SCALE EFFECT IN ANCHOR PULLOUT TEST
BY CENTRIFUGAL TECHNIQUE

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ABSTRACT

Centrifugal technique can be applied to the model tests of bearing capacity, earth pressure, anchor pullout, etc. in sand. In this method, the soil mechanics law of similarity is satisfied by performing the model tests in the centrifugal field. However, the problems on the grain size of soil and the magnitude of acceleration of the test field have not been clarified.

In this paper, the scale effect will be discussed based on the model tests of the anchor pullout resistance in dry sand by the centrifugal technique and the conventional model test in 1 g field. Important findings are: (1) no scale effect can be observed in the centrifugal model test for the 0.1~1.0 mm grain size of sand and for the approximately 10 mm width or diameter of model anchor, and (2) since the scale effect is observed even by the centrifugal technique, the acceleration level must be set considering the scale effect.

Key words: dimensional analysis, grain size, load, model test, sand (IGC: D0/E5)

INTRODUCTION

In soil mechanics model tests for frictional material such as sand, the effectiveness of the centrifugal technique is well known. This technique was initiated by Pokrovsky and Fedorov (1936) and others in USSR and in USA in the 1930's. Thereafter this method has begun to be actively used in Japan, the United Kingdom and the United States.

Such centrifugal tests can be used in soil mechanics problems such as bearing capacity of footing, bearing capacity of pile, earth pressure of retaining wall, stability of slope, consolidation due to selfweight of cohesive soil, static and dynamic soil-structure interaction, etc.

The law of similarity of the soil mechanics model test using a centrifugal testing machine will be detailed in the next section. It is said that the use of the same material as the actual soil in this machine will ensure the law of similarity of the phenomena such

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External force and acceleration of field:
Pf: Pullout force
V: Pullout velocity
t: Loading time
g: Acceleration of field

Material:
e: Void ratio
ρ: Mass density
θ: Angle of shear resistance
c: Cohesion
E: Young's modulus of soil
ν: Poisson's ratio of soil
d: Grain size

Eg : Young's modulus of soil particle
νg : Poisson's ratio of soil particle
σg : Breaking strength of soil particle

Initial stress in ground:
σn: Stress due to weight of soil

Response:
σ: Stress in soil
e: Strain of soil
δ: Displacement of anchor or deformation of soil

Anchor geometry:
Df: Depth of anchor center
B: Width of anchor
A: Area of anchor
α: Inclination of anchor (load inclination from vertical)

Fig. 1. Physical quantities concerning anchor pullout

as anchor pullout resistance, earth pressure, bearing capacity of footing, etc., eliminating the scale error due to difference in the failure condition of the prototype and the model. However, sufficient care should be exercised in using the centrifugal technique, which will also cause a problem of the law of similarity with respect to the grain size of sand and the acceleration of test field. In this paper, the scale effect and the law of similarity on the pullout resistance of anchor buried in dry sand will be discussed in detail.

LAW OF SIMILARITY ON PULLOUT RESISTANCE OF BURIED ANCHOR

The law of similarity on soil mechanics model test was studied and outlined by Rocha (1957) and Yamaguchi (1980), respectively. In this study, the law of similarity of the pullout resistance of a buried anchor is introduced by a dimensional analysis according to Buckingham’s π-theorem (1914). Fig. 1 shows the following physical quantities relating to the pullout resistance of a buried anchor in dry sand. F, T and L in parentheses are dimensions of force, time and length, respectively, and 0 being dimensionless.

1) Geometrical quantities

Df : Depth of anchor center (L)
B, D : Width and diameter of anchor (represented by width B) (L)
A : Area of anchor (L²)
α : Inclination of anchor (load inclination from vertical) (0)
2) Physical quantities of material
   \( e \): Void ratio of soil (0)
   \( \rho \): Mass density (\( FL^{-1}T^0 \))
   \( \phi \): Angle of shear resistance of soil (0)
   \( c \): Cohesion of soil (\( FL^{-2} \))
   \( E \): Young's modulus of soil as continuum (\( FL^{-2} \))
   \( \nu \): Poisson's ratio of soil as continuum (0)
   \( d \): Grain size of soil (\( L \))
   \( E_p \): Young's modulus of soil particle (\( FL^{-2} \))
   \( \nu_p \): Poisson's ratio of soil particle (0)
   \( \sigma_p \): Breaking strength of soil particle (\( FL^{-2} \))

