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Viscous behaviour of air-dried sand in model loading tests of strip footing

Comportement visqueux du sable sec dans le cadre d'essais de fondations superficielles en laboratoire

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ABSTRACT
A series of laboratory model tests of a surface strip footing on air-dried sand was performed to evaluate the effects of the material viscosity of sand on the residual displacement characteristics of footing. The viscous deformation properties in the model tests were quantified in the framework of a non-linear three-component rheology model and compared with those from laboratory stress-strain tests. The following conclusions can be derived from the test results in this study; 1) significant effects of the material viscosity of the sand were observed on the footing pressure and footing settlement relation when the footing settlement rate was changed stepwise and sustained loading and load-relaxation tests were performed during otherwise monotonic loading tests on a model footing on air-dried sand. 2) the material viscous property of the model ground was quantified in terms of the rate-sensitivity coefficient, β, defined in the framework of a non-linear three-component model not as the Newtonian viscosity.

RÉSUMÉ
Une série d'essais en laboratoire reproduisant des fondations superficielles sur un sable sec a été réalisée dans le but d'estimer les effets des propriétés visqueuses du sable sur les déplacements résiduels caractéristiques des fondations. Les propriétés visqueuses ont été évaluées dans le cadre d'un modèle rhéologique non linéaire à trois composantes et comparées à celles obtenues à partir d'autres essais variés en laboratoire. Les conclusions suivantes peuvent être dégagées de cette étude : 1) des effets importants liés aux propriétés visqueuses du sable ont été observés sur la relation contrainte/tassement de la fondation, quand la vitesse de tassement est changée, ou lorsque le chargement est maintenu, ou lorsque des périodes de relaxation du chargement sont observées au cours, par ailleurs, d'essais de chargements monotones. 2) les propriétés visqueuses du sol sous fondations ont pu être estimées par l'intermédiaire d'un modèle non linéaire à trois composantes (ne considérant pas une viscosité newtonienne).

1 INTRODUCTION

One of the important foundation engineering issues is the accurate prediction of residual structural displacements at working load. Even when having an ample safety factor against ultimate failure, the serviceability of a given structure may become unacceptable when the residual structural displacements caused by sustained dead load and/or continuing live load (e.g., traffic load) are too large. It is particularly the case with structures allowing a limited amount of residual displacement, such as piers and abutments for bridges. Recent investigation showed the following facts with respect to residual structural displacements and associated ground deformation (Tatsuoka et al., 2001):

1) The structural displacement rate is controlled by construction speed among other factors. As typically seen from Figure 1, the tangent stiffness of pressure-settlement relation increases with construction speed, which is due to the viscous properties of the geomaterials constituting the concerned ground (i.e., clay, sand, gravel and sedimentary soft rock). In Figure 1, the elastic component of settlement, S^e, was obtained based on the elastic deformation characteristics from field shear wave velocities while accounting for their stress state-dependency. The irreversible component of footing settlement, S^{ir}, was obtained by subtracting S^e from the measured footing settlement, S. The relationship between the footing average contact pressure, $(p)_{ave}$ and S^{ir} is rate-dependent.
2) The creep displacement rate during service increases with an increase in the construction speed immediately before the start of sustained loading. This trend of behaviour can also be observed in results from stress-strain tests of geomaterials in the laboratory.
3) The creep displacement rate becomes very small by preloading or even negative when unloaded largely.
4) The creep displacement rate increases when subjected to continuing cyclic loading, such as traffic load. Ko et al. (2003) showed that residual strains of sand taking place during a cyclic loading history consist of the following two components,

