Predicting consolidation settlements using small-strain, large-strain and stress path methods

Prédiction du tassement des sols consolidés en se servant des méthodes de contrainte basse, de contrainte élevée et du chemin d'écoulement

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ABSTRACT

Primary consolidation settlement has traditionally been estimated using 1-D linear elastic consolidation theory with various assumptions. Due to theoretical limitations, measured settlements in many cases are not in agreement with those predicted. One of the major limitations is the application of small strain theory to large strain deformation. Another limitation is the stress dependent behaviour of soil deformation. This paper summarizes the various factors affecting settlement predictions and compares results from conventional 1-D small strain theory, finite different modelling, finite element modelling applying large strain theory and the stress path method. The results are compared with actual field monitoring data from recent projects in Singapore at the Changi East Land Reclamation and Ground Improvement Project. The reasons for variations in measured results are also discussed.

RÉSUMÉ

Le compactage associé à la consolidation originale a traditionnellement été utilisé pour en estimer la valeur selon la théorie de consolidation unidimensionnelle, avec l'aide de certains postulats. En raison des restrictions théoriques, les compactages mesurés ne concordent pas toujours avec les valeurs estimées pour le compactage. L'une des restrictions principale est l'application de la théorie des faibles contraintes aux déformations dues à de fortes contraintes. Une autre restriction est le comportement de déformation des sols relié au travail. Cet article résume les différents éléments qui influencent la capacité de compression des sols et étudie les différences entre la valeur prévue du compactage selon l'application de la théorie conventionnelle des faibles contraintes unidimensionnelles, la modélisation des différences finies ainsi que la modélisation des éléments finis en appliquant la théorie des fortes contraintes et selon la méthode du trajet du travail. Les résultats sont ensuite comparés à des données de contrôle de terrain, obtenues lors de récents projets à Singapour, c'est-à-dire le « Changi East Land Reclamation and Ground Improvement Project. » Les raisons pour la variation dans les résultats obtenus sur le terrain sont aussi discutées dans cet article.

Keywords: consolidation, settlement, compressibility, stress, finite element modelling.

1 INTRODUCTION

Terzaghi's one dimensional (1D) consolidation theory is often used to predict the magnitude and time rate of settlements. With a precise measurement of soil compression of a thin layer of soil in the laboratory under one dimensional loading, engineers have often managed to predict performance very closely. However, in many cases more than a 20% variation is obtained despite exercising very good judgment. This is due to many reasons including; i) the field behaviour departs from the assumptions made in the 1D theory, ii) the field conditions differ from the laboratory conditions, iii) the rate of loading and the rate of strain experienced by the soil in laboratory and field differ and, iv) the limitations of the 1D theory for a three-dimensional (3D) problem. Limitations to conventional analysis have been illustrated with case studies by Duncan (1993) in his Terzaghi lecture. This paper discusses the various methods of settlement prediction and compares the predicted results with a well documented case study.

2 AVAILABLE METHODS

Settlement of compressible soil can be predicted by applying the following methods:

1. Using volume compressibility crudely in the stress range of interest in which stress history is not considered.
2. Using the compression parameters from both the recompression and virgin compression ranges below and above the yield stress, respectively.
3. 2D finite difference models (FD) which apply Terzaghi's effective stress theory but taken into consideration large strain deformation, submergence and non-linear stress-strain effects).
4. Lastly, a stress deformation analysis using 2D finite element modelling which considers all effects in FD plus a non-horizontal ground profile, various initial in-situ stress states and additional vertical deformation caused by horizontal displacement.
5. Alternatively, final settlement can be interpreted from field settlement data applying Asaoka (1978) or the hyperbolic methods (Sridharan & Rao 1981) provided records are available to at least the 60% degree of consolidation.

One of the key parameters in any of the above settlement predictions is the yield stress of soil, which will be discussed in details in the next section.

