New modelling of models for dynamic behavior of a pile foundation

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ABSTRACT

Demands for the testing of large prototypes in geotechnical engineering are increasing, while restrictions are recognized, such as costs and limited scale of testing facility. To resolve such demands and restrictions, Iai et al. (2005) proposed a 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. The objective of the present study is to investigate and point out issues on the applicability of the scaling law through the technique of “new” modelling of models for dynamic behavior of pile foundations in both dry and saturated sand ground. Through comparison in the prototype scale, the applicability of the scaling law to bending moments was confirmed on the condition that centrifugal acceleration was more than 4.9 g for dry condition, and 14.4 g for saturated condition of 1/100 scale model.

Keywords: Pile foundation, Centrifuge modelling, Scaling law, Liquefaction, Dynamic

1. INTRODUCTION

In the centrifuge model testing, the prototype behaviour is approximated in accordance with scaling laws\(^1\) so that it can qualitatively represent prototype behaviour. One of the major restrictions for application of physical modelling to an existing prototype is that a specific prototype cannot be tested due to restrictions associated with experimental conditions, such as the size of the model container and scaling effects on materials. For 1-g model testing, to overcome these restrictions, a size of the experimental facility has become larger and larger so that real-scale models can be tested [e.g., E-defense\(^2\)]. However, for geotechnical structures, development of larger research facility may still have limitations because, even with such a large facility, physical modelling with foundations and surrounding ground has to be reduced due to factors inherent in a large facility, such as the capacity of the shake table and budget.

Demands for the testing of large prototypes are increasing under the restrictions mentioned above. To resolve such demands and restrictions, the generalized scaling law by combining the scaling law for centrifuge testing with the one for 1-g dynamic model testing was proposed\(^3\). Tobita et al.\(^4, 5\) investigated its applicability with a flat dry and 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\(^6\) applied also in the present study and concluded that response in the prototype scale during shaking, such as accelerations and excess pore water pressure behaviour, except for its dissipation phase, were nearly identical for all the investigated cases.

In this study, the applicability of the generalized scaling law with particular emphasis on the scaling law for bending moments is investigated through dynamic response of model pile foundations.

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\(^7\). 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 (\(\mu\)) [column (1) of Table 1] can be multiplied with those for centrifuge tests (\(\eta\)) [column (2) of Table 1], resulting in much larger overall scaling factors \(\lambda = \mu \eta\) [column (3) of Table 1].
Model pile foundation was made of a set of four rectangular aluminum plates whose dimensions are found in Table 2. The pile length in prototype scale is 30 m. Both pile head and bottom are welded so that a perfectly rigid condition is achieved. To give a dynamic lateral inertial force, a mass (0.5 kg) was attached on top of the model foundation. Bending moments of a pile can be derived by strain recordings for 12 different depths.

To validate the generalized scaling law, the modelling of models technique is employed. As shown in Table 3, in a series of experiments, model ground is scaled down to 1/100 with various intermediate scales corresponding to various centrifugal accelerations (indicated by $\mu$ in Table 2). Those centrifugal accelerations were chosen so that bending stiffness, $E_I$, of all the cases in the prototype scale became identical, i.e., $E_I=2.84 \times 10^{10}$ (kNm²) (Table 3).

In Case 5 to 7, a viscous fluid made of the methyl-cellulose is used for pore fluid to accommodate a conflict of the scaling law of time between dynamic phenomena and water dissipation (consolidation). The viscosity of the pore fluid was also scaled for each case accordingly with the generalized scaling law.

To construct the model ground, firstly, a dry sand was air-pluviated in the box. The target relative density was 70% for dry ground (Cases 1 to 4) and 60% for saturated ground (Cases 5 to 7). For saturated cases, after completing the sand filling, the box was put into vacuum chamber, and the viscous fluid was injected into the box through two acrylic tubes fixed at the bottom of the box. In this way fully saturated model ground was built. However, as shown in Table 2, measured degree of saturation was as low as 96.1%. One of the causes of this low rate is that, to reduce time for saturation process, speed of injection of the viscous fluid was too fast and small amount of air bubbles might be left in the model ground.

Upon conducting the dynamic testing, the box was put on a base plate attached on the shaker on the swinging platform of the centrifuge, and the model ground is then consolidated under the specified centrifugal acceleration for five minutes. Then, under the specified centrifugal acceleration, the model was shaken.

