LIQUEFACTION-INDUCED GROUND DISPLACEMENT TRIGGERED BY QUAYWALL MOVEMENT

MASANORI HAMADA and KAZUE WAKAMATSU

ABSTRACT

Liquefaction-induced large ground displacement triggered by quaywall movement is investigated by case studies on the 1995 Hyogoken-Nambu and the 1964 Niigata earthquakes, and by a shaking table experiment on model ground. Permanent ground strain is discussed, as is its relationship with the damage rate to buried water and sewage pipes. The followings are obtained by summarizing the results of the case studies and the experiment: (1) the magnitude of the ground displacement 200–300 m away from the quaywall is still governed by the quaywall movement; (2) the damage rate of buried pipes for water and sewage has a close correlation with the tensile ground strain in the axial direction; (3) the behavior of the liquefied soil due to a boundary movement varied greatly depending on the magnitude of the boundary movement. The liquefied soil behaves as a solid body when the boundary movement is large. On the contrary, it behaves as a liquid when the boundary movement is small.

Key words: case history, deformation, earthquake damage, earthquake resistant, (ground displacement), (ground strain), (lifeline) liquefaction, model test, quay, sandy soil (IGC: E8/D7/H7)

INTRODUCTION

The Hyogoken-Nambu (Kobe) earthquake induced liquefaction on reclaimed land in coastal areas, causing devastating damage to quaywalls and foundations of various kinds of structures. Permanent ground displacement of as much as several meters in the horizontal direction due to the large quaywall movement inflicted disastrous damage on foundation piles and buried pipes (Hamada et al. 1996; Hamada and Wakamatsu 1996).

The authors have conducted case studies on liquefaction-induced ground displacement in past earthquakes such as the 1983 Nihonkai-Chubu, 1964 Niigata and the 1948 Fukui earthquakes and showed that there were two types of the ground displacement, as shown in Fig. 1. In the first type, the ground displaces from a higher to lower elevation on gently sloped ground. In the second type, a large movement of quaywalls causes ground displacement at the back of the walls on reclaimed land and along big rivers.

As for the displacement of sloped ground the authors have performed experiments on the characteristics of liquefied soil during the ground flow, and by summarizing the results from the case study and the experiments have proposed a semi-empirical and semi-theoretical formula for estimation of the magnitude of the horizontal displacement of sloped ground (Hamada and Wakamatsu, 1998). Furthermore, the authors have investigated the basic characteristics of ground displacement caused by quaywall movements in case studies on the 1964 Niigata and the 1995 Hyogoken-Nambu earthquakes, as well as by a shaking table test (Hamada and Wakamatsu, 1998).

In the present paper, the authors discuss the mechanism of the occurrence of ground displacement resulting from large quaywall movement by referring to the outcomes from the shaking table test and the case studies. They also investigate ground strain caused by liquefaction-related ground displacement and its relationship with the damage to buried water and sewage pipes.

![Fig. 1. Two types of liquefaction-induced ground displacements (Hamada and Wakamatsu, 1998)](image-url)
**CASE STUDY ON GROUND DISPLACEMENT DUE TO QUAYWALL MOVEMENT**

**Methods of Case Study**

Liquefaction-induced ground displacement observed on reclaimed lands in the Hyogoken-Nambu earthquake and along the Shinano River in the Niigata earthquake was the subject of the case study. An area in which all of the following conditions were satisfied was selected for analysis of the effect of various factors on the magnitude of ground displacement:

1) the direction and the magnitude of horizontal ground displacements are stable in a relatively wide area; 2) underground structures such as foundation piles and basements of buildings have no effect; and 3) it is easy to judge soil layers as being liquefied because the ground has a simple sandy structure. Ground having alternating sandy and non-sandy layers and improved ground were excluded from the case study.

Table 1 lists the earthquakes, ground surface displacements, soil type and thickness of liquefied soil, and quaywall displacement selected for the case study. Typical examples of grain size distribution curves for estimated liquefied soils in the studied areas are shown in Fig. 2. Figure 3 shows the location of the areas and the earthquakes used for the analysis. As an example, Fig. 4 shows ground displacement at the north side of Rokko Island, in Kobe. Paying attention to the land form after the earthquake in Fig. 4(c) the ground right behind the quaywall collapsed as the quaywall moved toward the sea and an inclined ground was then formed. In contrast, the ground surface at the rear of the inclined ground subsided uniformly and the ground surface was kept almost flat. The horizontal displacement, $D$, subject to the case study, shown in Table 1, is an average in the flat ground rear of the inclined ground, where the directions and quantities of horizontal displacement vectors were almost uniform, and an average of 50 m or more away from the quaywall. Refer to Hamada et al. (1986) and Hamada et al. (1995) for methods of measuring ground displacements and measurement accuracy.

