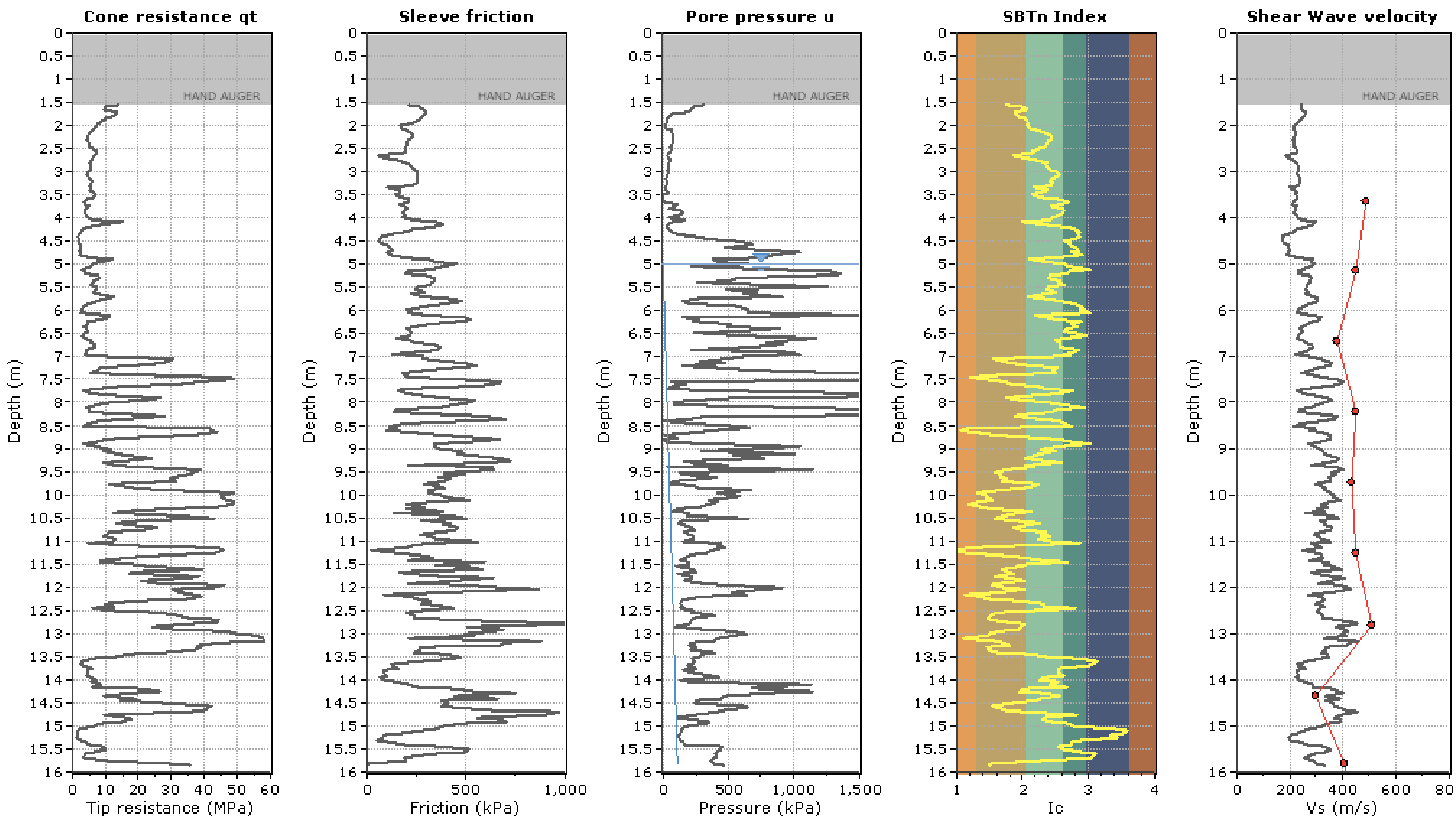

Figure 1- Representative CPT profile of the Terrace Deposits over the soft rock with the measured shear wave velocities.

