Discussion: On the applicability of geotechnical model tests

Discussion: Sur l'application des essais sur modèles réduits en géotechnique

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Geotechnical engineering is becoming an increasingly complex and challenging field. New construction methods, complex structural systems and difficult soil conditions are all being encountered as construction advances into harsher environments under pressures such as high density land use, new or improved infrastructure and demand for mineral resources.

Geotechnical model testing is a vital tool in the design and analysis of such structures because of the absence of accurate field data. Correct model tests can help to identify structural behaviour such as serviceability and limit state conditions and to validate design approaches and calculation methods. The appropriate choice of modelling technique is therefore critical to the design engineer.

There has been a long history and considerable investment in the use of 1g modelling in soil mechanics, but recent developments in miniature instrumentation and a rapidly developing worldwide capability for high g geotechnical centrifuge modelling has led to the growing importance of the high g approach and its acceptance internationally. In contrast to the limited scope of 1g model tests, high g tests allow the modeller considerably more flexibility to correctly reproduce prototype conditions in the model. A profile of effective stress and overconsolidation ratio can be created straightforwardly in a centrifuge model in an identical manner to the prototype.

As with many modelling process idealisations need to be made concerning the prototype boundary conditions in particular but also decisions have to be taken on the selection of soils and structural materials, and on instrumentation and data aquisition. These decisions will be influenced by the scale of the model as clearly at large scale considerably more detail may be included in comparison to a small scale model. However, the gradient of stress due to a increased self-weight in a centrifuge model which gives stresses identical in model and prototype greatly simplifies the design of models for testing under high g.

Examples are shown in Figs. 1 and 2, problems in which flexible deformations and stresses in the structure (Güttler et al. 1989), or crack development in brittle materials (Jessberger et al. 1987), or failure conditions in cohesive materials all play a governing role. By dimensional analysis it can be shown that under the prototype stress conditions in the centrifuge model the reduction of all model dimensions by the scaling factor enables the use of the same materials in model and prototype. In a 1g model, on the other hand, a significant modification of the material properties must be made. In clay, for example, the water content should be increased in a 1g model, (Schofield 1980), and in sands the relative density decreased to compensate for the reduction in stress level in the model (Schofield and Steedman 1988).

Such an increase in water content in a cohesive material may create a soil so sensitive that it cannot be handled during the preparation of the 1g model. Similarly the linings may require the fabrication of a very vulnerable lining for a 1g test.

Difficulties in the modelling of material strength in a 1g test are compounded by the problem of correctly reproducing stiffness. The deformation of a structure and the development of strain in the adjacent soil will govern the mobilisation of strength in the soil. Iai (1989) identifies the difficulty of modelling strain in a 1g model and comments that provided strains are small useful data may be recovered from 1g model tests which use the same soil in model and prototype. To change the soil in the model, however, is a complex and difficult task involving careful study of the mineralogy and strength characteristics of both the prototype and substitute model soils. Successful results have been achieved recently (Bolton and Lau 1989), but this remains an impractical route to the correct modelling of most geotechnical problems.

In conclusion, geotechnical model testing has an important role to play in the validation of calculations and the understanding of soil structure response. It can achieve this by generating realistic data of correctly scaled prototype events. The goal of realistic data showing the development of strains, the transition past yield and the development of failure can best be achieved in a geotechnical centrifuge. There may be particular circumstances, such as the study of very small prototypes or of behaviour at very low strain levels, in which a 1g model may be adequate and economical but in general the technology of centrifuge model testing has now advanced to such a level that it is becoming an international standard in geotechnical model testing.

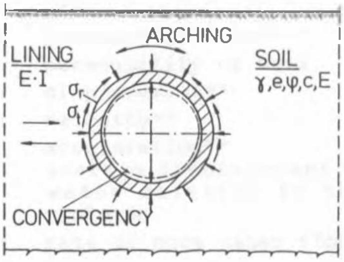

Fig. 1: Interaction soil / tunnel.

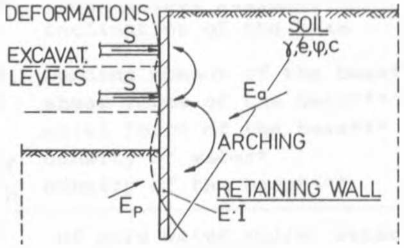

Fig. 2: Interaction soil / retaining structure.

