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LINK AMONG DESIGN, MODEL TESTS, THEORIES AND SAND PROPERTIES IN BEARING CAPACITY OF FOOTING ON SAND

CAPACITE DE CHARGE D'UN SOUBASSEMENT SUR SABLE: LIENS ENTRE LA CONCEPTION, LES ESSAIS DE MAQUETTE, LES THEORIES ET LES CHARACTERISTIQUES DU SABLE

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INTRODUCTION

In the current ordinary design practice, classical theories including those by Terzaghi and Meyerhof are used to estimate the bearing capacity factor by soil weight N_γ for a strip footing on cohesionless soil (Fig. 1). Despite the various theoretical bases (i.e., limit equilibrium, stress characteristics, upper bound or their mixture), they over-simplify the reality by ignoring the deformability of sand, the pressure-dependency of $\phi = \arcsin\{(\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3)\}_{max}$, strength anisotropy and the progressive failure of ground among others. Therefore, the sound link among design practice, theories, the behaviour of footing and soil properties is often missing.

MODEL TESTS AND ELEMENT TESTS

Fig. 2 shows the test data from a series of plane strain model tests in 1 g (Fig. 3) and various element tests using air-pluviated Toyoura sand. The data points on each horizontal line for each footing width B_0 mean the values of ϕ from the element tests performed at the average pressure in the model ground, which increases with B_0. When based on any classical theory, the whole data points for a single void ratio (e= 0.66) should collapse into a single point. They however scatter considerably due to the decrease in N_γ with B_0 (**the scale effect**) and the non-unique values of ϕ. The difference between the two values of ϕ (○ and ●) from plane strain compression (PSC) tests is due to the different angles δ of the σ_1 direction relative to the bedding plane (the strength anisotropy). The ϕ value differs largely also among the different testing methods.

For B_0= 50cm, for example, $N_\gamma \sim 800$ is obtained by substituting $\phi = 48^\circ$ from the PSC test at $\delta = 90^\circ$ into the relations by the classical theories, which is about eight times larger than the measured value of around 100. This over-estimation is due to both the strength anisotropy and the progressive failure of ground. Indeed, the peak strength ϕ is progressively mobilized along the potential failure planes (Kimura et al., 1985), as can be seen from Fig. 4; two shear bands developed only in the zones adjacent to the footing edges. In the design practice, it is implicitly assumed that this over-estimation could be balanced with the use of underestimated ϕ as evaluated from SPT N-values. It is likely however that most practitioners and many researchers are not aware of this point.

ESTIMATION BY MORE SOPHISTICATED METHODS

Physical model tests: In simulating a given large prototype footing, centrifuge tests can reproduce in a small model the prototype high pressure. However, when the prototype sand is used, the behaviour could be different

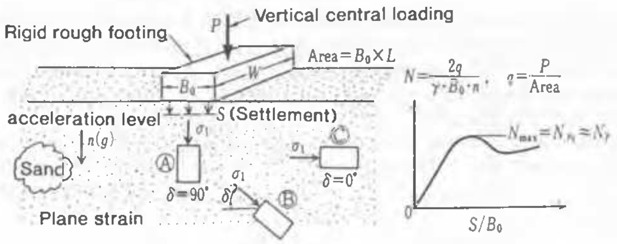

Fig. 1 Plane strain bearing capacity problem

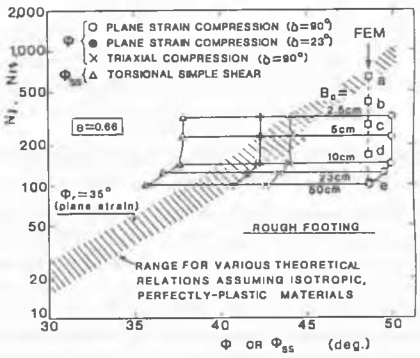

Fig. 2 Test results compared with the classical theories and FEM simulation (Tatsuoka et al., 1991)

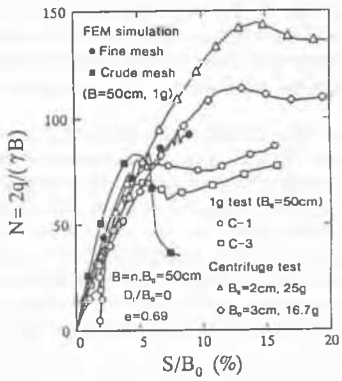

Fig. 3 Comparison of load-settlement relation for B= n·B_0 = 50 cm among 1g and centrifuge tests and FEM simulation

from the prototype. For example, Fig. 3 shows that despite the same equivalent footing size **B= n·B₀** (the physical footing width times the acceleration level) = 50 cm thus the same pressure level in the ground, a larger bearing capacity at a larger footing settlement is obtained in the centrifuge tests than in the 1 g tests. This difference

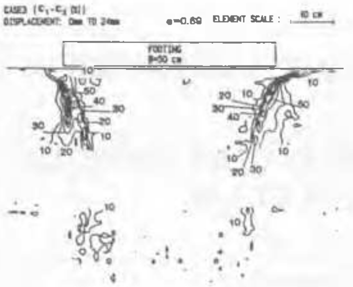

Fig. 4 Contour of $\varepsilon_1 - \varepsilon_3$ for a mesh size of 1 cm near the peak footing load state (S/Bo= 0.048) from pictures taken through a transparent side wall of sand box, Bo= 50cm, 1g