Table 2. Bending stiffness, moment of inertia of area and thickness of model pile

<table>
<thead>
<tr>
<th>Case</th>
<th>Bending stiffness $E_I$ (kN·m²)</th>
<th>Moment of inertia of area $I_a$ (m⁴)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 5</td>
<td>$2.84 \times 10^{10}$</td>
<td>$1.26 \times 10^8$</td>
<td>2.81x10⁶</td>
</tr>
<tr>
<td>2 &amp; 6</td>
<td>$2.84 \times 10^{10}$</td>
<td>$2.36 \times 10^8$</td>
<td>2.34x10⁶</td>
</tr>
<tr>
<td>3 &amp; 7</td>
<td>$2.85 \times 10^{10}$</td>
<td>$4.65 \times 10^8$</td>
<td>1.51x10⁶</td>
</tr>
<tr>
<td>4</td>
<td>$2.85 \times 10^{10}$</td>
<td>$3.64 \times 10^8$</td>
<td>8.84x10⁶</td>
</tr>
</tbody>
</table>

$E=71.4$GPa, $B=0.01$m
Table 3. Test cases and conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Ground condition</th>
<th>Virtual 1g field: $\eta$</th>
<th>Centrifugal field: $\mu$</th>
<th>$\lambda = \mu \eta$</th>
<th>Viscosity (cSt)</th>
<th>Degree of saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dry</td>
<td>2.00</td>
<td>50.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Dry</td>
<td>2.90</td>
<td>34.5</td>
<td>100</td>
<td>84.1</td>
<td>96.1</td>
</tr>
<tr>
<td>3</td>
<td>Dry</td>
<td>6.94</td>
<td>14.4</td>
<td>100</td>
<td>76.7</td>
<td>97.7</td>
</tr>
<tr>
<td>4</td>
<td>Dry</td>
<td>20.4</td>
<td>4.90</td>
<td>100</td>
<td>61.6</td>
<td>96.5</td>
</tr>
<tr>
<td>5</td>
<td>Saturated</td>
<td>2.00</td>
<td>50.0</td>
<td>100</td>
<td>84.1</td>
<td>96.1</td>
</tr>
<tr>
<td>6</td>
<td>Saturated</td>
<td>2.90</td>
<td>34.5</td>
<td>100</td>
<td>76.7</td>
<td>97.7</td>
</tr>
<tr>
<td>7</td>
<td>Saturated</td>
<td>6.94</td>
<td>14.4</td>
<td>100</td>
<td>61.6</td>
<td>96.5</td>
</tr>
</tbody>
</table>

3 RESULT AND DISCUSSION

Results shown below are converted to the prototype scale, unless otherwise noted.

3.1 Dry condition (Case 1 to 4)

Figure 3 compares the time histories of the input acceleration in model (Fig. 3(a)) and prototype (Fig. 3(b)) scale, whose maximum amplitude is 4.64 (m/s²), frequency is 1 Hz with 10 cycles. As shown in Fig. 3(a), each input acceleration has different amplitude and duration in model scale. However, in prototype scale shown in Fig. 3(b), they are nearly identical. Hence, if other physical parameters, such as bending moments and/or displacements, show similarity, the scaling law for that particular physical parameter may be validated.

As an example, the vertical profiles of bending moments are plotted in Fig. 4. The profile corresponds to the timing at the peak of pile head displacement shown with a red circle in the time history of the pile head displacement. The profiles significantly vary in model scale, while in prototype scale, their shape converges.

3.2 Saturated condition (Case 5 to 7)

The recorded input acceleration in model and prototype are, respectively, plotted in Fig. 5(a) and 5(b) whose target amplitude was 2.50 (m/s²), frequency was 0.6 Hz, and duration was 40 sec. In prototype scale, the maximum amplitude of Cases 5 and 6 exceeded to be 3 to 4 m/s². For Case 7, that is about 2.5 m/s².

Fig. 2 Cross section of the model and sensor location in model scale.

Fig. 3 Input acceleration for Case 1 to 4 (dry condition): (a) model and (b) prototype

Fig. 4 Profiles of bending moments of dry condition (Case 1 to 4): (a) model, (b) prototype, (c) time history of pile head displacement

As an example, profiles of the bending moments in model (Fig. 6(a)) and prototype (Fig. 6(b)) at the timing shown with a red circle in the time history of the pile head displacement are depicted in Fig. 6. In prototype scale, their curves tend to converge, except for those in deeper location. Time histories of bending moments measured at section 3 (GL. -4.5 m) (Fig. 7(a)) also show agreements among prototypes. However, as shown in Fig. 7(b), amplitude of bending moment measure at section 9 (GL. -13.5m) of Case 7 is significantly lower than the others. This may also be attributed to the smaller input acceleration.
4 CONCLUSIONS

The objective of the present study was to investigate and point out issues on the applicability of the generalized scaling law through the technique of “new” modelling of models for dynamic behavior of pile foundations in dry and saturated sand ground. Through comparison in the prototype scale, the applicability of the scaling law to bending moments was confirmed on the condition that centrifugal acceleration was more than 4.9 g for dry condition, and 14.4 g for saturated condition of 1/100 scale model.

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