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Discussion: Similitude in 1 g model test
Discussion: Similitude dans le modèle réduit 1 g

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An approach is suggested for interpreting the results of the shaking table tests on saturated soil-structure-fluid model in 1 g gravitational field. In 1 g gravitational field, scaled models behave under scaled stresses. Due to the non-linearity of the geotechnical materials, the strains corresponding to the scaled stresses are not scaled down in proportion to the scale of the stresses. Then, the question to be answered is : "what strains will be produced under the scaled stresses ?"

NORMALIZED STRESS-STRAIN RELATION

Laboratory data obtained under the confining pressures ranging from 5 to 392 kPa indicate that stress-strain relation of soil is determined irrespective of the confining pressures if appropriate scaling factors are introduced for the stress and the strain as shown in Fig.1, provided strain levels are lower than the strains at failure (Iai, 1989).

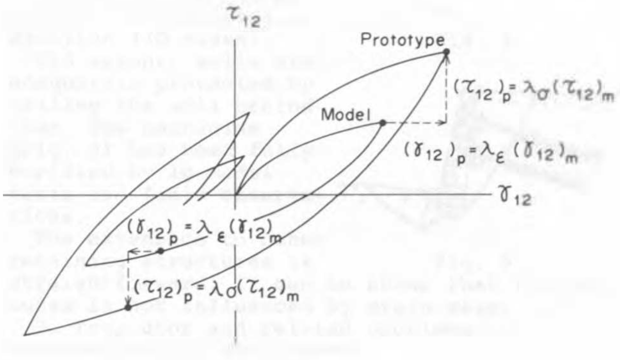

Fig.1 Stress-strain relations of soils in the model and the prototype

DYNAMIC MODEL TESTS

In dynamic model tests, effective stress path of saturated soil is usually confined within the failure lines. Dilatancy of medium and dense sand is the reason for this. Thus, in dynamic model tests, major concern is usually directed toward deformation rather than the ultimate state of stability.

Deformation which corresponds to shear strain levels of about 10 percent can often be considered seriously large in practice. Such deformation, however, can often be "small" in such a sense that (1) equilibrium for deformed shape can be approximated by that for undeformed shape and (2) strain can be approximated by a linear equation of first order derivative of displacement.

SIMILITUDE

With the conditions stated above, i.e. strain levels less than strains at failure and "small" deformation and strain, similitude is obtained by considering equilibrium and continuity of soil-structure-fluid system (Iai, 1989).

As shown in Table 1, displacement and time scales are affected by the scale for strain λ_ε.

Table 1 Similitude for model tests in 1 g gravitational field

	Items	Scaling factors (prototype/model)
x	length	λ
ρ	density of saturated soil	λ_ρ
ε	strain of soil	λ_ε
t	time	$(\lambda\lambda_\varepsilon)^{0.5}$
σ	total stress of soil	$\lambda\lambda_\rho$
σ'	effective stress of soil	$\lambda\lambda_\rho$
D	tangent modulus of soil, which generally depends on histories of effective stress, strain, etc.	$\lambda\lambda_\rho/\lambda_\varepsilon$
p	pressure of water*	$\lambda\lambda_\rho$
k	permeability of soil	$(\lambda\lambda_\varepsilon)^{0.5}/\lambda_\rho$
u	displacement**	$\lambda\lambda_\varepsilon$
$\dot{u}$	velocity**	$(\lambda\lambda_\varepsilon)^{0.5}$
$\ddot{u}$	acceleration**	1
w	average displacement of pore water relative to the soil skeleton	$\lambda\lambda_\varepsilon$
$\dot{w}$	rate of pore water flow	$(\lambda\lambda_\varepsilon)^{0.5}$
n	porosity of soil	1
K_f	bulk modulus of water*	$\lambda\lambda_\rho/\lambda_\varepsilon$
EI	flexural rigidity***	$\lambda^4\lambda_\rho/\lambda_\varepsilon$
EA	longitudinal rigidity***	$\lambda^2\lambda_\rho/\lambda_\varepsilon$
θ	inclination of the beam	λ_ε
M	bending moment of the beam***	$\lambda^3\lambda_\rho$
S	shear force of the beam***	$\lambda^2\lambda_\rho$
F	axial force of the beam***	$\lambda^2\lambda_\rho$
ρ_f	density of water*	λ_ρ
ρ_b	density of the beam****	$\lambda\lambda_\rho$

*	of pore water and/or external water
**	of soil and/or structure
***	per unit breadth of the beam
****	mass per unit length and breadth of the beam

Rigidities, i.e. tangent modulus of soil and flexural and longitudinal rigidity of structure, are also affected by the scale for strain because rigidity is a ratio of stress or reaction force over strain. Permeability of soil is also affected by the scale for strain.

