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DS1.2 - Invited discussion

Spoil heaps and waste dumps: Settlement calculations revisited

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1 INTRODUCTION

Classical settlement calculations rely on obtaining reliable soil deformation characteristics from one-dimensional compression tests performed in an oedometer. The success of the settlement predictions hinges heavily on our ability to obtain representative undisturbed specimens from the site for which the settlement is being calculated. It is generally accepted that a correct determination of the preconsolidation stress is of a paramount importance in the design and for the correct forecast of expected settlement (Leonards and Altschaeffl, 1964). However, unavoidable sample disturbance during boring, sample retrieval and laboratory specimen preparation procedures affects the deformation characteristics of the soil and especially the value of the preconsolidation stress. Methods, have been devised to correct for such disturbances and to reconstruct the "*in situ*" compression curve for the soil (Schmertmann, 1955).

The above approach has served us well for routine applications and in soils where undisturbed samples could be obtained with a reasonable effort and with standard equipment. In the cases when sampling is difficult and when even the "undisturbed" samples are severely disturbed, the geotechnical engineer is left without a suitable method to determine the consolidation characteristics and to forecast the settlements. Such conditions are often encountered in young sediments and during the reclamation of the waste dumps such as mine tailings and dredging spoils ponds.

In the following we present our observations of one-dimensional compression characteristics of both normally-consolidated and overconsolidated soils. Then we demonstrate that "undisturbed" samples are not a prerequisite for a reliable prediction of anticipated settlements and that a more cost effective site investigation strategy could be substituted for undisturbed sampling.

2 ONE DIMENSIONAL COMPRESSION

Liu and Znidarčić (1991) proposed an expression for modeling one-dimensional compression characteristics of soils in the form:

$$e=A(\sigma'+Z)^{B} \qquad (1)$$

in which e is the void ratio, σ' is effective stress and A, B (always negative) and Z are the model parameters. It was also demonstrated that the analytical expression is flexible enough to properly model the one-dimensional compression behavior of various soils ranging from overconsolidated clays to normally consolidated materials and even to sensitive Mexico City clay.

It is noted that the number of model parameters (three) is the same as for the conventional model (C_c, C_s, σ'_p) and without a need for a reference void ratio.

Several other advantages of the model can be cited. The void ratio is defined for zero effective stress state and the void ratio is always positive irrespectively of the effective stress magnitude. In addition there is no discontinuity in the function nor in its derivative as is the case for the conventional model. This certainly simplifies its implementation in any numerical code. The compressibility is obtained as the derivative of the compression function in the form:

$$de/d\sigma' = AB(\sigma'+Z)^{B-1} \tag{2}$$

or

$$de/d\sigma' = A^{1/B}Be^{(1-1/B)} \tag{3}$$

The model exhibits some interesting characteristics that are worth noting in relation to the behavior of normally consolidated and overconsolidated soils. For a normally consolidated sample the Z parameter will have a low value, while for an overconsolidated sample the Z parameter will have a value that approximates the preconsolidation stress. The effective stress and the Z parameter are addends in the model and they are undistinguishable to the resulting void ratio. Thus, an overconsolidated sample has the same compressibility characteristics under low normal stresses as a normally consolidated sample of the same material but at a higher stress level. In other words, the compressibility of a soil element depends only on the current void ratio (for a saturated sample that means on the current water content) and is not affected by the stress level, as shown in Eq. 3. This might appear at first as a revolutionary idea, but, as the example presented here will demonstrate, the above approximation generates only errors acceptable to the engineering application of an oedometer test.

3 SETTLEMENT CALCULATIONS

Settlement of a structure is obtained by integrating strains of the underlying soils over the depth of influence, i.e. in the zone where the stress increase is significant and where the strains are substantial. The stress increase is often calculated from the Bousinesque solution to the stress distribution problem, or by any other method that satisfies the equilibrium conditions, while the initial stresses are calculated from the geostatic loads. From the oedometer test the change in the void ratio is obtained for each sublayer for which the stress change could be considered uniform. The strain is then obtained by:

$$\varepsilon = \frac{\Delta e}{1+e_o} \tag{4}$$

Alternatively, the oedometer test is presented directly in the form of strain as a function of stress. It is noted that in this procedure, irrespectively of the form in which the oedometer test is presented (in terms of void ratio or strain), the initial void ratio for each sublayer is obtained from the stress calculations and the oedometer test performed on the "representative" sample. Thus, it does not necessarily represent the actual *in situ* void ratio for each sublayer. Alternative to this procedure, the initial void ratio could be obtained by directly measuring it on specimens obtained at frequent intervals in the zone of influence bellow the structure. In the case of saturated layers the void ratio distribution could be obtained by measuring water content on either disturbed samples (as long as the sampling procedure prevents water content change) or from nondestructive *in situ* tests (e.g. using neutron probes). Then, the settlement calculations depends only on our ability to predict the final void ratio under the new loading conditions for each sublayer in the zone of interest.