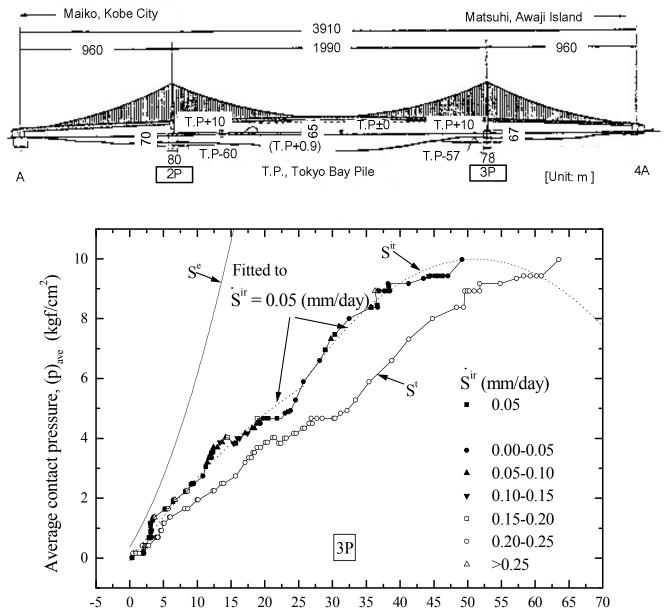

Figure 1. Settlement of Pier 3P, Akashi Strait Bridge, decomposed into elastic and irreversible components (Tatsuoka, 2000).

which are linked to each other; a) the time-dependant component due to material viscosity (i.e., so-called creep strains); and b) time-independent component due to effects of cyclic straining loading, which is therefore independent of loading frequency for the same number of loading cycles. Both components becomes larger as approaching the failure state, while the latter component becomes more important with an increase in the ratio of shear stress amplitude to the confining pressure in particular when the principal stress direction rotates by 90 degrees.

In view of the above, a series of laboratory model tests of a surface strip footing on air-dried sand was performed to evaluate the effects of the material viscosity of sand on the residual displacement characteristics of footing. To this end, the displacement rate was stepwise changed many times as well as sustained loading and load-relaxation tests were performed during otherwise monotonic loading (ML) at a constant settlement rate of the model footing. The viscous behaviour in the model tests was quantified in terms of the rate-sensitivity coefficient β defined in the framework of a non-linear three-component rheology model and compared with those from laboratory stress-strain tests on granular materials.

2 APPURATUS AND TESTING PROCEDURE

A 65 cm-deep model sand layer was prepared in a sandbox (80 cm-high, 180 cm-long and 40 cm-wide; Figure 2) by pluviating air-dried particles of Toyoura sand through air using multiple sieves. Toyoura sand is a uniform quartz-rich sub-angular sand. The target of initial relative density D_r was 90 %. The deformation of the sand layer during model tests was observed through a transparent side wall made of a 3 cm-thick Acrylic plate, which was stiffened with an aluminum frame. The inner face of the sidewalls was lubricated by using a 0.3 mm-thick latex membrane sheet smeared with a 30 μm-thick layer of Dow high vacuum silicone grease. Direct shear test results showed that the friction angle between the lubrication layer and Toyoura sand is four degrees at a normal stress of 10 kPa, which increases and decreases with a decrease and an increase in the normal stress. A 10 cm-wide strip rigid footing having a rough base, to which a piece of sandpaper #150 was glued, was used. To obtain the distributions of shear and normal stresses at the footing base, five two-component load cells were arranged at the footing base. Vertical and central footing load was applied by using a unique gear-type axial loading device, which can control the vertical displacement rate of the model footing with a resolution of less than one μm without backlash at load reversal.

