Settlement prediction of footings considering stress history based on V_S

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ABSTRACT: A new settlement prediction method, which is based on shear wave velocity (V_S) measurement and nonlinearity of soil, was developed and verified by a centrifuge test. The development was derived from the conceptual framework of Schmertmann's method (1978). The procedures for obtaining confinement and strain-dependent modulus values from V_S-profile considering pressure distribution under the footing were developed. The developed method was, then, refined considering stress history of ground based on OCR (overconsolidation ratio) evaluation to incorporate plastic deformation of soils on settlement calculation. A relationship between G_o and OCR from V_S measurement was adopted to identify the stress history of subsurface. From the evaluated OCR, an empirical coefficient (f) was determined to consider the plastic deformation over elastic region. Finally, the refined method using the empirical coefficient (f) was validated by a centrifuge testing result.

1 INTRODUCTION

The Schmertmann's method (1978) has been extensively applied for predicting the settlement of shallow foundations by engineers due to its simplicity and intuitive concept based on elasticity theory. The method utilizes CPT tip resistance (q_c) to evaluate the Young's modulus using soil-type-based empirical coefficients. For predicting settlement, the crucial factor is, however, deformation related stiffness and not the strength. Even though modulus determination from SPT-N or CPT-q_c is generally adopted, the penetration resistance is strongly related to the soil strength and requires additional empirical coefficients to convert soil strength to soil modulus. This is the intrinsic limitation of using strength parameters in the settlement prediction.

The shear wave velocity (V_S) could be an alternative parameter in the settlement prediction to resolve the aforementioned problem. The V_S is directly related to the deformation characteristics of soil (i.e., the maximum shear modulus, G_o). The entire soil deformation characteristics could be established by combining the V_S and laboratory tests. Hence, the V_S can be used as a key soil property for the deformation analysis of soil-foundation systems.

This study aims to develop a new approach for predicting load-settlement behavior of shallow footings based on the V_S and nonlinearity of soil. The development of the new method was based on the conceptual framework of Schmertmann's method (1978) which is one of the commonly used methods in engineering practice. The developed method, then, was refined to incorporate the plastic deformation over elastic region because the Schmertmann's method was originated from the theory of elasticity.

2 NEW SETTLEMENT PREDICTION METHOD

2.1 *Schmertmann's approach using V_S*

A new settlement prediction method based on Schmertmann's approach is proposed combining modulus derived from V_S (G_o) considering soil nonlinearity and strain influence factor profile (I_z) from the elasticity theory. The deformation modulus, E_{ij}, of each soil layer considering both the stress-dependent stress-strain relationship and nonlinear stress-strain hyperbolic equation can be expressed as:

$$E_{ij} = E_{o,j}\left(\frac{\sigma_{o,j}+q_i I_{z,j}}{\sigma_{0,j}}\right)^n \left(1 - f\left(\frac{q_i I_{z,j}}{\sigma_{max}}\right)^g\right) \tag{1}$$

where, $E_{0,j}$ is the initial small strain Young's modulus equal to $E_o=2G_o(1+\nu)$, $\sigma_{0,j}$ is the initial vertical stress at depth z_j, q_i is footing load, n is stress exponent, f & g are model parameters to have flexibility of changing the shape of the stress-strain curve and to adjust the model to approach failure at finite strain, and σ_{max} is ultimate axial bearing capacity. Total settlement of each sublayer corresponding to the applied stress q_i can be calculated using the following nonlinear stress-dependent modulus:

$$s = q_i \sum \frac{I_{zi}\Delta z_i}{E_{o,i}\left(\frac{\sigma_i+qI_{zi}}{\sigma_i}\right)^n\left(1-f\left(\frac{qI_{zi}}{\sigma_{max}}\right)^g\right)} \tag{2}$$

Finally, the footing settlements can be calculated based on the Schmertmann's framework using V_S. In this method, the elastic load-settlement response of vertically loaded footings placed in granular soil was only considered while the plastic deformation of soil caused by the particle movement was not considered.

2.2 *Considering stress history on settlement*

There is a certain limitation in the developed method for ground governed by plastic deformation such as normally consolidated (NC) loading condition. To resolve this problem, an empirical coefficient depending on the NC and OC loading conditions was incorporated in the developed method for extending the applicability of the method over elastic region. Leonards and Frost (1988) also proposed a similar method to consider the different settlement or the soil stiffness for NC and OC stress conditions by adopting the ratio of the stress increment corresponding to the NC portion and the OC portion in a given layer to the total increment of stress in the layer.

In order to evaluate whether the subsurface is in the OC loading condition or the NC loading condition according to the surface design load, the stress condition of the ground should be estimated. For this, the overconsolidation ratio (OCR) evaluation technique from V_S measurement was adopted. Cho et al. (2016) proposed a relationship between small strain shear modulus (G_o) and OCR based on V_S measurement to identify the stress history of centrifuge model ground. By establishing the relationship for the testing soil, in-flight stress states of centrifuge model ground was investigated in terms of OCR. The OCR evaluation accomplished that the OCR value of centrifuge model ground could be estimated based on Vs measurements irrespective of normally-consolidated (NC) or over-consolidated (OC) loading conditions even for cohesionless soil.