**Discussion on Ground Displacement and Quaywall Movement**

Figures 5 and 6 show the relationships between ground displacement on the surface in the horizontal direction, and thickness of liquefied soil, and that between ground displacement and quaywall displacement, respectively. The quaywall displacement was measured on the crest of quaywalls by aerial photographs taken before and after these earthquakes, as is the case with the measurement of ground displacements. As is clear from Fig. 5, there is little correlation between the ground surface displacement and liquefied soil layer thickness. However, as can be

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Site No.</th>
<th>$D$ (m)</th>
<th>Liquefied soil</th>
<th>$H$ (m)</th>
<th>$D_{x}$ (m)</th>
<th>$\phi \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964 Niigata</td>
<td>Ng11</td>
<td>3.0</td>
<td>Medium sand</td>
<td>6.3</td>
<td>4.9</td>
<td>3.9</td>
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<td></td>
<td>Ng12</td>
<td>3.6</td>
<td>ditto</td>
<td>11.1</td>
<td>8.6</td>
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<tr>
<td></td>
<td>Ng13</td>
<td>4.1</td>
<td>ditto</td>
<td>14.0</td>
<td>7.3</td>
<td>3.4</td>
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<tr>
<td></td>
<td>Ng14</td>
<td>1.9</td>
<td>ditto</td>
<td>11.7</td>
<td>4.2</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>Ng15</td>
<td>4.7</td>
<td>ditto</td>
<td>11.5</td>
<td>6.7</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Ng16</td>
<td>3.7</td>
<td>ditto</td>
<td>10.0</td>
<td>6.2</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Ng17</td>
<td>6.6</td>
<td>ditto</td>
<td>10.0</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>1995 Hyogoken-Nambu</td>
<td>Hg1</td>
<td>0.7</td>
<td>Decomposed granite (sand &amp; gravel)</td>
<td>6.9</td>
<td>2.1</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Hg2</td>
<td>0.9</td>
<td>ditto</td>
<td>10.8</td>
<td>3.8</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Hg3</td>
<td>2.1</td>
<td>ditto</td>
<td>11.0</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Hg4</td>
<td>1.9</td>
<td>ditto</td>
<td>10.4</td>
<td>3.8</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Hg5</td>
<td>0.7</td>
<td>ditto</td>
<td>10.7</td>
<td>3.0</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Hg6</td>
<td>1.4</td>
<td>ditto</td>
<td>15.0</td>
<td>3.2</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>Hg7</td>
<td>1.4</td>
<td>Decomposed granite &amp; marine fine sand</td>
<td>7.7</td>
<td>2.2</td>
<td>3.4</td>
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<tr>
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<td>Hg9</td>
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<td>Decomposed granite</td>
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</tr>
<tr>
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<td>9.0</td>
<td>1.7</td>
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<tr>
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<td>Hg11</td>
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<td>ditto</td>
<td>7.8</td>
<td>2.7</td>
<td>8.6</td>
</tr>
</tbody>
</table>

$D$: Ground surface displacement  
$H$: Thickness of liquefied soil  
$D_{x}$: Quaywall displacement  
$\phi$: Gradient of inclined ground behind quaywall
LIQUEFACTION-INDUCED GROUND DISPLACEMENT

(a) 1964 Niigata Earthquake
(b) 1995 Hyogoken-Nanbu Earthquake

Fig. 3. Location of measuring lines of ground displacement in the districts subjected to case study

Fig. 4. Displacements of the ground at the back of quaywalls and typical pre- and post-earthquake land forms (Hamada and Wakamatsu, 1998)

Fig. 5. Relationship between horizontal ground surface displacement and thickness of liquefied soil (Hamada and Wakamatsu, 1998)