3.1 Method 1 – Finite Element Analysis Using Winkler Foundation Model Over Elastic Subgrade

The Winkler foundation model considers a linear relationship between the bearing pressure and foundation deflection. This model is presented with a simple equation as follows:

$$P = k_s w \tag{1}$$

Where, P is bearing pressure, k_s is the subgrade modulus, and w is the foundation deflection. Terzaghi (1955) recommended adjusting the subgrade modulus k_s for full-sized footings based on plate-load tests and foundation size for clay as follows:

$$k_s = k_1 \frac{B_1}{B} \tag{2}$$

k_1 is the subgrade modulus based on a 30x30cm (B_1 = 30 cm) plate load test. Vesic (1961a and b) correlated the subgrade reaction modulus to modulus of elasticity of subgrade and foundation size as presented in Equation 3.

$$k_s = \frac{0.65}{B} \sqrt[12]{\frac{E_s B^4}{E_f I_f}} \frac{E_s}{1-\mu^2} \tag{3}$$

Where E_s and E_f are modulus of soil and foundation, and B and I_f are footing width and its moment of inertia based on cross section, respectively. Since the twelfth root of any value times 0.65 will be close to 1, Equation 3 may be simplified to Equation 4 for practical purposes.

$$k_s = \frac{E_s}{B(1-\mu^2)} \tag{4}$$

Based on the measured shear wave velocities from seismic CPT, the average shear wave velocity was estimated to be 335 m/s for the upper 15 m of bedrock below the mat slab, which resulted in a bedrock Young's Modulus of 600 MPa (1,250 ksf) assuming a Poisson ratio of 0.35. The subgrade modulus (k_s) was estimated to be 15.5 MN/m^3 (57 pci) for a 42.7 by 42.7 m mat slab using Equation 4. The maximum settlement of the mat slab was estimated to be about 15mm using FEA. Figure 2 presents the settlement contours in inches for this case. A parametric study showed that the maximum total settlements varied between 5 mm and 47 mm for subgrade modulus of 68 MN/m^3 (250 pci) and 3.6 MN/m^3 (13 pci), respectively.