3) Physical quantities relating to external force, loading velocity and acceleration of field
   \( P_e \): Pullout force (\( F \))
   \( V \): Pullout velocity (\( LT^{-1} \))
   \( t \): Time (\( T \))
   \( g \): Acceleration of field (\( LT^{-2} \))

4) Physical quantity of body force (initial stress in ground)
   \( \sigma_S \): Stress due to weight of soil (\( FL^{-2} \))

5) Physical quantities of response
   \( Q_u \): Ultimate pullout resistance of anchor (\( F \))
   \( \sigma \): Stress in soil (\( FL^{-2} \))
   \( \varepsilon \): Strain of soil (0)
   \( \delta \): Displacement of anchor or deformation of soil (\( L \))

The law of similarity with respect to the anchor pullout resistance can be derived by Buckingham's \( \pi \)-theorem (1914), as shown below. In this case, the model test is to be performed on the assumption that using a \( S=1/\lambda \) scaled model, the same soil as that of the prototype is used under the same compacting condition in the centrifugal field of the acceleration \( \lambda g \). In the following analysis, the suffixes \( p \) and \( m \) are used to indicate the quantities for the prototype and the model, respectively, and 1, the same quantities in the dimensional analysis.

From the above assumptions,
\[
\frac{B_m}{B_p} = \frac{1}{\lambda} \tag{1}
\]

\( B \): representative length, e.g. width of anchor, scale \( S=1/\lambda \)

\[
\frac{e_m}{e_p} = 1 \tag{2}
\]
\[
\frac{d_m}{d_p} = 1 \tag{3}
\]
\[
\frac{\rho_m}{\rho_p} = 1 \tag{4}
\]
\[
\frac{\phi_m}{\phi_p} = 1 \tag{5}
\]
\[
\frac{\nu_m}{\nu_p} = 1 \tag{6}
\]
\[
\frac{\nu_{pm}}{\nu_{pp}} = 1 \tag{7}
\]
\[
\frac{g_m}{g_p} = \lambda \tag{8}
\]

1) Similarity on geometry

\[
\frac{D_{fm}}{D_{fp}} = \frac{B_m}{B_p} = \lambda^{-1} \tag{9}
\]
\[
\frac{A_m}{A_p} = \left( \frac{B_m}{B_p} \right)^2 = \lambda^{-2} \tag{10}
\]
\[
\alpha_m = \alpha_p \tag{11}
\]

2) Similarity on material

\[
\frac{d_m}{d_p} = \frac{B_m}{B_p} = \lambda^{-1} \tag{12}
\]
\[
\frac{c_m}{c_p} = \frac{\rho_m}{\rho_p} \frac{g_m}{g_p} \frac{B_m}{B_p} = 1 \tag{13}
\]
\[
\frac{E_m}{E_p} = \frac{\rho_m}{\rho_p} \frac{g_m}{g_p} \frac{B_m}{B_p} = 1 \tag{14}
\]
\[
\frac{E_{pm}}{E_{pp}} = \frac{\rho_m}{\rho_p} \frac{g_m}{g_p} \frac{B_m}{B_p} = 1 \tag{15}
\]
\[
\frac{\sigma_{pm}}{\sigma_{pp}} = \frac{\rho_m}{\rho_p} \frac{g_m}{g_p} \frac{B_m}{B_p} = 1 \tag{16}
\]

Eq. (12) contradicts Eq. (3), showing the presence of a problem with the law of similarity regarding the grain size of soil. This matter will be discussed later in detail.

