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Application of the Generalized Scaling Law to Ground Settlements of Dry Sands

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Synopsis

To verify the generalized scaling law, dynamic centrifuge tests under two different centrifugal accelerations of 25 g and 50 g are conducted. The model ground constitutes of a flat dry sand layer. With the scaling law, a prototype ground is scaled down to 1/100. A sinusoidal input acceleration of frequency 1.0 Hz, maximum amplitude 0.5 g, and duration 14 sec in prototype scale is applied to the model ground. Each model is exposed to the identical input motion sequentially 10 times. In total nine accelerometers are installed in the model. Surface settlements are measured by laser displacement transducers. Settlements at three different depths (300, 200 and 50 mm – model scale - from the surface) are measured by settlement gauges. Measured settlements after the initial shake in prototype scale show agreements between the two models when the intensity of shaking is nearly identical.

Keywords: centrifuge modelling, scaling law, dynamic, dry sand

1. Introduction

Demands for physical model testing of large proto-types are increasing. To resolve such demands and restrictions, Iai et al. (2005) generalized the scaling law by combining the scaling law for centrifuge testing with the one for 1-g dynamic-model testing. They call it the "generalized scaling law" in dynamic centrifuge modelling. Tobita et al. (2011) investigated its applicability with a flat saturated sand bed. They conducted a series of centrifuge model tests to verify and find issues on the generalized scaling law under the scheme of the modelling of models technique. They encountered some difficulty in scaling of displacement, because scaling factor of displacement becomes relatively large and, therefore, precise measurement of displacement is required. Thus in this study, the applicability of the generalized scaling law, in particular, the scaling law of displacement is investigated through the measurement of settlement of dry sand deposit after shaking.

1.1 Brief review of the generalized scaling law

Scaling factors for physical model tests can be introduced in general forms by choosing a set of basic physical properties to be independent and deriving the scaling factors for other properties via governing equations of the analysed system. In the concept of the generalized scaling law, a model on a shaking table in a geotechnical centrifuge is considered to be a small-scale representation of a 1-g shaking-table test. Figure 1 visualizes this concept by introducing a virtual 1-g model to which the prototype is scaled down via a similitude for 1-g shaking-table tests (Iai, 1989). The virtual 1-g model is subsequently scaled down by applying a similitude for centrifuge tests to the actual physical model. In this way, the geometric scaling factors applied in 1-g tests (μ) [row (1) of Table 1] can be multiplied with those for centrifuge tests (η) [row (2) of Table 1], resulting in much larger overall scaling factors λ=μη [row (3) of Table 1].

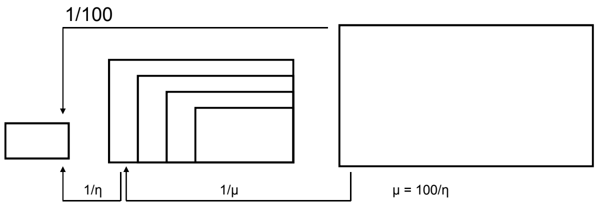

Figure 1. Relationship among prototype, virtual 1G model and centrifuge model for the case of scaling factor of 1/100 (λ=μη=100)

Table 1. Scaling factors in physical model testing (Iai, 1989, Iai, et al. 2005)

	(1) Scaling factors for 1g test	(2) Scaling factors for centrifuge test	(3) Generalized scaling factors
Length	μ	η	$\mu\eta$
Density	1	1	1
Time	$\mu^{0.75}$	η	$\mu^{0.75}\eta$
Frequency	$\mu^{-0.75}$	$1/\eta$	$\mu^{-0.75}/\eta$
Acceleration	1	$1/\eta$	$1/\eta$
Velocity	$\mu^{0.75}$	1	$\mu^{0.75}$
Displacement	$\mu^{1.5}$	η	$\mu^{1.5}\eta$
Stress	μ	1	μ
Strain	$\mu^{0.5}$	1	$\mu^{0.5}$
Stiffness	$\mu^{0.5}$	1	$\mu^{0.5}$
Permeability	$\mu^{0.75}$	η	$\mu^{0.75}\eta$
Pore pressure	μ	1	μ
Fluid Pressure	μ	1	μ