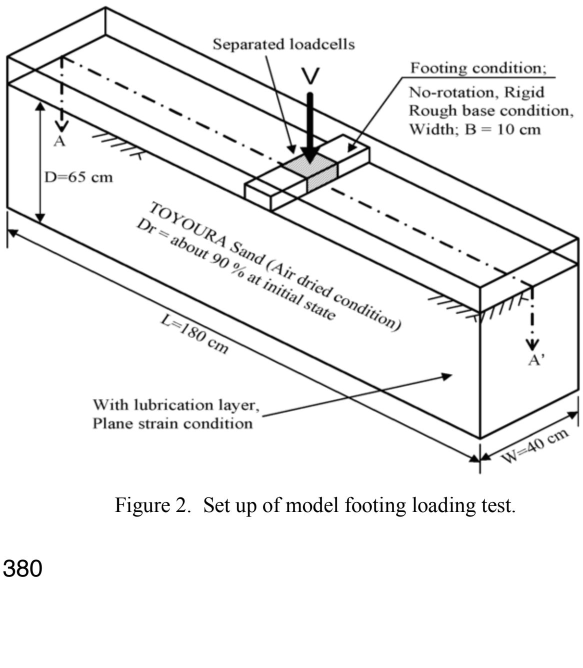

Figure 2. Set up of model footing loading test.

3 TEST RESULTS AND DISCUSSIONS

Figure 3a shows an overall relationship between the averaged vertical stress, $(p)_{ave}$, and the footing settlement, s, from a typical test, while Figure 3b shows a zoom-up for a stress range from 90 to 190 kPa. The following trends of behaviour can be seen from these figures:

1) The $(p)_{ave}$ value increases and decreases suddenly upon a step increase and a step decrease in the footing settlement rate, $\dot{s}$. In a broad sense, this trend is consistent with the full-scale behaviour shown in Figure 1.

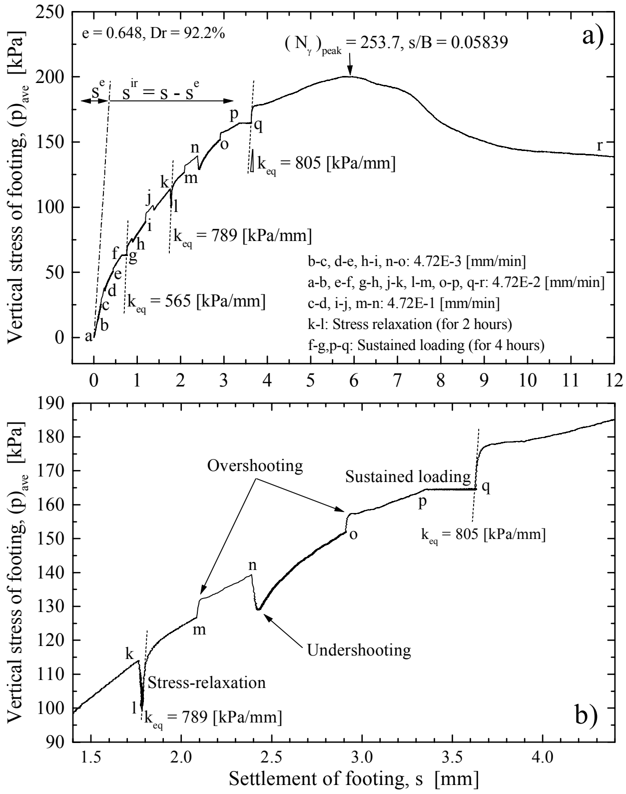

Figure 3. Viscous behaviour of sand in a typical model footing test.

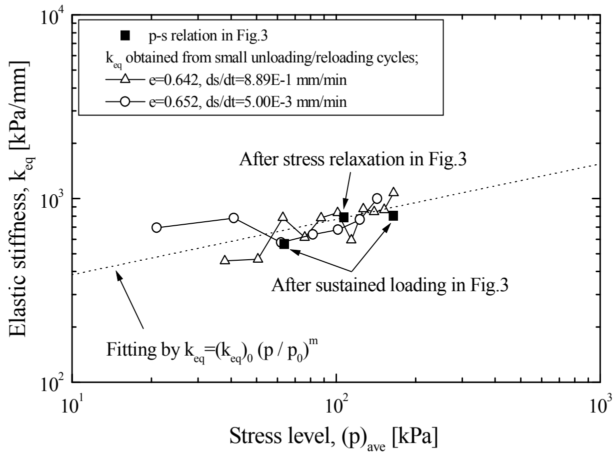

Figure 4. Relationships between elastic stiffness, k_{eq}, and average pressure level, $(p)_{ave}$.