3 YIELD STRESS

Yield stress (σ'_y) is generally obtained from e log σ'_v curves from laboratory oedometer data by applying the Casagrande graphical method (Casagrande, 1936). However, there are

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uncertainties involved in this determination. It is well known that yield stress determination is heavily affected by sample disturbance. Bo et al. (1997a) also demonstrated that different interpretation methods may provide up to 20 or 30% greater σ'_y than the Casagrande method. Furthermore a different σ'_y can be obtained from the same test results when the void ratio scale is varied. Furthermore, obtaining a reliable σ'_y from the 1D consolidation test is somewhat questionable as deformation of soils are also known to be stress/strain dependent. Leroueil (1985) and Bo et al. (1998) have demonstrated that σ'_y generally increases with stain and loading rates.

A more general method when carrying out 3D settlement prediction is to obtain yield stresses along different stress paths and determine the yield locus. More accurate settlement prediction can then be made using yield locus or an elasto-plastic stress-strain analysis.

The in situ σ'_y can also be interpreted from field stress-deformation measurements under a 1D assumption using settlement gauges and pore pressure piezometer data.

4 PREDICTION OF SETTLEMENT USING STRESS PATH METHOD

It is known that stress paths for normally consolidated soil are geometrically similar. Furthermore, points representing equal strain fall approximately in a straight line passing through the origin in a p' vs q' plot. These two basic observations for effective stress paths are useful in predicting settlement of soft clay by the stress path method.

The effective stress path varies depending upon the major and minor principal stresses applied and affects the axial versus lateral deformation. However for normally consolidated clays, volume change between any two points on 2 effective stress paths on the the p' vs q' plot is assumed to be equal while the axial strain varies depending upon the stress path. For example, in isotropic compression there will be equal strain in all directions whereas under k_0 compression, there will be only axial strain. Between isotropic compression and $k_{0,}$ more axial compression with some lateral deformation will occur. A stress path above the k_0 line would contribute more lateral strain than axial strain. Therefore, an advantage of the stress path is that both axial and lateral deformation can be estimated depending upon the effective stress changes during load application.

To analyze the settlement manually using the stress path method, one has to carry out a 1D consolidation test in conjunction with consolidated undrained triaxial tests on the sample at several confining pressures. Stress-strain contours are generated on the p' vs q' diagram. Using the effective friction angle obtained from CU tests the k_0-line is generated on the stress-strain contour. Knowing the in situ stress state and the stress increment, the stress path can be plotted on the p' vs q' diagram. The strain can be obtained from the strain contour on the p' vs q' diagram, and subsequently settlement calculated. This process must be repeated for all sub-layers and summed to obtain the ultimate primary consolidation settlement.

5 CASE STUDY

Several pilot test embankments were built in the course of the 2000 ha, $3 billion Changi East Reclamation Project to monitor deformation of underlying soils. Various geotechnical and ground improvement aspects have been extensively published previously by Bo et al., Arulrajah et al. and Chu et al. between 1997 and 2008. In most test embankments prefabricated vertical drains (PVD) were installed to accelerate the consolidation process so that final settlement could be realized earlier and performance of PVDs at various spacings could be assessed. The fill loads applied were well beyond σ'_y to ensure the underlying soils compressed into the virgin compression range. Test embankments were instrumented with settlement gauges and piezometers at various levels. One test embankment with soil profile and instrumentation is shown in Figure 1.

5.1 *Soil profile and characteristics of compressible soils*

In order to characterize the strength and compressibility of underlying soils, conventional boring and sampling as well as various specialist in-situ tests including strain controlled Field Vane Shear (FVT), Cone Penetration (CPT), Dilatometer (DMT), Self-boring Pressuremeter (SBPT) and BAT Permeameter (BAT) were carried out. The seabed at the reclamation area ranged from –3 to –15 mCD (Admiralty Chart Datum, where the mean sea level is at +1.6 mCD). A typical soil profile is shown in Figure 2. The profile can be divided into 4 layers: the upper marine clay, the intermediate stiff silty clay or/and the silty sand, the lower marine clay and the old alluvium. As indicated in Figure 2, the upper and lower marine clay is highly compressible and high in water content. Except for the top few meters, the marine clays are lightly overconsolidated. The intermediate layer is overconsolidated, stiff and low in both compressibility and moisture content. A summary of soil parameters including critical state parameters is shown in Table 1. The profile of yield stress can be found in Figure 2. More detailed descriptions of Singapore Marine Clay can be found in Bo et al. (1997b, 1998) and Chu et al. (2002).