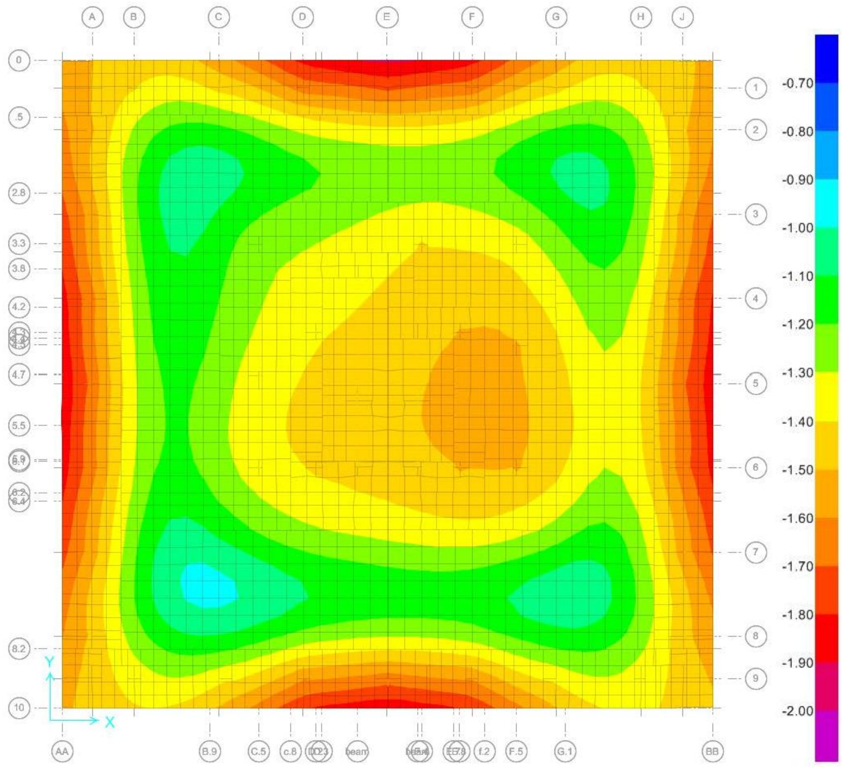

Figure 2- Mat slab settlement contours in centimeters under 100% of dead loads for $k_s = 15.5$ MN/m^3 (57 lbs/in^3)

3.2 Method 2 – 1-D Terzaghi's Consolidation Theory Using Consolidation Laboratory Tests

The second method used was the conventional 1-D consolidation theory. Since the mat slab was supported by 1.5 m of engineered fill compacted to 95% relative compaction per ASTM D1557 and bedrock, the slope of the consolidation test rebound curve was used to evaluate the mat slab settlement. Seven consolidation tests were performed on samples of the bedrock obtained using a thick walled Modified California driven sampler. Three consolidation tests were also performed on compacted fill samples. Due to the over-consolidated nature of the bedrock and compacted fill, the settlements under the building loads were expected to be predominately elastic and to occur along the unloading curve. The slope of the bedrock rebound curves ($C_{\varepsilon s}$) ranged between 0.6% and 2.8% with an average of 1.59%, standard deviation of 0.78%, and a minimum value of 0.6%. The compacted engineered fill behaved more uniformly with a $C_{\varepsilon s}$ range of 0.23% to 0.4% with an average of 0.32%. A settlement of 57 mm was estimated below the middle of the mat slab using the average $C_{\varepsilon s}$ of 1.59% for bedrock with $C_{\varepsilon s}$ of 0.32% for engineered fill. The settlement magnitude was reduced to 21.6 mm when the minimum $C_{\varepsilon s}$ of 0.6% was used for the bedrock.

3.3 Method 3 – 1-D Terzaghi's Consolidation Theory Using Constrained Modulus from CPT Data

The soil 1-D constrained modulus "M" can be estimated utilizing CPT data (Robertson, 2009). M is linked to consolidation parameters as follows, where m_v is the 1-D coefficient of compressibility:

$$M = \frac{1}{m_v} = \frac{\delta\sigma_v}{\delta\varepsilon} = \frac{2.3\,(1+e_o)\sigma'_{v0}}{C_c} \tag{5}$$

The constrained modulus is correlated to CPT tip resistance by the following empirical relationship:

$$M = \alpha_M\,(q_t - \sigma_{vo}) \tag{6}$$

Robertson (2009) recommended the following correlations between α_M and q_t, which consider the soil behavior type index (I_c) in addition to the cone penetration tip resistance:

If $I_c > 2.2$:

$\alpha_M = Q_t$ $\quad$ $Q_t < 14$

$\alpha_M = 14$ $\quad$ $Q_t > 14$

If $I_c < 2.2$:

$$\alpha_M = 0.0188\,[10^{(0.55\,I_c + 1.68)}] \tag{7}$$

Robertson (2009) also suggests that estimation of drained 1-D constrained modulus from undrained cone penetration will be approximate, and the estimation may be improved by additional soil information such as plasticity index, natural moisture content and in-situ shear wave velocity. Finally the volumetric strain of soil and the settlement may be calculated using Equations 8 and 9, respectively.

$$\varepsilon_{vol} = {\Delta\sigma'_v}/{M} \tag{8}$$

$$s = \left({\Delta\sigma'_v}/{M}\right)H \tag{9}$$

Two CPTs were performed within the tower footprint. Using the constrained modulus, total settlements of 16.5 mm and 18 mm were estimated at these locations for a uniformly distributed total load.