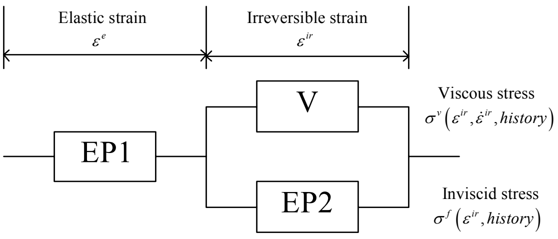

Figure 5. Non-linear three-component model (Tatsuoka at al. 2002: Di Benedetto et al. 2002).

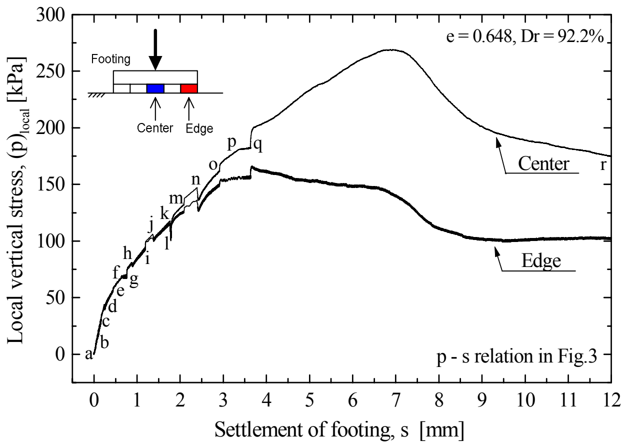

Figure 6. Relationships between local footing pressure and settlement at the footing center and edge.

2) The change in $(p)_{ave}$ value that has taken place upon a step change in $\dot{s}$ is not persistent, but it decays with an increase in the footing settlement.
3) Noticeable creep settlements of the model footing and stress relaxation of the footing load take place corresponding to the loading rate effects described above.

Figure 4 shows the relationships between the elastic stiffness, k_{eq}, and the $(p)_{ave}$ value at which the respective k_{eq} value was measured that were obtained by applying five unload/reload cycles with an amplitude of s of about 0.002 mm at different load levels during otherwise ML. It may be seen that the k_{eq} value is essentially independent of $\dot{s}$, while it increases with an increase in $(p)_{ave}$ in the manner represented by a dotted line. The relationships between $(p)_{ave}$ and the elastic component of the footing settlement obtained by integrating the increment, $ds = d(p)_{ave}/k_{eq}$, where k_{eq} is a function of $(p)_{ave}$ (as shown in Fig. 4), are depicted for reference in Figs. 3a & 3b. It may be seen that the stiffness immediately after the restart of ML at a constant $\dot{s}$ following a sustained loading or load-relaxation stage is very high while close to the elastic one.

These trends of viscous behaviour described above are consistent with those observed in the drained plane strain and triaxial compression tests on Toyoura sand and other types of clean sand (Di Benedetto et al., 2002; Tatsuoka et al., 2002). It has been shown that the material viscosity observed in the laboratory stress-strain tests can be formulated in the framework of a nonlinear three-component rheology model (Figure 5), and results from the laboratory stress-strain tests can be simulated by the three-component model. The numerical simulation of those model footing test results as a boundary value problem is possible only by means of the FEM incorporating the three-component model (Tatsuoka, 2005). The numerical analysis method should be able to predict such local behaviours as presented in Figure 6. It may be seen from Fig. 6 that the local footing pressure at the footing edge starts decreasing before the peak value is exhibited at the footing cen-

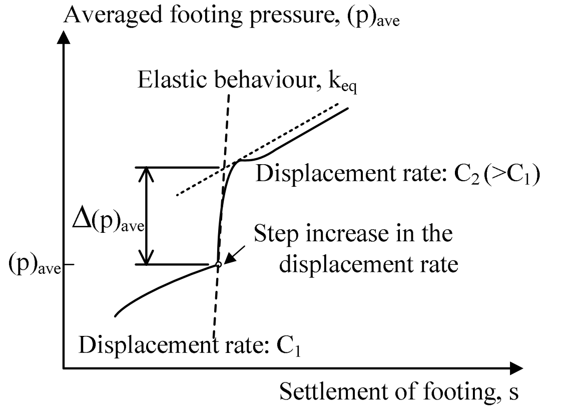

Figure 7. Definition of footing pressure jump upon a step change in the footing displacement rate.