3) Similarity on external force, loading velocity and acceleration of field

\[
\frac{P_{fm}}{P_{fp}} = \frac{A_m}{A_p} \frac{\rho_m}{\rho_p} \frac{g_m}{g_p} \frac{D_{fm}}{D_{fp}} = \lambda^{-2} \tag{17}
\]

Since the anchor problem on sandy soil is the phenomenon governed by acceleration.

\[
\frac{V_m}{V_p} = \sqrt{\frac{g_m}{g_p} \frac{B_m}{B_p}} = 1 \tag{18}
\]
\[
\frac{t_m}{t_p} = \frac{B_m}{B_p} \cdot \frac{V_p}{V_m} = \lambda^{-1}
\]

(19) \[
\frac{\delta_m}{\delta_p} = \frac{B_m}{B_p} = \lambda^{-1}
\]

(24)

4) Similarity on body force (similarity on initial stress in ground)

\[
\frac{\sigma_{gm}}{\sigma_{gp}} = \frac{\rho_m}{\rho_p} \cdot \frac{g_m}{g_p} \cdot \frac{B_m}{B_p} = 1
\]

(20)

5) Similarity on response (stress, strain and deformation)

\[
\frac{Q_{um}}{Q_{up}} = \frac{A_m}{A_p} \cdot \frac{\rho_m}{\rho_p} \cdot \frac{g_m}{g_p} \cdot \frac{D_{lm}}{D_{lp}} = \lambda^{-2}
\]

(21)

\[
\frac{\sigma_m}{\sigma_p} = \frac{\rho_m}{\rho_p} \cdot \frac{g_m}{g_p} \cdot \frac{B_m}{B_p} = 1
\]

(22)

\[
\frac{\varepsilon_m}{\varepsilon_p} = 1
\]

(23)

Based on the above dimensionless quantities, the law of similarity on geometry, material and body force (stress in ground) of a \(S=1/\lambda\) scaled model test performed in the conventional \(1 g\) field and that of a \(S=1/\lambda\) scaled model test in a centrifugal \(\lambda g\) field using a centrifugal technique are obtained as shown in Table 1, provided in both cases, the same soil material as for the prototype is used as the model soil under the same compacting condition.

In Table 1, the similarity on material and stress in soil (body force) cannot be satisfied.

<table>
<thead>
<tr>
<th>Table 1. Law of similarity for anchor pullout test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prototype</strong> Scale: (S=1/1) Acceleration of test field: (1g)</td>
</tr>
<tr>
<td>Similarity on geometry</td>
</tr>
<tr>
<td>(a)</td>
</tr>
<tr>
<td>(e)</td>
</tr>
<tr>
<td>(\frac{d}{B})</td>
</tr>
<tr>
<td>(\gamma)</td>
</tr>
<tr>
<td>(\phi)</td>
</tr>
<tr>
<td>Similarity on material</td>
</tr>
<tr>
<td>(E_g)</td>
</tr>
<tr>
<td>(\nu)</td>
</tr>
<tr>
<td>(\nu g)</td>
</tr>
<tr>
<td>(\frac{\sigma_g}{\rho g B})</td>
</tr>
<tr>
<td>Similarity on initial ground stress</td>
</tr>
</tbody>
</table>

Model soil: Same material and same condition as for prototype.
in the conventional model test performed in the acceleration field of 1 g. Accordingly, the response (anchor pullout resistance, stress in soil due to pullout of anchor and anchor displacement) would not be satisfied.

On the contrary, in the centrifugal model test, all physical quantities will be satisfied, except the grain size of soil if the \( \lambda g \) acceleration is applied. Hence, if the phenomena are not affected by the non-similarity of the grain size, the centrifugal model test on anchor pullout resistance will become highly significant.

DISCUSSION ON THE LAW OF SIMILARITY AND THE SCALE EFFECT IN PULLOUT RESISTANCE OF BURIED ANCHOR

1) Soil mechanics failure criteria

A similar analysis to the above clearly shows that the use of the same material in a model test as used for the prototype satisfies the law of similarity on the soil mechanics failure criteria (e.g. Mohr-Coulomb's criteria) by the centrifugal technique but not in the conventional model test.

In the test in the 1 g field, moreover, it is also a big problem in soil mechanics that the failure mechanism is different between the prototype and the model, as described later.

2) Grain size

The use of the same material in the centrifugal technique as used for the prototype does not satisfy the law of similarity on the grain size. This may cause a difference in failure mechanism between the prototype and the model, leading to a possibility of causing a difference in the dimensionless ultimate pullout resistance. The failure mechanism of sand is governed by the relative magnitude of the grain size of sand to the width of the foundation or anchor rather than by the absolute grain size. The average grain size of soil used in centrifugal model tests is 0.1~0.3 mm, while the width of the foundation model or anchor model is 10~100 mm, which can be considered to be sufficiently large to the grain size of soil.