2. Dynamic centrifuge tests on flat loose dry sand deposit

To investigate the applicability of the generalized scaling law described above, a series of dynamic tests was conducted following the principle of “modelling of models.” This technique was introduced by Schofield (1980) to assess the behaviour of a prototype through repetition of the test at different scales and comparison of the results in prototype scale. In the present study, without changing the actual size of the physical model but varying the virtual 1-g dimension, the overall scaling factor (λ=μη=100) is kept constant (Fig. 1). Here, it is set to a fixed value comprising different combinations of the scaling factors for 1-g model testing, μ, and centrifuge testing, η. Table 2 lists the applied geo-metric scaling factors as well as frequencies and amplitudes of the input motions employed in the study. As shown in Table 2, the scaling factors of dis-placement are relatively larger than the other physical quantities (200 in 25 g and 141.42 in 50g). This fact demands precise measurements in displacement. In total 5 tests [3 tests in 25 g (25 g_1, 25g_2, and 25g_3) and 2 tests in 50 g (50g_1 and 50g_2)] are conducted. In what follows, units are in prototype unless otherwise specified.

2.1 Test setup

A series of dynamic tests under two different centrifugal accelerations of 25 g and 50 g are conducted with the geotechnical centrifuge (arm length=5.0 m) at the IFSTTAR (Institut français des sciences et technologies des transports, de l'aménagement et des réseaux), Nantes, France. The model ground constitutes of a flat dry sand layer, which is constructed with airpluviation method (pluviation height=0.6 m, slot width=4 mm) to form the relative density of 50% of the Fontainebleau sand NE34 (e_{min}=0.545, e_{max}=0.866). With the scaling law, a prototype ground is scaled down to 1/100. The flexible ESB (equivalent shear beam) box whose inside dimension is 800 (W) x 400 (H) x 340 (D) (mm) in model scale is employed (Fig. 2). A sinusoidal input acceleration of frequency 1.0 Hz, maximum amplitude 0.5 g, and duration 14 sec is applied to the model ground. Each model is exposed to the identical input motion sequentially 10 times in order to increase the number of measurements.

In total nine accelerometers are installed in the model (Fig. 2). Surface settlements are measured by laser displacement transducers. Settlements at three different depths (300, 200 and 50 mm – model scale - from the surface) are measured by settlement gauges, which are made of a plate, and a rod connected to potentiometers.

Settlement gauges are carefully placed at the specified depth (Fig. 2) with fishing strings. The

PVC plates without attaching the potentiometers are in-stalled for comparison purposes. Three potentiometers are mounted after completing model ground.

Table 2. Test cases and scaling factors used in the present study

Quantity	Case 1 scaling factor 1g test	25 G scaling factor centrifuge test	generalized scaling factors	Case 2 scaling factor 1g test	50 G scaling factor centrifuge test	generalized scaling factors
Length	4.00	25.00	100.00	2.00	50.00	100.00
Density	1.00	1.00	1.00	1.00	1.00	1.00
Time	2.83	25.00	70.71	1.68	50.00	84.09
Frequency	0.35	0.04	0.01	0.59	0.02	0.01
Acceleration	1.00	0.04	0.04	1.00	0.02	0.02
Velocity	2.83	1.00	2.83	1.68	1.00	1.68
Displacement	8.00	25.00	200.00	2.83	50.00	141.42
Stress	4.00	1.00	4.00	2.00	1.00	2.00
Strain	2.00	1.00	2.00	1.41	1.00	1.41
Stiffness	2.00	1.00	2.00	1.41	1.00	1.41
Permeability	2.83	25.00	70.71	1.68	50.00	84.09
Pore pressure	4.00	1.00	4.00	2.00	1.00	2.00
Fluid Pressure	4.00	1.00	4.00	2.00	1.00	2.00