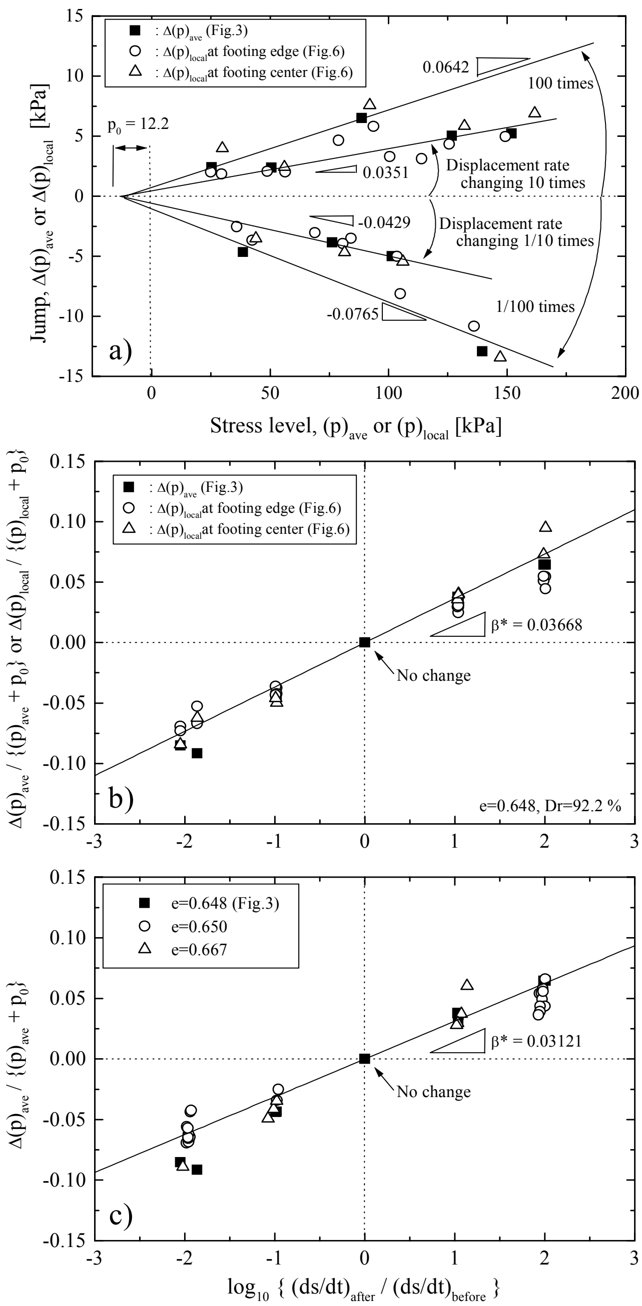

Figure 8. a) Footing pressure jump upon a step change in the footing displacement rate; b) definition of viscosity coefficient, β*, from the model footing test 3; and c) summary for $\Delta(p)_{ave}$ from three similar tests.