For the purpose of investigating the effect of grain size, Ovesen (1981) performed anchor pullout tests in the vertical and 45° directions in the centrifugal field and in the site as changing \( \lambda \) and \( D \) so that the product \( \lambda D \) of the acceleration of the test field and the width of the anchor would become constant, and demonstrated that there was no change in the dimensionless ultimate pullout resistance in case of the ratio of the anchor width to the average grain size being greater than 25.

Ovesen (1979) also demonstrated in a bearing capacity test of a circular footing using the same technique that there was no difference in the bearing capacity factor by the grain size. In these two references, he also added that the conventional model test might provide overestimated values for the prototype.

Yamaguchi, Kimura and Fuji (1977) performed a bearing capacity test of a shallow foundation with 20~40 mm width in the 10~40 g acceleration field using glass ballotini having two different grain sizes, demonstrating that there were no differences in the
bearing capacity factor and in the load-settlement characteristics. The ratio of the foundation width to the average grain size in this case was 36~286.

From the above, it is considered that anchors having a width or diameter of about 15~48 mm will cause no difference in the failure mechanism by the grain size (average grain size being 0.1~0.2 mm).

3) Scale effect in soil mechanics model test

Scale effect must be sufficiently examined in any model test. Especially, bearing capacity, earth pressure, anchor pullout resistance, etc., in soil mechanics, should show the different status of soil failure between the prototype and the model due to the initial stress condition of soil and the compressibility of soil corresponding thereto.

Baker and Kondner (1966) used circular anchors of diameters of 25.4 mm, 38.1 mm, 50.8 mm and 76.2 mm in an anchor pullout test performed in sandy soil in the 1g field and obtained the results as shown in Fig. 2. This figure shows the relation between the anchor diameter and the dimensionless ultimate pullout resistance of anchor (anchor uplift coefficient) $Q_o/A_f D_f$ with respect to the three relative depths of buried anchors. This figure shows the scale effect in the conventional anchor model test in sandy soil.

![Chart](attachment:image.png)

**Fig. 3. Scale effect in anchor pullout test (Dimensionless ultimate pullout resistance, Ovesen, 1981 and present test)**

<table>
<thead>
<tr>
<th>Anchor model: Circular anchor</th>
<th>Relative depth</th>
<th>Inclination of anchor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovesen ($D_o=29.1$ mm)</td>
<td>$D_r = 1.03$</td>
<td>$a=0^\circ$</td>
</tr>
<tr>
<td>Ovesen ($D_o=29.1$ mm)</td>
<td>$D_r = 1.99$</td>
<td>$a=0^\circ$</td>
</tr>
<tr>
<td>Ovesen ($D_o=30.0$ mm)</td>
<td>$D_r = 3.10$</td>
<td>$a=0^\circ$</td>
</tr>
<tr>
<td>Present test $D_o=48$ mm</td>
<td>$D_r = 2.37$</td>
<td>$a=0^\circ$</td>
</tr>
<tr>
<td>Present test $D_o=119.8$ mm</td>
<td>$D_r = 4.03$</td>
<td>$a=0^\circ$</td>
</tr>
<tr>
<td>Present test $D_o=120.9$ mm</td>
<td>$D_r = 3.60$</td>
<td>$a=45^\circ$</td>
</tr>
<tr>
<td>Present test $D_o=108.0$ mm</td>
<td>$D_r = 3.60$</td>
<td>$a=45^\circ$</td>
</tr>
</tbody>
</table>

Soil used by Ovesen:
- Dense Dansk Normal Sand No.1
- Grain size of soil particle
  - $d=0.3~0.6$ mm
- Relative density $D_r=108\%$

Soil used in present test:
- Dry dense Ottawa Sand
- Effective unit weight $\gamma=18.8$ kN/m$^3$
- Angle of shear resistance $\phi_d=35.1^\circ$
- Relative density $D_r=76.7\%$
- Pullout velocity in present test $V=4.13~25.6$ mm/sec.
That is, the dimensionless ultimate pullout resistance is not constant to the anchor diameter. The smaller anchor diameter shows the greater dimensionless ultimate pullout resistance and this tendency becomes more distinct as the relative buried depth becomes greater.