Table 1. Soil parameters used for full-scale analysis of PVD.

Material	Reclamation Sandfill	Upper Marine Clay	Intermediate Stiff Clay	Lower Marine Clay
Model	Mohr-Coulomb	Soft Soil	Soft Soil	Soft Soil
Response	Drained	Drained	Undrained	Undrained
γ_{unsat} (kN/m³)	17.00	15.00	15.00	15.00
γ_{sat} (kN/m³)	20.00	15.50	15.50	16.00
k_h (m/day)	1.000	4.67E-6	1.10E-5	4.95E-6
k_v (m/day)	1.000	2.34E-6	5.50E-6	2.48E-6
E (kN/m^2)	13000	–	–	–
ν (–)	0.3	–	–	–
G (kN/m^2)	5000	–	–	–
E_{oed} (kN/m^2)	17500	–	–	–
c (kN/m^2)	1.00	1.00	1.00	1.00
φ (°)	31	27	32	27
ψ (°)	0.00	0.00	0.00	0.00
λ^* (–)	–	0.150	0.060	0.170
κ^* (–)	–	0.018	0.011	0.025
ν_{ur} (–)	–	0.150	0.150	0.150
k_0^{nc} (–)	–	0.55	0.47	0.55

Legend: γ = soil unit weight; c = cohesion; k = hydraulic conductivity; φ = friction angle; E = Young's modulus; ψ = dilatancy angle; ν = Poisson's ratio ; λ^* = modified compression index; G = shear modulus; κ^* = modified swelling index; E_{oed} = oedometer modulus.

5.2 *Prediction of final settlement*

Predictions of final settlement were made with various methods:

1. Conventional one dimensional theory. Compression parameters from relevant stress levels were used to calculate together with appropriate yield stress values.
2. Finite difference method (FDM) applying 1D effective stress theory considering large strain effects, soil

parameter changes during consolidation, non-linear deformation and consolidation behaviour, submergence effects. The same parameters as Method 1 were used; however, the duration of consolidation was analyzed until no change in settlement occurred. Stage construction was applied for each stage of loading including change in groundwater level.

3. Finite element method (FEM) applying stress deformation analyses considering all effects described above. Conventional soil parameters were converted to plain strain critical state parameters. Stage construction and groundwater level changes were applied. Consolidation was allowed until excess pore pressures dissipated to 1 kPa at each soil element.
4. The Asaoka and hyperbolic methods using monitoring data at 80% consolidation (described in detail by Bo et al. (1997a).
5. The stress path method using the yield locus obtained from stress path tests (described in Section 4 above).

In the analyses, σ'_y obtained from Janbu (1969) was used as this method does not involve errors arising from graphical methods. For the stress path method an appropriate yield stress was obtained from the yield locus.

Results of the analyses are presented in Table 2. Settlements reported in Table 2 are at the centre point of the test embankment where maximum settlement was recorded (variations occurred across the embankment due to the variation of stress influence, principle stress rotation and back pressure effect from outside the embankment (Bo et al. 1999a). In addition, predicted settlements discussed herein are Class "A" prediction for Methods 1 & 2, Class B for Methods 3 & 4 and Class C for Method 5 (Lambe 1973). The predictions discussed here are for a 1.5 X 1.5 m PVD spacing for which a high degree of consolidation was achieved during monitoring.

Table 2 indicates that the Class A prediction using 1D consolidation theory predicted up to 34 % higher ultimate settlement despite incorporating thickness changes during two stages of construction. The FD method as used in design was closer, over-predicting by 11% as it takes into consideration many realistic effects explained earlier except for principal stress rotation and strain rate effects. The FEM proved even more accurate, within 1%, taking into consideration stress distribution as well as strain rate effects. Note, however, that the latter was a Class B prediction as it was carried out only halfway through consolidation. An FEM analysis output is shown in Figure 3.