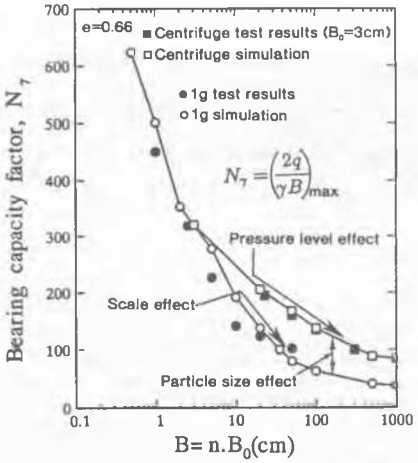

Fig. 5 Summary of model tests and FEM simulations (Siddiquee, 1991, Tatsuoka et al., 1991)

is due to the different ratios of the sand particle size or the mean particle size D_{50} (= 0.16mm) to **Bo**. Since the shear band width **w** is about 20 times D_{50} while independent of **Bo**, a larger ratio D_{50}/**Bo** in a small centrifuge model leads to a larger ratio **w/Bo**. Shear bands has already appeared partly at the peak footing load state (Fig. 4). Then, a larger D_{50}/**Bo** or **w/Bo** in the centrifuge tests leads to a less degree of strain localization into shear bands at a given **S/Bo** and a larger N_γ at a larger **S/Bo**. On the other hand, in Fig. 3, for the same **B**, the N~S/Bo relation before S/Bo~0.05 is similar between the 1 g and centrifuge tests, due probably to small effects of shear banding at the initial stage of loading.

The summary of the model test results (Fig. 5) shows that "the decrease in N_γ in the 1 g tests known as the **scale effect**" is a combination of "**the pressure-level effect** as observed in the centrifuge tests for a constant Bo" and "**the particle size effect** as the difference between the 1g and centrifuge tests for an identical **B= n·Bo**". Therefore, the centrifuge tests using the prototype sand while under otherwise the same conditions with the prototype may overestimate the N_γ of the prototype footing.

FEM: Another method is by the FEM validated by relevant model tests. To this end, the FEM based on a non-associated strain-hardening and -softening elasto-plastic model developed by Tanaka and Kawamoto (1988) has been used (Siddiquee, 1991, Tatsuoka et al., 1991). Fig. 2 illustrates the effects of different assumptions on the results of the FEM analysis for Bo= 50 cm, 1 g and e= 0.66. The FEM solutions of N_γ shown in Fig. 2 are the largest values of N until **S/Bo**= 0.7 attained in these analyses. The analysis a assumed that the sand be isotropic and perfectly-plastic with a constant ϕ = 48° from the PSC tests at low pressures at δ = 90°. This analysis predicted a bearing capacity far larger than the measured one, while close to the solutions by the classical theories. In the analyses **b. c** and **d**, the pressure-dependency of ϕ, the strength anisotropy and the post-peak softening were taken into account one by one (n.b. the result by the analysis **d** is mesh size--dependent). Correspondingly the predicted bearing capacity decreased one by one. The analysis **d** took into account additionally the shear banding in that the manner of strain-softening in each finite element is the same as that in the PSC test in which the area of specimen σ_2 plane is the same as that of the finite element. For a given sand type, the post-peak softening is therefore mesh size-dependent; i.e., when the mesh size is proportional to **Bo**, the degree of post-peak softening becomes smaller as the mesh size decreases, namely as **Bo** decreases. However, the result could be independent of mesh size unless the mesh is too coarse. Only the analysis **d** in which the pressure-dependency of ϕ, the strength anisotropy, the material non-linearity, post-peak strain-softening and shear banding were properly modelled could properly simulate the test result. Also in Figs. 3 and 5, the results by the analysis **d** are presented. As seen from Fig. 5, the FEM analyses simulate successfully the **the scale effect, the pressure level effect** and **the particle size effect.**

The FEM analyses described above were performed by load--control using a relatively coarse mesh. In Fig. 3 also presented is the result when a very fine mesh (2 x 560 nodes for the whole area of 4 m times 7 m) and a hour-glass mode suppression technique were used. Although an improved result was obtained by these refinements, the N_γ value remained virtually unchanged; namely, the FEM solutions shown in Figs. 2 and 5 are rather objective.

CONCLUSIONS

The use of classical bearing capacity theories for N_γ in the design practice is relevant only when the design soil strength is properly reduced to attain a balanced result. Any improvement in one or several, but not all, of the approximations used in the theories may lead to the loss of the balance. Only the numerical analysis which takes into account properly the pressure-dependency of ϕ, the strength anisotropy, the material non-linearity, post-peak strain-softening and shear banding among others can predict the bearing capacity of footing consistently better than the classical theories. In simulating shear banding, the effect of particle size relative to the footing size should be properly modelled. On the other hand, when the bearing capacity of a given prototype footing is evaluated by physical model tests, the effect of particle size as well as pressure level should also be modelled.

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