Ovesen (1981) performed vertical pullout tests of a circular anchor of 29.1 mm in diameter in the 1 g field and in the 50 g centrifugal field, and gave Fig.3. In this figure, his original graph is modified by taking $\gamma GD$ as abscissa, which is connected by a similar curve to that shown in the test results by the authors of this paper. The ordinate shows the dimensionless ultimate pullout resistance $Q_d/A\gamma GD_f$.

The authors of this paper obtained the similar results in the conventional test in 1 g field and the centrifugal test. In these tests, the centrifugal testing machine of California Institute of Technology was used, whose outline is shown in Fig.4. It has a maximum acceleration of about .175 g with the

![Fig. 4. Centrifugal testing machine of California Institute of Technology](image1)

![Fig. 5. Anchor models](image2)

![Fig. 6. Grain size distribution curve of Ottawa Sand](image3)

![Fig. 7. Result of triaxial compression test (Dry dense Ottawa Sand, CD-test)](image4)
1030 mm rotation radius and is provided with a parallelepiped soil container (inside dimensions of 370 mm × 294.5 mm × 254 mm). Fig. 4 also shows the instrumentation system for the centrifugal testing machine. The models used in the present test were the circular anchors of which diameters were 30 mm and 48 mm with the sufficiently long rigid shaft to be buried as shown in Fig. 5. Dry dense Ottawa Sand was used, whose grain size distribution curve and the results of triaxial compression test (consolidated drained test) are shown in Figs. 6 and 7, respectively. In this test, the specified amount of Ottawa Sand was placed into the soil container in layers of 20~30 mm. The soil in each layer was compacted all over with a vibrator and a compacting rod to an even density as much as possible to keep the constant density for all test cases. The average relative density of the model ground was 76.7%. When the test soil was filled up to the level specified for the anchor model to be placed, the anchor model was set at the specified position and angle. The test soil was further added in layers, each of which was compacted as above. In the data analysis, the shaft resistance and the weight of anchor model were excluded based on the preliminary shaft resistance test and the measurement, respectively, to discuss the net anchor pullout resistance. The test results of dimensionless ultimate pullout resistance are shown in Fig. 3 together with those of Ovesen (1981). Also, the test results of an anchor buried at 45° to horizontal and pulled out perpendicularly to its surface (at 45° to vertical) were shown in Fig. 3. The small range along the abscissa is the range of conventional test and the greater range is the range of the prototype or the centrifugal test.

Fig. 8 shows the relation between the displacement of anchor, which is made dimen-

Anchor model: Circular anchor

<table>
<thead>
<tr>
<th>Relative depth</th>
<th>Inclination of anchor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present test</td>
<td>α=0°</td>
</tr>
<tr>
<td>(D_r=48\text{mm})</td>
<td>(\alpha=0°)</td>
</tr>
<tr>
<td>Present test</td>
<td>α=0°</td>
</tr>
<tr>
<td>(D_r=58\text{mm})</td>
<td>(\alpha=0°)</td>
</tr>
<tr>
<td>Present test</td>
<td>α=45°</td>
</tr>
<tr>
<td>(D_r=68\text{mm})</td>
<td>(\alpha=45°)</td>
</tr>
</tbody>
</table>

Soil used in present test:
Dry dense Ottawa Sand
Effective unit weight
\(\gamma=16.8 \text{ kN/m}^3\)
Angle of shear resistance
\(\phi_d=35.1°\)
Relative density: \(D_r=76.7\%\)
Pullout velocity in present test:
\(V=4.13-26.6 \text{ mm/sec.}\)

\(\gamma GD \text{ (N/cm}^2\)

Fig. 8. Scale effect in anchor pullout test (Dimensionless ultimate displacement, present test)
sionless by the anchor diameter (dimensionless ultimate displacement $\delta_{\text{max}}/D$), in the pullout direction at the maximum pullout resistance and $\gamma GD$. Although the data are dispersed, as a whole, including errors in measurement, the dimensionless ultimate displacement $\delta_{\text{max}}/D$ is constant with respect to $\gamma GD \geq 3.0 \text{N/cm}^2$, the same as the case of dimensionless ultimate pullout resistance.