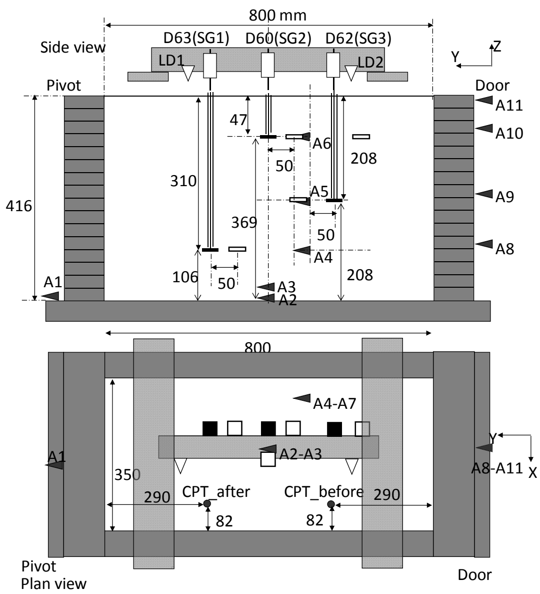

Figure 2. Schematic view and sensor location of the model

3. Response of the model grounds

3.1 Input and ground acceleration

As shown in Fig. 3, nearly identical input accelerations are given to the model ground. Figure 4 summarizes intensity of input motion in the form of Ari-as intensity (Arias 1970) for all the cases employed in the present study. As shown in Fig. 4, at all the shaking, the intensity is almost identical, except for the first 4 cases in 50 g tests. This variation may be due to the instability of shake table control. As explained later, this small variation might cause smaller ground settlements in the case of 50g_1.

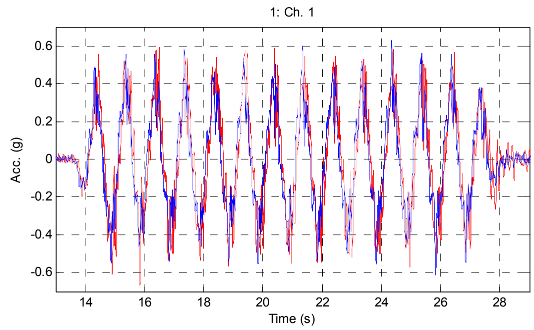

Figure 3. Time histories of input acceleration in prototype scale (red 25g_1, blue 50g_1)

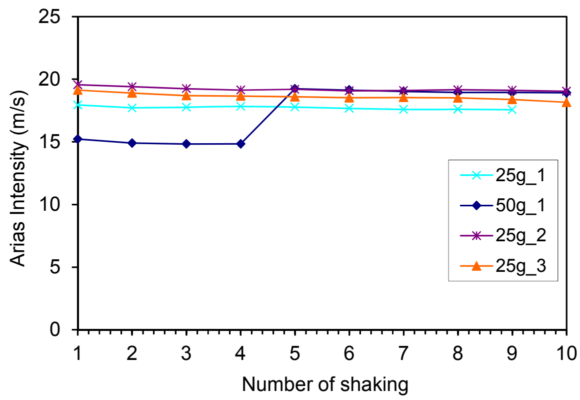

Figure 4. Arias intensity of the recorded input acceleration in prototype scale

3.2 Penetration resistance

Before the initial shaking and after the 10th shaking, resistance of the model ground was measured by the miniature penetrometer. As shown in Fig. 5(a), penetration resistance in depth under 50 g in model scale is, as it is expected, larger than that of 25 g. While in prototype scale [Fig. 5(b)], they approach each other and the curve of 25 g becomes slightly larger. This clearly shows that the generalized scaling law works correctly for the scaling of penetration resistance.

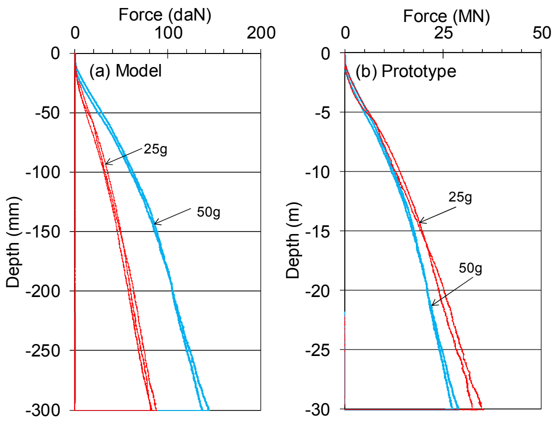

Figure 5. Penetrometer resistance before the initial shaking in model scale (a) and prototype scale (b).

3.3 Ground settlements

Ground settlements at the ground surface are measured by laser displacement transducers, and those in the ground are by settlement gauges. Before shaking, the ground is consolidated by applying the specified centrifugal accelerations consecutively 3 times to stabilize the ground and the stabilization was con-firmed.

Amounts of settlements after each shaking are summarized in Fig. 6. If the generalized scaling law works correctly, those curves in prototype scale should be identical. Results show [see Fig. 6(a)], for example, after 10th shaking, the ground settlement is about 2,800 mm (50 g) and 3,400 mm (25 g). As number of shaking increases, the difference of settlements between 25 g and 50 g seems to be increasing. However, at the initial shaking [see Fig. 6(b)], the amount of settlements is about 900 to 1,100 mm, variation of difference in settlement between 25 g and 50 g is much smaller than those after 2nd shaking. Thus, in what follows, settlements after the 1st shaking are investigated in detail.