Fig. 6. Relationship between horizontal ground surface displacement and quaywall displacement (Hamada and Wakamatsu, 1998)
seen from Fig. 6, there is an approximately linear correlation between the horizontal ground surface displacement and quaywall displacement in the data taken during both the Niigata and the Hyogoken-Nambu earthquakes, but in the Hyogoken-Nambu earthquake the data itself varies greatly. Approximation of the relationship between horizontal ground surface displacement and quaywall displacement with a straight line intersecting the origin gives the equation as shown, with the solid line in Fig. 6, where the surface displacement of flat ground far from the quaywall is mostly one half of the quaywall movement. However, it should be noted that according to the experimental results mentioned later, the magnitude of the liquefied-ground displacement due to the boundary movement is strongly affected by the duration of input motion, namely by the duration of the liquefaction, as well as by the critical shear strain at which the liquefied soil recovers its stiffness besides the boundary displacement.

The results in Fig. 6 reveal that the horizontal ground displacement of the flat ground far away from the quaywall are also affected by quaywall displacement. Therefore, in order to estimate ground displacements, it is essential to estimate quaywall displacements with reliability.

Figure 7 shows the relationship between water depth at the front of the quaywall and displacement of caisson quaywalls measured on the crest of the walls in the Hyogoken-Nambu earthquake. Although there are some variations, displacement is shown to increase relative to an increase in water depth. Quaywall displacement can be considered to be affected by intensity of earthquake ground motion, type of structure, degree of deterioration, design seismic coefficient, and whether or not liquefaction occurs. With these parameters taken into account, an equation to esti-
mate quaywall displacement was proposed before the Hyogoken-Nambu earthquake (Uwabe, 1983), a new estimation method based on the results of case studies on past earthquakes including the Hyogoken-Nambu earthquake has been proposed (Iai et al., 1997), and an attempt has been made to numerically estimate quaywall displacements by the finite element method (Iai, et al., 1995).

Figure 8 shows the relationship between the horizontal distance from quaywalls and horizontal ground surface displacement in the Hyogoken-Nambu earthquake, as listed in Table 1. The displacement decreases within a range of 50–100 m from quaywalls and remains mostly unchanged outside this range. The area in which the ground surface was displaced extended as far as 200–300 m. One of the reasons why the ground displacement continued far from the quaywall is thought to be that the subject of the case study was ground displacement in an area with underground structures such as foundation piles and basements of buildings, and where no soil improvement was carried out.

Figures 9 and 10 show the relationships of quaywall displacement to length and gradient of the inclined ground right behind the quaywalls, respectively. The number of the referred data is small and so no definite conclusion can be obtained from the results in the figures, but no clear correlation is found.

LIQUEFACTION-INDUCED GROUND STRAIN AND DAMAGE RATE OF BURIED PIPES

A huge number of buried pipes were broken in the liquefied ground in the coastal filled area during the Hyogoken-Nambu earthquake. A large permanent ground strain on the horizontal plane resulting from liquefaction-induced ground displacement is one of direct causes of this damage. Therefore, the ground strain was calculated from the measured ground displacement, and the relationship between the magnitude of the ground strain and the damage rate of water and sewage pipes was investigated.

The ground strain was calculated according to the following procedures:
1) It is assumed that the displacement in a mesh (Fig. 11) where the ground strain is calculated is expressed by following linear functions;

\[
u(x, y) = \alpha_1 x + \beta_1 y + \gamma_1
\]

Fig. 8. Relationship between horizontal distance from quaywalls and horizontal ground surface displacement (Hamada and Wakamatsu, 1998)

Fig. 9. Relationship between quaywall displacement and length of inclined ground at the back of quaywall

Fig. 10. Relationship between quaywall displacement and gradient of inclined ground

Fig. 11. Calculation of ground strain
(2) By the least mean square method the coefficients $a_1 - y_2$ can be determined from the measured ground displacement in the mesh, and the ground strain obtained.

Figure 12 shows the area for the calculation of the ground strain which covers two big artificial islands (Rokko and Port Isls.) and the filled areas in the main island side from Kobe to Nishinomiya.

