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EVALUATION OF MECHANICAL PROPERTIES OF SAND COMPACTION PILE USING CONE PENETRATION TEST

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1. Introduction

Almost all Southeast Asian capital cities suffer from problems caused by thick deposits of soft clay due to, high compressibility and very low shear strength. As a method of improving the engineering properties of soft soil such as shear strength and compressibility, Sand Compaction Piles (SCPs) are widely used in Japan. SCPs reduce the total settlement as well as the differential settlements, and increase the bearing capacity.

2. Behavior of SCP Improved Ground

The ground improved by the low replacement SCP should be evaluated as a composite ground consisting of sand piles and soft soil. In this case, sand piles are expected not only to bear the load placed on the ground but also to drain pore water in soft soil to enhance consolidation of the soil. The strength of the composite ground increases with time when a low replacement SCP is applied.

When a soft clayey ground is improved by SCPs, the angle of internal friction (ϕ'), of the SCP improved ground is usually evaluated from *N*-value obtained by Standard Penetration Test (SPT) using empirical correlations derived for sandy ground. Sand piles are usually very slender and it is very difficult to make the bore at the exact center of the SCP. Even if SPT is carried out at the center, the area of sand pile is not so wide as in the sandy ground in which the empirical N-ϕ' relation were obtained. This means that the *N* value obtained for this small area may be underestimated, because the ambient clay has low strength. Therefore it is necessary to find a more reliable method to evaluate strength parameters of SCP. Due to simplicity, speed, continuous profiling and amenability to theoretical modeling, Cone Penetration Test (CPT) can be used to evaluate ϕ' of SCP.

3. Theoretical Study of Vesic and Cavity Expansion Theory

Cavity expansion theory was used to develop a theoretical model to determine the strength parameters of improved ground by combining stress-strain relationships of SCPs. Conditions of axial symmetry and plain strain prevail for the expansion of the cylindrical cavity, while the conditions of spherical symmetry hold for the expansion of a spherical cavity. In a finite medium, internal and external radii of shell after expansion are denoted by R_u and R_s+u_s respectively (Fig.1). Initially the radii of the internal and external boundaries are R_i and R_s and a hydrostatic pressure q acts throughout the soil. When the internal pressure increases monotonically from its initial value q, zone around the cavity will pass into a state of plastic equilibrium. This plastic zone will expand up to R_p until the pressure reaches the value of P_u at the expansion of cavity R_u.

In general, each SCP is surrounded by many SCPs, in addition to surrounding soft clay. These SCPs provide additional stiffness towards soft clay and this effect can be analyzed by considering this as a composite ground with different area replacement ratios (a_s). In the cavity expansion theory, composite ground action with different a_s may be modeled as a spring with different coefficient of subgrade reaction (k_h).

It is assumed that the soil in the plastic zone behaves as a compressible plastic soil, characterized by Coulomb shear strength parameters c'(cohesion) and ϕ'(friction angle), as well as an average volumetric strain Δ, which can be determined from a known state of stress in the plastic zone and volume change-stress relationships. Beyond the plastic zone the soil is assumed to behave as a linearly deformable, isotropic soil with a Young's modulus E and Poisson's ratio ν. By using compatibility condition and isotropic elastic stress-strain relationship in the elastic zone, displacement at outer boundary (u_s) and displacement at the elastic-plastic boundary (u_p) for spherical cavity can be obtained.

$$u_s = \frac{\frac{3}{2}(1-\nu)(\sigma_p - q)R_p^3}{k_h\left[(1-2\nu)R_s^3 + \frac{(1+\nu)}{2}R_p^3\right] + \frac{E}{R_s}\left(R_s^3 - R_p^3\right)} \tag{1}$$

$$u_p = \frac{-R_p(\sigma_p - q)}{E\left(R_s^3 - R_p^3\right)}\left\{\frac{\frac{9}{4}(1-\nu)^2 k_h R_s^3 R_p^3}{\left\{k_h\left[(1-2\nu)R_s^3 + \frac{(1+\nu)}{2}R_p^3\right] + \frac{E}{R_s}\left(R_s^3 - R_p^3\right)\right\}} - \left[(1-\nu)R_p^3 + \frac{(1+\nu)}{2}R_s^3\right]\right\} \tag{2}$$

where σ_p is the normal stress at the elastic-plastic boundary.

By using Mohr-Coulomb yield criteria with $c'=0$ and compatibility and elastic stress–strain relationship, the normal stress at the elastic-plastic boundary can be obtained as following.

$$\sigma_p = \frac{3\alpha q R_s^3 - \dfrac{\frac{9}{2}\alpha k_h(1-\nu)R_s^3 R_p^3 q}{k_h\left[(1-2\nu)R_s^3 + \frac{(1+\nu)}{2}R_p^3\right] + \frac{E}{R_s}\left(R_s^3 - R_p^3\right)}}{\left[(2+\alpha)R_s^3 + 2(\alpha-1)R_p^3\right] - \dfrac{\frac{9}{2}\alpha k_h(1-\nu)R_s^3 R_p^3}{k_h\left[(1-2\nu)R_s^3 + \frac{(1+\nu)}{2}R_p^3\right] + \frac{E}{R_s}\left(R_s^3 - R_p^3\right)}} \tag{3}$$

where $\alpha = \frac{1+\sin\phi'}{1-\sin\phi'}$

The equation of equilibrium in the plastic zone is,

$$\frac{\partial\sigma_r}{\partial r} + \frac{\beta(\sigma_r - \sigma_\theta)}{r} = 0 \tag{4}$$

where $\beta = 1$ for cylindrical cavity and $\beta = 2$ for spherical cavity.