Figure 7 compares settlements of all the sensors recorded after the 1st shaking for all cases. As mentioned earlier that due to the variation of input intensity, case 50g_1 had lower and case 50g_2 had slightly larger intensity of shaking. This trend is found in the amount settlement shown in Fig. 7. Considering that the intensity of case 50g_2 is close to the ones in 25 g, the amount of settlement in prototype scale seems to be matching quite well.

Scaling factor of settlements (displacement) is as large as 200 for 25 g and 141 for 50 g. In each case, it is possible to have minor variation in constructing the model ground, in sensor setups, and in the input accelerations. Those minor variations may cause large difference in results.

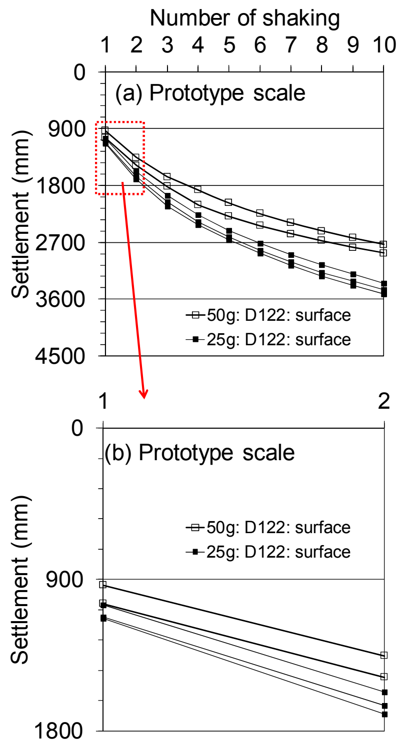

Figure 6. Cumulative settlements after each shaking in prototype scale: (a) number of shaking 1 to 10, (b) enlarged section for the number of shaking 1 to 2.

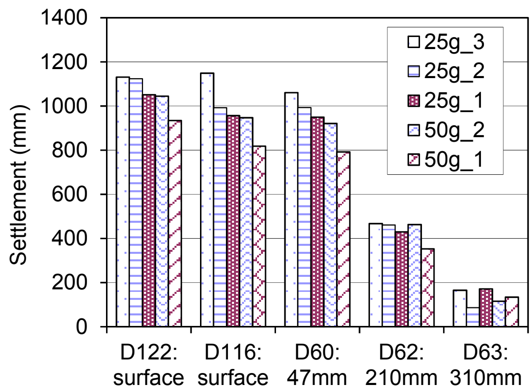

Figure 7. Summary of settlements measured in all the test cases in prototype scale

4. Conclusions

To examine the applicability of the generalized scaling law, a series of dynamic tests under two different centrifugal accelerations of 25 g and 50 g were conducted. The model ground constituted of a flat dry sand layer. A prototype ground and input accelerations were scaled down to 1/100 according with the scaling law. A sinusoidal input acceleration of frequency 1.0 Hz, maximum amplitude 0.5 g, and duration 14 sec in prototype scale was applied to the model ground. Each model was exposed to the identical input motion sequentially 10 times. Measured settlements after the initial shake in prototype scale showed agreements between the two models when the intensity of shaking was nearly identical.

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乾燥砂地盤における沈下挙動に対する拡張型相似則の適用性

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要　旨

遠心場において拡張型相似則の検証を行う。着目したのは乾燥砂地盤の振動による沈下量である。同相似則の適用性の確認は、測定された各物理量の実物スケール換算値が全実験ケースで一致することをもってなされる。模型地盤はフォンテーヌブロー砂による水平成層乾燥砂地盤(Dr=40%)であり，加速度計10台とレーザー式変位計1台および沈下計3台を設置した。実験は模型縮尺を1/100とし、25gと50gの遠心場における地盤の挙動を計測した。実験ケースは，全5ケースである。各ケースにおいて，正弦波加振を10回行った。また，加振前と10回の加振後に貫入抵抗の計測を行った。入力加速度については，Arias Intensityを計算し，プロトタイプスケールでほぼ一様な入力がなされていることを確認した。地表面の沈下量について，加振第1回目の実物換算値は全ケースで約900㎜となり，同相似則の適用性が確認できた。

キーワード:遠心模型実験，相似則，動的試験，乾燥砂