Figs. 2, 3 and 8 show the scale effect in the anchor pullout test. The scale effect will appear more remarkable as the buried depth of anchor becomes greater, while $Q_a/\gamma GD'$ or $Q_a/\gamma GD_f$ will become greater and $\delta_{\text{max}}/D$ will become smaller as $D$ or $\gamma GD$ becomes smaller. In case of Ottawa Sand, the dimensionless ultimate pullout resistance $Q_a/\gamma GD_f$ and the dimensionless ultimate displacement $\delta_{\text{max}}/D$ become constant for $\gamma GD \geq 3.0 \text{N/cm}^2$ from Figs. 3 and 8.

Yamaguchi, Kimura and Fuji (1977) and Kimura, Fuji, Saito and Kusakabe (1982) performed bearing capacity tests of shallow foundations using model soils of Toyoura Sand and glass ballottini and model footings of 20 mm, 30 mm and 40 mm in width and at accelerations of 1~60 g in the centrifugal field and in the 1 g gravitational field and with the depths of embedment at 0, 0.5 $B$ and 1.0 $B$ ($B$: width of footing) and obtained the same result as above. They indicated that the bearing capacity factor $N_T$ will become greater as the acceleration of test field becomes smaller, that this tendency will be increased as the depth of embedment becomes greater, and that Toyoura Sand, used in their test, makes the bearing capacity factor constant for the foundation width greater than about 900 mm in 1 g field. Also, they indicated that the ratio of the settlement of foundation to its width at the maximum load intensity on a dense sandy ground will be increased and gradually become constant as the foundation width is increased in the same relation as in Fig. 8.

From Figs. 2, 3 and 8 and the above conclusions by Yamaguchi, Kimura and Fuji (1977) and Kimura, Fuji, Saito and Kusakabe (1982), in the anchor pullout test and in the bearing capacity test, the model size or the acceleration of the test field must be determined properly in consideration of the scale effect. To practically designing the large prototype, the experiment should be conducted within the range of the abscissa ($\gamma GD$) where the value of the ordinate ($Q_a/\gamma GD_f$) becomes constant.

4) Loading velocity

As described before, the loading velocity of the model becomes equal to that on the actual structure according to the law of similarity. The loading velocity of the prototype depends on the object to be anchored and the condition of external forces. If the anchor pullout resistance in the model test is greatly governed by the visco-elastic behavior of sand, the loading velocity must be carefully examined to perform the anchor pullout test by using the centrifugal technique. Therefore, the test using Ottawa Sand was performed to verify the degree of effect of loading velocity on anchor pullout resistance.

Fig. 9 shows the relation between the pullout velocity and the dimensionless ultimate pullout resistance of two circular anchors of 30 mm and 48 mm in diameter which were buried horizontally in dry dense Ottawa Sand to a given depth and pulled out at three pullout velocities each. Fig. 9 also shows the relation between the pullout velocity and the dimensionless ultimate pullout resistance of a circular anchor of 30 mm in diameter which was buried at 45° to horizontal and pulled out perpendicular to its surface (45° to vertical) at two pullout velocities. From Fig. 9, it is clear that the dimensionless ultimate pullout resistance becomes greater, although slightly, as the pullout velocity becomes greater. This may be considered due to the dynamic effect of loading. The amount of its increase is so small that, together with the law of similarity on pullout velocity, as described before, the results of the pullout test of buried anchor in centrifugal field, is considered to be applicable to the prototype.
5) Summary of law of similarity on pullout resistance of buried anchor

As discussed above, the use of centrifugal technique with the same compacting condition as for the prototype for dry sand completely satisfies the law of similarity on pullout resistance of a buried anchor and a conversion table from

| Table 2. Model-prototype conversion table for anchor pullout test by centrifugal technique |
|---------------------------------|---------|-----------|-----------------|
| Physical quantity               | Symbol  | Dimension | Conversion ratio from model to prototype |
| Geomtery                        |         |           |                               |
| Length                          | L_r     | L         | λ                             |
| Area                            | A       | L^2       | λ^2                           |
| Inclination of anchor           | α       | O         | 1                             |
| Pullout force                   | P       | F         | λ^2                           |
| Pulout velocity                 | V       | LT^-1     | 1                             |
| Time                            | t       | T         | λ                             |
| Acceleration of field           | g       | LT^-2     | λ^-1                          |
| Response                        |         |           |                               |
| Ultimate pullout resistance    | Q_u     | F         | λ^2                           |
| Stress                          | σ       | FL^-2     | 1                             |
| Strain                          | ε       | O         | 1                             |
| Displacement                    | δ       | L         | λ                             |

Scale: $S = \frac{1}{\lambda}$
model to prototype can be obtained, as shown in Table 2. In this table, the scale of models and the acceleration in the centrifugal field must be $S = 1/\lambda$ and $\lambda g$, respectively.