Figures 13 and 14 show the frequency of occurrences of tensile and compressive strains, respectively. The tensile and compressive strains mean the maximum and minimum principal strains in each mesh, respectively. The magnitudes of the calculated strains mean an average values in each mesh, whose size is about 100 m. In the figures, Zone I means the area where the meshes locate within less than 100 m from the quaywall line, while Zone II means other areas. The tensile strain in Zone I is much larger than that in Zone II, because the ground near the quaywall moved largely toward the sea due to the movement of the quaywalls. The maximum tensile strain in Zone I reaches over 3.0%, and the mean value is about 1.0%. However, the magnitude of the tensile strain in more than 70% of the meshes is less than 0.5%. The compressive strain in Fig. 14 is much smaller than the tensile strain, and has mostly the same magnitude in Zones I and II.

Figure 15 shows the relationship between damage rate of ductile iron pipes for water supply and magnitude of the tensile ground strain. The damage rate means the total number of breakages of the pipeline per 1 km. The total length of the water pipes subjected to the present study is about 8.3 km. It was reported that above 95% of the damage was the pull-out of the joints (Japan Water Association, 1995), but a small amount of damage in the form of push-ins and cracks at joints was also reported. A correlation can be found between the damage rate and the tensile ground strain. It should be noted that the damage rate of the water pipes reached over 30 points/km, when the tensile ground strain was more than 4%.

Figure 16 shows the relationship between the damage rate of concrete, vinyl chloride and ceramic pipes for sewage and the magnitude of the tensile ground strain. The damage rate means the ratio of number of damaged spans between two neighboring manholes to the total number of the spans. It was also reported that the most of the damage to sewage pipes was pull-out and cracks at joints, but some damage such as push-into manhole, circumferential and longitudinal cracks was observed besides the damage at joints (Japan Sewage Association, 1995). A mostly linear correlation can be found between the damage rate and the tensile ground strain, and it should be noted that almost half of the total spans were damaged when the tensile ground strain was more than
2.0%.

The performances of jointed pipes is greatly affected by the existence of ground fissures resulting from large tensile strain. Figure 17 shows a comparison of the frequency of occurrences of tensile ground strain in those meshes where ground fissures were observed with that in those meshes where they were not observed. It can be understood that ground fissures were caused in all meshes when the tensile strain was more than 1.0%. In ordinary earthquake resistant design procedure for buried pipes, design ground strains are taken into consideration. However, in the case of such a large ground strain as caused by liquefaction, the effect of the ground fissure should be taken into account in the design of buried pipes, in particular, of jointed pipes.

Figure 18 shows the frequency of the distance between two neighboring ground fissures. The distance is mostly less than 10 m, but it is conjectured that the distance basically depends on factors such as the thickness of the overlying non-liquefied soil and tensile strength of the non-liquefied soil.

MODEL EXPERIMENT ON GROUND DISPLACEMENT CAUSED BY THE MOVEMENT OF A BOUNDARY

The authors have conducted case studies and shaking table tests on liquefaction-induced displacement of sloped ground and concluded that liquefied soil behaves as a liquid with non-linear viscosity under a condition when external disturbance such as earthquake motion and seepage of porewater were stopped (Hamada and Wakamatsu, 1998). Based on these case studies and experiment the mechanism of the occurrence of large ground displacements is discussed.

In this subsection, the authors conduct a shaking table test on fundamental characteristics of the behaviors of the liquefied soil when its boundary moves by using idealized and simplified model ground, in order to deepen the understanding of the findings from the case studies on the ground displacement due to quaywall movement during past earthquakes and to investigate its mechanism.

The test was conducted using a 2.0 m long and 0.5 m wide soil box as shown in Fig. 19. Toyoura standard sand
was used to prepare the model ground of 20 cm in thickness with a flat surface. The initial relative density of the model ground was set as 25–32%. The experiment was carried out in the following steps. The soil box was shaken in the longitudinal direction of the soil box (in the direction of ground displacement) with a sinusoidal wave having a maximum amplitude of 700 cm/s² at 5.0 Hz. After the occurrence of perfect liquefaction was checked with piezometers installed at four depths of 5–20 cm, the shaking was brought to a stop, and boundary A as shown in the figure was removed upward. The ground was then caused to displace toward boundary B which had been set in front of boundary A. In Experiment (I) the soil box was not vibrated after boundary A was removed, while in Experiment (II) it was shaken again by the same sinusoidal waves after boundary A was removed. Horizontal and vertical ground displacements were measured by marks placed on the model ground surface.