Scale for strain is either approximated by $\lambda_\varepsilon = \lambda^{0.5}$ or, more accurately given by using shear wave velocities of model and prototype $(V_s)_m$ and $(V_s)_p$ as $\lambda_\varepsilon = \lambda/[(V_s)_p/(V_s)_m]^2$.

There has been a skepticism on interpreting the results of shaking table tests in 1 g field. The similitude presented here will be useful to correlate the results of 1 g model tests with those of prototype or centrifuge model if the deformation of soil-structures under earthquake loading are of major concern in the model test.

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As 1g model tests imply a low stress level, they cannot directly be transferred to prototypes as centrifuge tests. Carried out with sufficient precision, however, they can serve to validate theories. This is demonstrated by some examples. The scale effect due to grain size, which is not allowed for in centrifuge tests normally, is also outlined.

1. Retaining structures

A back-tied wall can fail with a combined mechanism (Fig. 1). Model tests with dry sand and correctly scaled anchors yielded the same mechanism and critical height.

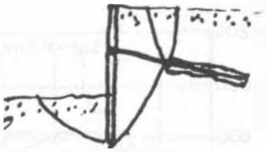
Fig. 1

A similar mechanism is predicted for soil nailing (Fig. 2), and has been verified likewise. The sequence of excavation and nailing is shown to be without influence. The same method was also applied to an elliptic excavation (3D cases).

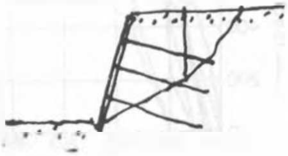
Fig. 2

Old masonry walls are adequately protected by nailing the soil behind them. The mechanism (Fig. 3) has been fully verified by 1g model tests and field observations.

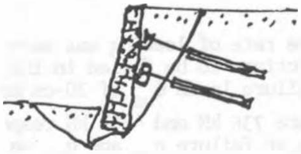
Fig. 3

The extension to other retaining structures is straightforward. It can be shown that the mechanism is not influenced by grain size.

2. Trap door and related problems

Terzaghi's trap door problem was studied in 1g model tests with X-ray observation. The maximum passive force occurs with two nearly vertical shear bands. There is a marked grain size effect beyond the peak. The growth of shear bands cannot yet be predicted.

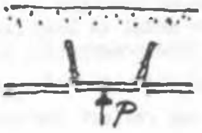

Fig. 4

Punching of a cohesionless layer into a soft cohesive one involves a similar mechanism (Fig. 5). A theory worked out for the 3D case was verified by 1g tests. The grain size effect on the punching force seems to be negligible.

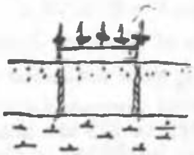
Fig. 5

Collapse of soil into a tunnel without lining or with internal pressure is governed by a similar mechanism (Fig. 6). For frictional soils, the theory is rather unsafe due to the unknown earth pressure. 1g model tests, including 3D cases, gave some support.

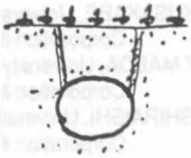
Fig. 6

An idealized silo problem was studied in model tests with walls of different roughness and distance (Fig. 7). The grain size influences dimensionless forces at bottom and walls quite markedly. A numerical Cosserat model, i.e. allowance for internal rotations and non-symmetric stress tensor, explains these effects with surprising precision.

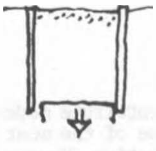
Fig. 7

3. Concluding remarks

Some general features of 1g tests are outlined: scaling laws, transfer to prototype, experimental requirements, simplicity, basis for new theories.

Discussion

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Centrifuge modeling has been discussed and accepted as one of the most useful tools for geotechnical model testing. However, the application of centrifuge model test results to geotechnical design may require further examination through direct comparisons between prototype and centrifuge behaviors. One of the areas where 1-g model tests play a role may be to provide well documented data on prototype behaviors of large scale models with extensive site investigation results. We will, then, have chances to examine the applicability of the geotechnical centrifuge modeling to actual design purposes, as well as the accuracy of design calculations currently adopted. This paper reports an ongoing test program of a series of 1-g model loading tests of large scale shallow footing on a naturally deposited scoria (volcanic sand) layer, of which SPT N values are as high as 150.