5.3 *Field measurements and comparison*

Other Class B predictions using field settlement data collected at 80% consolidation applying the Asaoka and hyperbolic methods still overestimated the ultimate settlement by 11%. It has been reported by Bo et al. (1999b) and Arulrajah et al. (2004 & 2008) that results are affected by data duration for both methods, and the time interval selected for the Asaoka method. A smaller time interval used in the Asaoka method predicted slightly greater settlement. The hyperbolic method generally predicts higher settlement with longer duration data, in this case, both methods still overestimated the ultimate settlement and further study of this is currently in progress.

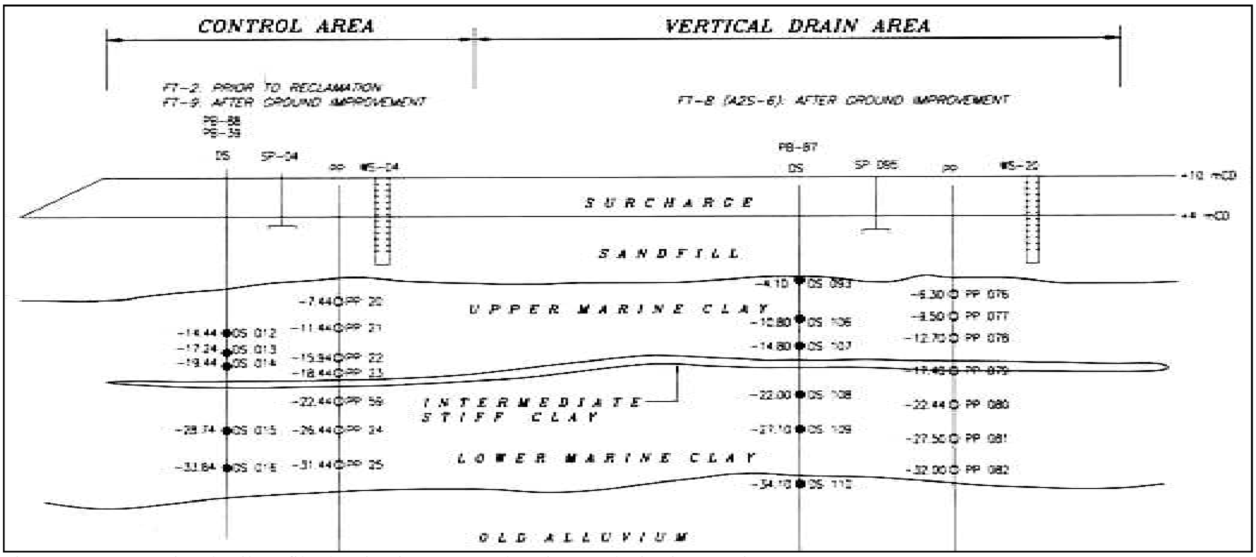

Figure 1. Cross sectional soil profile showing instrument elevations at the in situ test site.