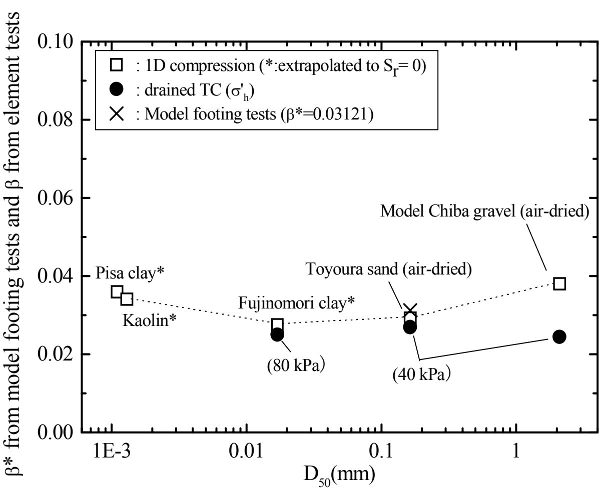

Figure 9. Comparison of viscosity coefficients β^* from model footing tests with coefficients β from element tests (Tatsuoka, 2004).

ter. This phenomenon is due to the progressive failure of ground below the footing.

The footing pressure jumps, $\Delta(p)_{ave}$ and $\Delta(p)_{local}$, upon a step change in $\dot{s}$, defined in Figure 7, were obtained from the results presented in Figures 3 & 6 and summarized in Figure 8a. The values of $\Delta(p)_{ave}$ and $\Delta(p)_{local}$ are rather proportional to the respective instantaneous value, $(p)_{ave}$ or $(p)_{local}$, for the same corresponding ratio of the displacement rates after and before a step change. It may be seen by examining the data plotted in Fig. 8a that all the relations have a common intersect at the horizontal axis, p_0 (= 12.2 kPa). Therefore, the ratio, $\Delta(p)_{ave}/((p)_{ave}+p_0)$ and $\Delta(p)_{local}/((p)_{local}+p_0)$, was plotted against the logarithm of the ratio of the footing settlement rates after and before a step change (Figure 8b). It may be seen that the relations for $(p)_{ave}$ and $(p)_{local}$ are essentially the same while the average relation is highly linear. The slope of the relation can be called the rate-sensitivity coefficient (Di Benedetto et al., 2004; Tatsuoka, 2005), denoted as $\beta*$, which should represent the viscosity of Toyoura sand.

Figure 8c summarizes the data in terms of $\Delta(p)_{ave}/((p)_{ave}+p_0)$ from three similar model footing tests including those presented in Figure 8b. The $\beta*$ value (i.e., the average slope) of the relation is 0.03121, which is close to the value presented in Fig. 8b. Figure 9 compares $\beta*$= 0.03121 from the model footing tests on air-dried Toyoura sand and the values of the similar rate-sensitivity coefficient, β, obtained from the $\Delta\sigma_v/\sigma_v$ and $\log\{(\dot{\varepsilon}_v)_{after}/(\dot{\varepsilon}_v)_{before}\}$ relations, not using an intersect, from one-dimensional and triaxial compression tests on different types of geomaterials, including Toyoura sand, where σ_v and ε_v are the vertical and vertical strains (Tatsuoka , 2005). It may be seen that, with Toyoura sand, the β* value from the model footing tests and the β value form the laboratory stress-strain tests are surprisingly similar.

As shown above, the trends of viscous behaviour seen from the model footing tests, which are structural viscous properties of a system, are consistent with the material viscous property from element tests not only qualitatively but also quantitatively. Tatsuoka (2005) showed that FEM analysis incorporating the three-component model while using the material properties of Toyoura sand determined by element tests can simulate very well the trends of viscous behaviour observed in the model footing tests described above.

4 SUMMARY

The following conclusions can be derived from the test results of this study presented above:

1) The significant effects of the material viscosity of Toyoura sand were observed on the relationships between the footing pressure (local and averaged) and the footing settlement when the footing settlement rate was changed stepwise and sustained loading and load-relaxation tests were performed during otherwise monotonic loading tests on a model footing placed on air-dried sand.
2) The viscous properties of Toyoura sand ground observed in the model footing tests were quantified in terms of the rate-sensitivity coefficient defined in the framework of a nonlinear three-component model. The general trends of the viscous behaviour in the model tests were very similar, not only qualitatively but also quantitatively, to the material properties of Toyoura sand from one-dimensional and triaxial compression tests. This result indicates that the viscosity of sand is not linear as the Newtonian viscosity, but highly nonlinear.

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