From the compressibility relationship presented in the form of Eq. 1, follows that the void ratio is a unique function of the effective stress and such a function can be obtained from a disturbed sample representative of the material (or materials) *in situ*. The sample is reconstituted in the lab by adding water (from the site if possible) so that a homogeneous slurry sample could be tested in the seepage induced consolidation test (Abu-Hejleh and Znidarčić, 1996). The parameters A, B and Z are obtained from the test representing the "virgin" behavior of the material. In general the Z parameter value will be low and will depend on the initial void ratio at which the slurry was prepared. From the normally consolidated relationship the Z parameter value for each sublayer can be obtained from the measured initial *in situ* void ratio and the initial effective stress using Eq. 1. The A and B parameters are the same as obtained from the seepage induced consolidation test on the slurry specimen. Thus, compressibility relationships are obtained for each sublayer from which the final void ratio for the sublayer is calculated. With the *in situ* measured initial void ratio and using Eq. 4, the strain for the sublayer is determined. The final settlement calculation is obtained in the same fashion as in the conventional analysis.

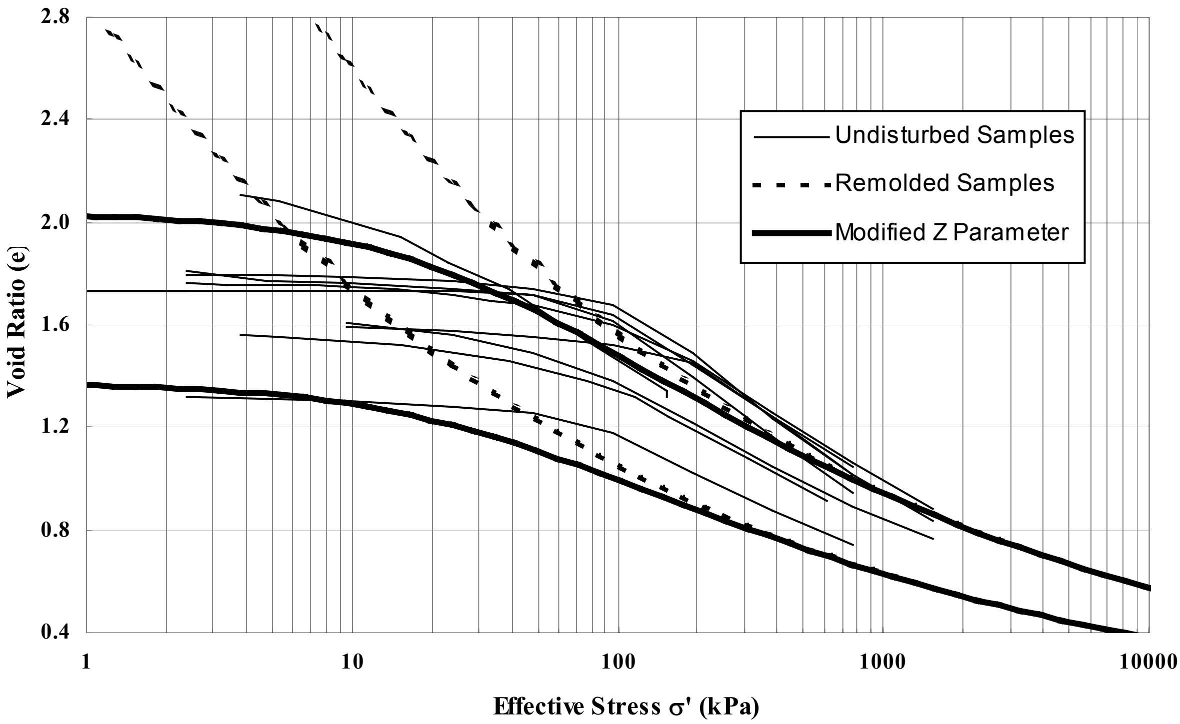

Figure 1. Compressibility Characteristics from Remolded and Undisturbed Samples of San Francisco Bay Mud.

The procedure described here is demonstrated in Fig. 1 in which the results of the seepage induced consolidation test on remolded samples of San Francisco Bay Mud are compared with the compression curves obtained from undisturbed samples from the same area. When the Z parameter is modified so that the initial void ratios of the undisturbed samples are matched, the "undisturbed" curves and the curves obtained from the remolded samples approximate each other quite well. While some difference is noted, the corresponding settlement calculations might not produce significantly different values. One also wonders how "undisturbed" the undisturbed samples really were.

4 CONCLUSIONS

The discussion presented here indicates that reliable, *in situ*, compressibility characteristics can be obtained from remolded specimens in the laboratory. The laboratory determined curves are modified to match the *in situ* void ratios, which can be obtained from the simple water content measurements. The settlement is then calculated from the expected void ratio changes and the initial void ratios.

The presented approach requires much more economical field work and allows for settlement calculations at the sites where is not possible to obtain good quality undisturbed samples. The procedure is certainly applicable to young sediments, such as waste dumps, but it is possible to apply it to the conventional terrestrial sites with overconsolidated clays. Its reliability in such situations still needs to be verified by carefully conducted field studies.

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