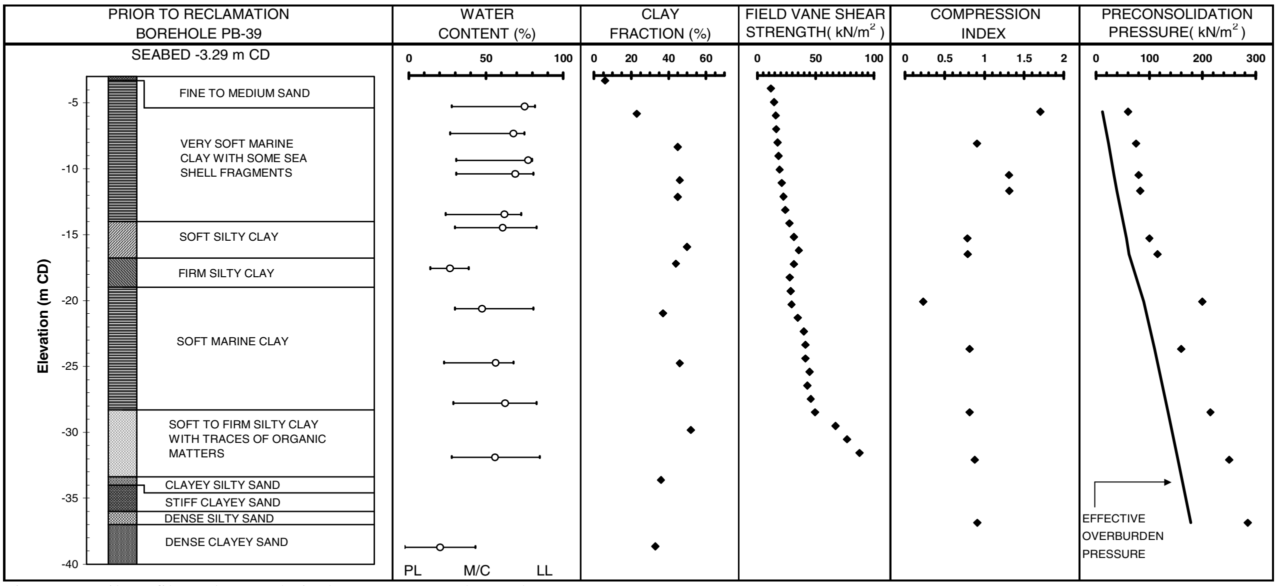

Figure 2. Soil profile and geotechnical parameters at the study area.

Table 2. Ultimate settlements estimated using various methods.

Type	Method	Settlement (m)
Class A	1D	3.615
	FD	3.005
Class B	Asaoka	3.000
	Hyperbolic	3.005
	FEM	2.640
Class C	Stress Path	2.908
Measured	At 20 months after fill placement	2.404
	Final	2.703

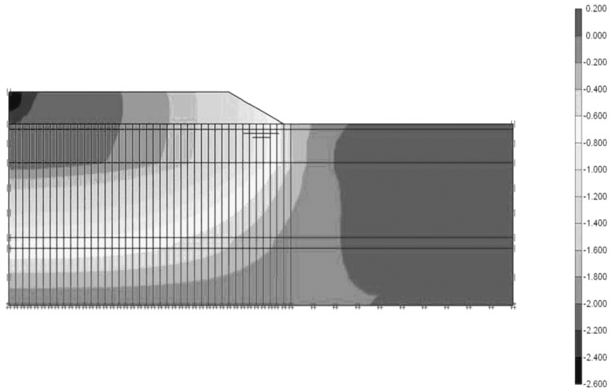

Figure 3. Contours of vertical displacement by full-scale finite element analysis.

The stress path method, despite the after-the-fact Class C prediction, only predicts within 8% accuracy. Stress path method predicts much better than 1D and FD as it takes into consideration a more accurate yield stress and stress path. However it cannot take into consideration large strain and submergence effects. That is likely the reason the stress path method predicts slightly higher.

The prediction experience for Singapore marine clay indicated that accurate prediction of ultimate settlement, requires precisely measured insitu tests (CPTU, FVT, DMT, SBPM), all under controlled strain rate with well calibrated equipment. Furthermore, compressibility and yield stress parameters must be correctly interpreted from laboratory tests carried out in a controlled environment with precisely calibrated equipment on carefully retrieved and transported samples. Also essential are an accurate pre-fill soil profile, existing surface level, magnitude and rate of loading, construction sequence and any changes in post reclamation groundwater level.

6 CONCLUSIONS

There are several methods that can be used to predict the ultimate consolidation settlement of soft soil: conventional 1D consolidation test, finite difference, finite element, stress path and methods based on field monitoring data. While the conventional method suffers several limitations, the finite difference method can consider large strains, submergence and non-linear strain effects. The finite element method can apply stress deformation analysis and take into account plain strain behaviour, principal stress rotation and strain rate effects.

Based on the case study carried out for a test area at the Changi East reclamation project in Singapore, an FD Class A prediction over-predicted the settlement by 11%. The most accurate prediction was a Class B FEM method. The Asaoka and hyperbolic methods (Class B) slightly overestimate ultimate settlement, whereas the stress path method (Class C) predicted more closely than FD.

Regardless of the method used, accurate settlement prediction required accurate geotechnical parameters using good quality in-situ and laboratory tests together with a complete understanding of site conditions and construction sequence.

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