Figures 20 and 21 show the results from Experiment (I), in which the shaking was not conducted after the boundary was removed, when boundary displacement was 30 cm and 2.5 cm, respectively. The results reveal that the behavior of the liquefied soil at the back of the boundary varies greatly depending on the magnitude of the boundary displacement. The results when the boundary displacement is large, 30 cm, as shown in Fig. 20 indicates that the ground right behind the boundary collapsed when the boundary moved, and an inclined ground was then formed. Although the ground at the rear of the inclined ground uniformly subsided, the ground surface was kept mostly flat. The horizontal displacement decreases linearly from that at the boundary along the slope to a fairly constant value on the flat ground.

In contrast, the result of the case where the boundary displacement is small, 2.5 cm as shown in Fig. 21, shows that no inclined ground appeared and the ground surface subsided uniformly over the entire area. In addition, the horizontal ground displacement, although it was scattered, was almost equal to the boundary displacement.

From results of experiments on a model ground displacement (Hamada et al., 1994) and hollow-cylindrical shear tests of perfectly liquefied soil (Yasuda et al., 1994; Katada et al., 1994) it was revealed that the liquefied soil firstly behaves as a liquid, but recovers its stiffness under a specific amount of shear strain, so-called critical shear strain, before behaving again as a solid body. It was shown by summarizing the model ground experiments and the shear tests that the magnitude of the critical shear strain depends on the relative density of the soil as shown in Fig. 22.

The experimental results shown in Figs. 20 and 21 can, by taking the concept of this critical shear strain into the consideration (Hamada and Wakamatsu, 1998), be interpreted as follows. When the boundary displacement was large, the shear strain was increased by the displacement of liquefied soil, the stiffness of liquefied soil was recovered when the shear strain reached the critical shear strain, and the characteristics of a solid were restored.
This caused the ground right behind the boundary to collapse and the inclined ground to appear. Further, the shear strain in the flat ground at the rear of the inclined ground reached critical shear strain, the stiffness was recovered and ground displacement was brought to a standstill. This explanation is supported by the fact that displacements on the flat ground proved to be almost constant.

When the boundary displacement was smaller, the shear strain of the ground did not reach critical shear strain, and the liquefied soil constantly showed the characteristics of a fluid. For this reason, the ground surface was not inclined but merely subsided and stayed flat. In this case, the horizontal ground displacement was almost equal to the boundary displacement, although the measurements vary greatly since the characteristics of a fluid were predominant.

Figure 23 shows a relationship between the displacement of the flat ground at the rear of the inclined ground and the boundary displacement. The black circles show the results in the case where the shaking of the soil box was not conducted after the boundary was removed (Experiment (I)). In this case, the horizontal ground displacement was almost equal to the boundary displacement, although the measurements vary greatly since the characteristics of a fluid were predominant.

In the experiment in which the shaking was continued after the boundary moved (Experiment (II)), as is clear from Fig. 23, the ground displacement increased with the duration of shaking after the boundary movement. The ground displacement will be equal to the boundary displacement if the shaking is continued for a certain period of time to keep the characteristics of liquefied soil as a fluid. That is, the ground displacement approaches the displacement denoted by a dotted line in Fig. 23.

Figure 5 shows the relationship between the quaywall displacement and horizontal ground surface displacement at the back of quaywalls in the Niigata and the Hyogoken-Nambu earthquakes. It indicates that the horizontal ground surface displacement is almost a half of the quaywall displacement. However, as shown in the experiment, it should be noted that the behavior of the liquefied soil strongly depends on the magnitude of the boundary displacement and that the displacement of the liquefied soil is largely affected by the duration of the earthquake motion.

Figures 24 and 25 show relationships between the boundary displacement, and length and angle of the inclined ground, respectively, in the Experiment (I) where the vibration was not conducted after the boundary moved. The length and the angle of the inclined ground is mostly zero when the boundary displacement is less than about 5 cm, but gradually increases in proportion to the boundary displacement and reaches a mostly constant value. This result also shows that the liquefied soil behaves as a liquid when the boundary displacement is smaller, but behaves as a solid body when the boundary displacement is larger. The mostly constant value of the slope angle when the boundary displacement is large (20–28°) is almost equal to the angle of repose of Toyoura standard sand in the water of about 22–25°.