Integrating above equation and applying boundary conditions, the stress at the elastic-plastic boundary can be also obtained. Considering the compatibility condition in the plastic zone, Equation (5) can be derived.

$$R_u^3 - R_i^3 = \left[R_p^3 - (R_p - u_p)^3\right] + \left(R_p^3 - R_u^3\right)\Delta \tag{5}$$

Similar equations can be developed for the cylindrical cavity problem. By solving the above simultaneous equations with $R_i=0$, the cavity pressure for R_u, which is assumed as cone radius, can be obtained.

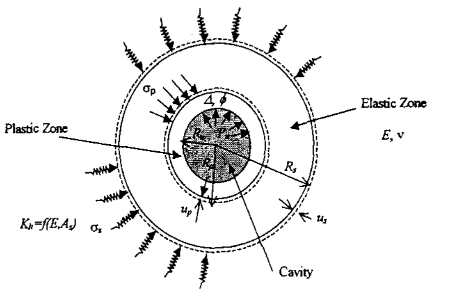

Fig.1 – Expansion of cavity in a finite soil ground

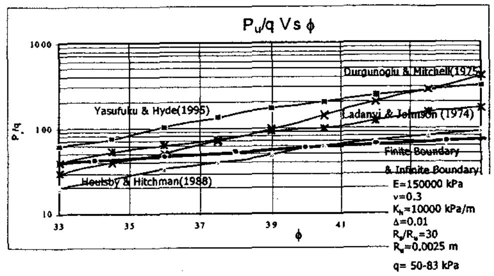

Fig.2 – Correlation between Cone Resistance and Friction Angle

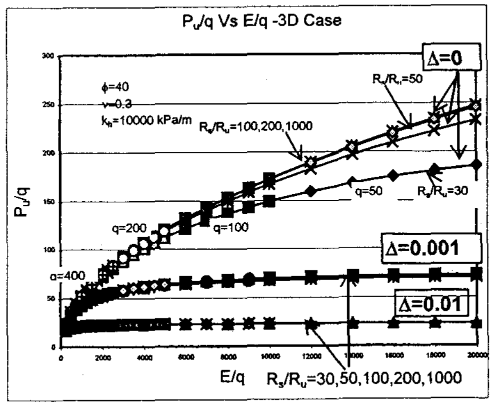

Fig.3 – Normalized cavity pressure versus normalized modulus of elasticity

4. Correlation between Cone Resistance and Friction Angle

The relationship between the internal friction angle ϕ' of the sand and the normalized cavity pressure P_u/q for both finite and infinite boundary conditions was obtained with fixed coefficient of subgrade reaction k_h, average volumetric strain Δ, SCP radius to cone radius ratio R_s/R_u, modulus of elasticity E and Poisson's ratio ν. The E was estimated by using its relation with q suggested by Kuwano and Chaudhary (2001) for Toyoura sand, that is, E is linearly proportional to the $q^{1/2}$. Fig. 2 shows the comparison of the solution in this study with those given by previous studies using cavity expansion type approaches (Ladanyi & Johnson, 1974 and Houlsby & Hitchman, 1988) and conventional bearing capacity analysis type approaches (Durgunoglu & Mitchell, 1975 and Yasufuku & Hyde, 1995).

The bearing capacity type approach seems to give consistently higher values of normalized cavity pressure for all values of friction angle and mean stress levels. The analytical solution of this research also shows the similar correlation in terms of normalized cavity pressure against friction angle. It might be suggested that the cavity expansion type approach provides a more accurate prediction of cone resistance than the bearing capacity analysis type approach, because the influence of stiffness and compressibility of sand can all be adequately taken into account.

5. Effect of other parameters on normalized cavity pressure

Relationship between P_u/q and E/q is depicted for different Δ and R_s/R_u ratio with fixed ϕ', ν and k_h as shown in Fiq.3. P_u/q values for zero volumetric strain were high compared to others, independent of whatever the confining pressure used. It was a notable factor that, finite boundary condition can be idealized to infinite boundary condition, which is equivalent of Vesic theory (1972), when R_s/R_u ratio reaches to a certain value (Table 1) and it basically depends on the volumetric strain

6. Conclusion

The analytical approach presented in this study provides a means to evaluate the mechanical properties of SCP by using CPT. The limited evidence of this study suggested that cavity expansion approach provides a more accurate prediction of cone resistance than bearing capacity theory, because the influence of soil stiffness and compressibility can all be adequately taken into account. Furthermore, cavity expansion theory can be idealized to Vesic theory (1972) when R_s/R_u ratio reaches to a certain value. This limiting value is higher for low volumetric strain when compared with higher volumetric strain.

Volumetric Strain (Δ)	R_s/R_u Ratio	
	Spherical Cavity	Cylindrical Cavity
0	100	400-500
0.001	30-50	100-200
0.01	30-50	30-50

Table 1 – R_s/R_u ratio corresponding to infinite boundary condition

7. Reference

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