However, to obtain a practical solution of pullout resistance of large buried anchor in sand, the test should be performed within a range that provides greater $\gamma GD$ and constant values of the dimensionless ultimate pullout resistance $Q_u/A_\gamma GD_f$.

CONCLUSIONS
In order to clarify the meaning of the soil mechanics model test for dry sand, the conventional soil mechanics model test in $1g$ field and the test by the centrifugal technique have been discussed in detail and the applicability of the centrifugal technique shown and the soil mechanics law of similarity of a plate anchor buried mainly in dry sand obtained.

The main conclusions are as follows:
1) Conventional test
   (1) In the conventional soil mechanics test by scaled model in $1g$ field, no law of similarity is constituted for frictional material such as sand.
   (2) If a prototype is inferred from the results of the conventional soil mechanics test by scaled model in $1g$ field such as bearing capacity test, earth pressure test, anchor pullout test, etc., in sand, the actual bearing capacity, earth pressure and anchor pullout resistance will become greater leading to a danger in design.
2) Centrifugal model test
   (1) When a bearing capacity test, an earth pressure test, an anchor pullout test, etc., are performed in an acceleration field of $\lambda g$ using a scaled model of $S = 1/\lambda$, the centrifugal technique and the same soil material as for the prototype, all the similarity of geometry, material, external force, body force (initial stress in ground) and response, and on the soil mechanics failure criteria are generally satisfied for dry sand. A model test using centrifugal testing machine is effective for pullout of an anchor buried in frictional material such as sand in which body force (initial stress in ground) governs the phenomena. The conversion rate from the model to the prototype based on the law of similarity is shown in Table 2.
   (2) Although there is a problem in scaling of grain size of sand even by the centrifugal technique, no effect of the grain size of sand on the law of similarity by the use of actual sand is observed in a model test at an ordinary scale of about $S = 1/10 \sim 1/100$.
   (3) Even by the centrifugal technique, scale effect will be observed in the anchor pullout test. Therefore, the acceleration of the centrifugal field should be determined properly in the consideration of the scale effect. To practically designing the large prototype, the test must be performed within a range in which the ultimate anchor pullout resistance made dimensionless by the body force (stress in ground) and the displacement of anchor at ultimate pullout resistance made dimensionless by the diameter of anchor will become constant with respect to $\gamma GD$. That is, it is necessary to perform the test within a range of value of $\gamma GD$ somewhat greater than that to be governed by soil characteristics. (In case of Ottawa Sand, $\gamma GD \geq 3.0$ N/cm² with respect to the anchor pullout resistance.)

NOTATION

$A$ = area of anchor
$B$ = width of anchor or footing
$D$ = diameter of circular anchor
$D_f$ = depth of anchor center
$d$ = grain size of soil
$E$ = Young's modulus of soil as continuum
$E_p$ = Young's modulus of soil particle
$F$ = dimension of force
$G$ = acceleration level of field
$g$ = acceleration of field
$L$ = dimension of length
$N_F$ = bearing capacity factor of footing
$P_f$ = pullout force
$Q_u$ = ultimate pullout resistance of anchor
$S$ = scale
$T$ = dimension of time
$t$ = time
$V$ = pullout velocity
$\alpha =$ inclination of anchor or load inclination from vertical (degrees)
$\delta =$ displacement of anchor or deformation of soil
$\delta_{max} =$ displacement of anchor in pullout direction at ultimate pullout resistance
$\nu_p =$ Poisson's ratio of soil particle
$\sigma =$ stress in soil
$\sigma_p =$ stress due to weight of soil
$\sigma_b =$ breaking strength of soil particle

REFERENCES