4 OBSERVED SETTLEMENTS

The mat slab settlement was measured at several locations at different times during the building construction. The final measured settlements were surveyed when approximately 83% of the dead loads were applied (i.e., 100% of steel and concrete, 50% of studs, and 15% of drywall loads). The surveys were not continued due to budget and measurement difficulties. The measured settlement at 83% of the dead load was 20.1mm. Although the mat slab was relatively thick, FEA indicated that the foundation is still flexible enough to have bearing pressure concentration differences between the inner core and the area between the core and the outer column on the order of 3 times. In order to compensate for the uneven distribution of the bearing pressures, a minimum uniform stress distribution was considered below the mat foundation and additional segments of stress were applied independently as separate foundations at different areas to model the stress concentrations. The calculated settlements were later added for different sections of the mat foundation. Since the engineered fill and bedrock deformations were assumed to occur along the consolidation rebound curves and are elastic deformation, this approach was considered acceptable.

Therefore, considering 83% of the dead load at the time of the final survey at the site and the stress concentration below the mat slab, the following table compares the maximum estimated settlement of the mat slab using different methods with the observed settlements:

Table 1 – Comparison of the maximum observed settlement and estimated settlements

Estimation Method	**Settlement (mm) @ 83% Dead Load**
1-D Consolidation (Ave. $C_{\varepsilon s}$, Max. $C_{\varepsilon s}$, Min. $C_{\varepsilon s}$)	52.6, 92.7, 19.8
FEA* using Winkler Foundation Model and k_s from Vs	12.7
CPT	15.3 - 19.3
Measured Settlements	**20.1**

* FEA: Finite Element Analysis, interpolated based on the percentage of the applied dead load at the time of measurement (i.e., 83% dead load).

The modulus values based on laboratory consolidation tests resulted in the widest range of estimated settlement. While the estimated settlement based on the average rebound slopes resulted in a settlement more than 2.5 times the measured value, the maximum measured rebound slope resulted in excessive settlements, and the minimum measured rebound slope (assuming it was the least disturbed sample) resulted in a reasonable value. Sample disturbance can have a major effect on the results from consolidation tests. The FEA using the elastic subgrade modulus underestimated the settlement due to the sole use of elastic bedrock properties.

Finally, the CPT provided an easy method for estimating the settlement predicting the elasto-plastic bedrock deformation by the constrained modulus. The CPT data resulted in significantly less variation than the consolidation tests.

5 SUMMARY

This paper presents an evaluation of settlement of a large mat foundation constructed over Monterey Formation soft rock in southern California. Monterey Formation is silty clay to clayey silt soft California bedrock. The samples used for laboratory consolidation tests are generally obtained by hammering a thick wall Modified California sampler into the ground. Due the sampling method, the samples are disturbed and the traditional consolidation tests result in high settlement estimates. The sample disturbance may be significantly reduced using a high quality sampling method such as Pitcher Tube sampling and careful sample set up.

Bedrock settlement is generally associated with elastic deformations as opposed to plastic deformations. Therefore, the deformation analysis using the elastic properties of the bedrock, such as subgrade modulus obtained from measured rock elastic properties, results in a reasonable estimate of the mat slab settlement. However, the settlements are expected to be underestimated since only the elastic deformation of the soft rock is considered in the analysis.

This case history demonstrates that using conventional consolidation test results may direct the geotechnical engineer to much more conservative design recommendations such as potentially recommending deep foundations since engineers generally use the maximum potential settlements to reduce their liabilities due to the high uncertainties shown by the test results.

CPT results combined with constrained modulus approach resulted in: i) reliable evaluation of the site based on continuous measured properties of the subsurface material, ii) introduction of no sample disturbance, iii) the least variation, and therefore iv) a reasonable estimate of the bedrock settlement considering both elastic and plastic deformation of the bedrock. CPTs have the penetration limitation and refusal wherever a hard layer is encountered. If the hard layer is consistent below the refusal depth, its contribution to the settlement may be considered negligible, otherwise, the hard layer should be predrilled and CPTs should be continued.

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