Variation in the bearing capacity factor N_γ of dense sands with footing width, so called scale effect, has been recognized by the results of 1-g model loading tests as well as centrifuge model tests. Reliable evaluation of bearing capacity of shallow foundations is of highly importance for safe and economic design of highway bridges. A series of large 1-g model loading tests up to 19,130kN of loading force has been planned by the Japan Highway Corporation, and is being carried out on the dense scoria originated from the Old Hakone Volcano near Mt. Fuji in Japan.
These heavy loading tests are made possible by making use of weight of a pneumatic caisson of 16 m in diameter and 18 m in embedded length. The loading tests are to be performed under compressed air in the working chamber of the pneumatic caisson being built and sunk. Sizes of model footings are 30cm x 30cm, 70cm x 70cm, 130cm x 130 cm, 40cm x 40cm, 40cm x 120cm and 40cm x 200cm, by which scale effect and shape factor are to be examined. The test model footings are placed on the horizontal surfaces of the excavated ground beneath the caisson at three different ground levels during the course of construction as shown in Fig. 1.

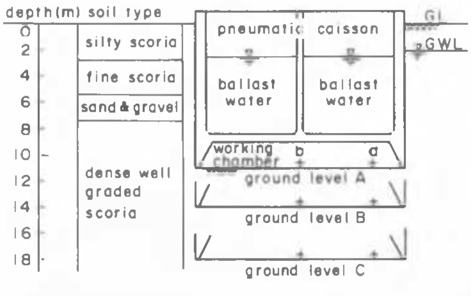

Fig.1 Caisson and test ground levels.

Several soil blocks are to be sampled at each ground level for triaxial and plane strain compression tests. The first loading test was carried out on September 5, 1989 and a complete set of data on all loading tests and laboratory shear tests will be available at the end of 1989. The authors are planning to publish these data in near future.

The air pressure in the chamber is kept equal to the hydrostatic pressure of ground water at the depth of the test ground level for making the ground beneath the test model in submerged state. The reaction of the loading force is withheld by the weight of the caisson body with the ballast water filled in it. The maximum mass of the caisson with the ballast water at the ground depth level C will be 1,950,000 kg.
All loading procedure is remote-controlled with monitoring the test site through two TV cameras. The test data are monitored and recorded at the monitoring room above the ground surface with various electronic systems.
In September, 1989, two square models of B=30cm and B=70cm placed on the ground level A in Fig.1 were loaded to failure. Loading sequence of the two tests are presented in Fig.2 in the form of the load intensity(q)-settlement(s).

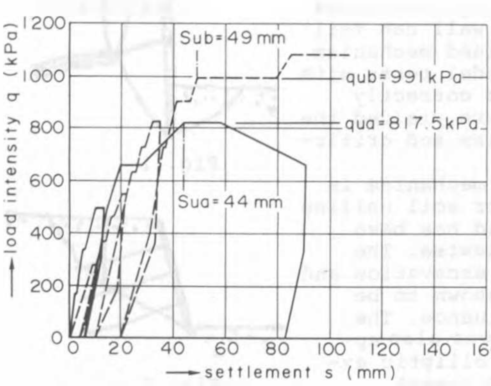

Fig.2 Load intensity - settlement curve.

The rate of loading was selected so as to ensure the footings to be failed in the drained condition. The failure loads Q_{ua} of 30-cm model and Q_{ub} of 70-cm model were 736 kN and 4856 kN respectively. The load intensities at failure q_{ua} and q_{ub} were 817.5 kPa and 991 kPa, respectively.

The value of $N_{\gamma a} = 2\,q_{ua}/\gamma' B_a$ for 30-cm model is 1.48 times the value of $N_{\gamma b} = 2.6\,q_{ub}/\gamma' B_b$ for 70-cm model provided that the scoria has no cohesion term and that 70-cm model is load tested at the point a in Fig.1 where the cone-penetration resistance q_c is approximately 1.3 times the value of q_c at the point b. The ratio of $N_{\gamma a}$ to $N_{\gamma b}$ may reflect the scale effect.

Laboratory test results on undisturbed soil samples taken from the ground level A suggest that the submerged unit weight $\gamma' = 8.34$ kN/m^3, the cohesion $c_d = 18.9$ kPa and the angle of internal friction $\varphi_d = 34.0^\circ$ respectively. c_d and φ_d were estimated on the basis of the data on drained triaxial compression tests with the confining pressure of 147 kPa to 275 kPa which are roughly equivalent to the stress condition in the bearing layer at failure. It has been observed that overwhelming crushing of coarse porous grains of the scoria under high pressure took place and the failure envelope of the scoria was not a straight line, implying that it has characteristics of stress dependency.

Although we have not reached the stage where the complete test data with interpretation are reported, the authors are aware that stress dependency of the friction angle and the existence of cohesion term in naturally deposited sands must be taken into consideration to scrutinize the scale effect from the viewpoint of theory of plasticity and to arrive reasonable interpretation of the tests results.