Figure 26 shows a schematic explanation of volume transport of the liquefied soil due to boundary displacement. If settlement of the ground due to compaction of
the soil is neglected, the following balance of the volume will be kept:

\[ V_1 = V_2 + V_3 \]  

(3)

where,

\( V_1 \): Volume of liquefied soil which flowed from the boundary A
\( V_2 \): Volume due to inclination of the ground surface
\( V_3 \): Volume due to liquefaction-induced ground displacement on the flat surface area

The displacement at the rear of the inclined ground can be expressed as a product of the critical shear strain \( \gamma_c \) and the thickness of the liquefied soil \( H_m \), when it is assumed that the critical shear strain along the depth is constant. When the boundary displacement \( D_{b,m} \) and the angle of the slope, \( \phi_m \), are given in Eq. (3), the length of the inclined ground \( L_m \) can be obtained as follow;

\[ L_m = \frac{2D_{b,m}H_m - \gamma_c H_m^2}{\tan \phi_m} \]  

(4)

Figure 27 is the relationship between the length of the inclined ground calculated by Eq. (4) and the one measured in the model ground experiment. A good coincidence shows that the concept of the volume transport of the liquefied soil above-mentioned is rational in the case of ground displacement due to quaywall movement.

CONCLUSIONS

The authors investigated liquefaction-induced displacement triggered by large quaywall movement and ground strain through case studies on the 1995 Hyogoken-Nambu and the 1964 Niigata earthquakes. They also discussed correlation between the damage rate of buried pipes for water and sewage, and the magnitude of the tensile ground strain. Furthermore the authors examined the relationship between the occurrence of ground fissures and the tensile ground strain. The result of this study can be summarized as follows:

(1) The magnitude of the ground displacement due to liquefaction at the back of quaywall has a close correlation with the quaywall displacement. In the case study on the 1964 Niigata and the 1995 Hyogoken-Nambu earthquakes, the ground displacement is mostly one half of the quaywall displacement. However, no clear correlation could be found between the ground displacement and the thickness of liquefied soil.

(2) The ground displacement at the back of a quaywall decreases to about one half in the area 50–100 m from the quaywall line, but extends to the inland
area 200-300 m far from the wall.
(3) The quaywall displacement towards the sea is nearly
in proportion to the depth of water in the case of
caisson quaywalls during the Hyogoken-Nambu
earthquake.
(4) The maximum tensile ground strain in the filled
ground reached over 3% in a zone which locates
less than 100 m from quaywall line, since the quay-
wall largely moved towards the sea and triggered
the displacement of the ground behind it.
(5) The tensile ground in the pipes’ axial direction has a
close correlation with the damage rate to water and
sewage pipes. The number of breakages of water
pipes reached over 30 points/km when the tensile
ground strain was more than 4%.
(6) The model experiment on ground displacement due
to boundary movement showed that the behavior of
the liquefied soil at the back of the boundary varied
greatly depending on the magnitude of the bound-
ary displacement. When the boundary displacement
was large, the liquefied soil firstly behaved as a liq-
uid and then recovered its stiffness, because the
shear strain reached the so-called critical shear
strain. The ground right behind the boundary col-
lapsed and an inclined ground was then formed.
Although the ground at the rear of the inclined
ground uniformly subsided, the ground surface was
kept mostly flat. In contrast when the boundary dis-
placement was small, the liquefied soil constantly
behaved as a liquid and the ground surface subsided
uniformly, but kept flat.
(7) It was also found from the model experiment that
the ground displacement behind the quaywall was
governed by the critical shear strain and greatly de-
pended on the duration of the shaking.

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tude to the people of the Central Technical Laboratory
of Tokyo Gas Co. for use of the shaking table.

NOTATIONS

The following symbols are used in this paper:

\[ D = \text{Horizontal displacement on ground surface;} \]
\[ D_{h} = \text{Horizontal displacement of quaywall or boundary;} \]
\[ L = \text{Length of inclined ground behind quaywall or boundary;} \]
\[ H = \text{Thickness of liquefied soil;} \]
\[ T = \text{Duration of shaking after boundary movement;} \]
\[ \phi = \text{Gradient of inclined ground behind quaywall or boundary;} \]
\[ \gamma_{c} = \text{Critical shear strain;} \]
\[ m = \text{Model ground.} \]

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