For determination of the empirical coefficient (f) with depth, elastic limit profile, which is directly related to the past maximum previous vertical stress (MPS) with depth, should be established to compare with the profile of vertical stress increment transmitted by surface design load. The MPS profile is determined for shallow and deep depth, separately. For deep depth, the MPS can be calculated by multiplying the evaluated OCR value and theoretical vertical effective stress with depth. In case of shallow depth that dominates the total settlement, equivalent-past surcharge load that causes same level of MPS (from OCR) at the initial point can be estimated using I_z from elasticity theory. The MPS converted from OCR at the nearest depth from surface give a solution to determine the equivalent-past surcharge load through backward calculation using I_z from elasticity theory. The combination of the equivalent-past surcharge load and I_z from elasticity makes the MPS profile for shallow depth. Finally, the entire MPS profile can be drawn with depth for precise determination of elastic limit of subsurface as shown in Fig. 1.

The vertical stress increment profile caused by surface design load and the elastic limit of subsurface can be compared as shown in Fig. 2. Since the design stress with depth can be expressed as a ratio of the stress transmitted by the surface design load to theoretical vertical effective stress, i.e., design OCR, and the elastic limit can also be expressed as OCR (inherent OCR), the empirical coefficients (f) can be determined by comparing the design stress profile expressed as design OCR with inherent OCR of model ground at each depth as shown in Fig. 3. Then, the determined empirical coefficient (f) is adopted in developed settlement prediction method. The empirical coefficient (f) is only multiplied to settlements caused by stress of NC portion exceeding the elastic limit at each depth.

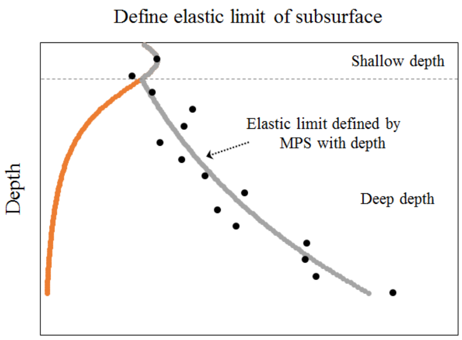

Figure 1. Determination of elastic limit profile of subsurface using the concept of MPS converted from OCR for shallow depth and deep depth, respectively

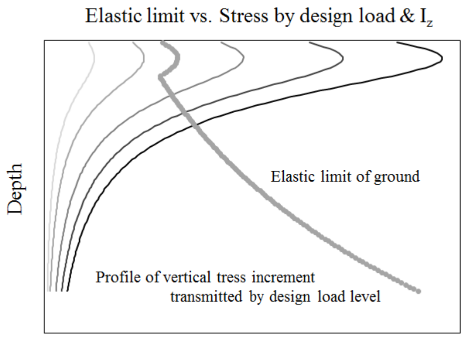

Figure 2. Comparisons of the profiles of vertical stress increment with depth transmitted by surface design load and the elastic limit of subsurface

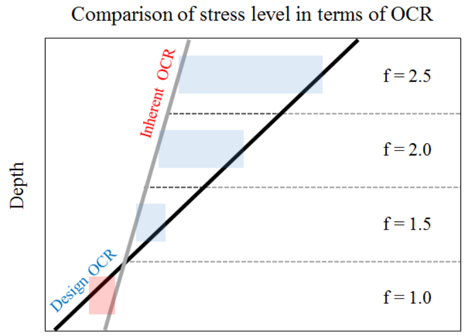

Figure 3. Determination of the empirical coefficient (f) according to difference between design OCR and inherent OCR.

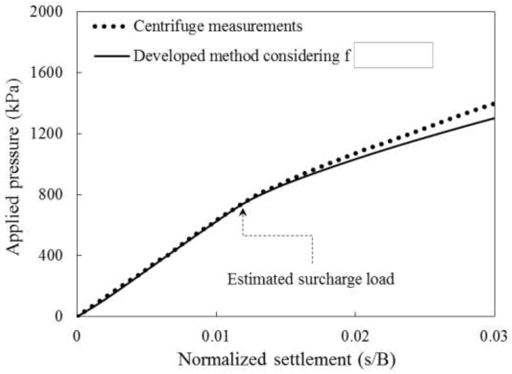

Figure 4. Comparison of load-settlement curve with predictions

2.3 *Centrifuge study*

The settlement predicted by the developed method is compared with a centrifuge test result as shown in Fig. 4 for footing having L/B ratio of 2.5.

3 CONCLUSION

In this chapter, a new settlement prediction method based on Vs measurement was developed and verified by a centrifuge test. Complete load-settlement behavior of footing could be predicted using Vs-based Schmertmann's framework considering soil non-linearity, and further plastic deformation of soil was considered using an empirical coefficient (f) from OCR evaluation.

4 ACKNOWLEDGEMENTS

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