Study on seismic behavior of special levees of rivers using centrifuge dynamic tests

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ABSTRACT

Since we concern about physical damage of levees due to liquefaction by a large earthquake such as the anticipated Tokyo Metropolitan earthquake and the Nankai trough earthquake, we are strongly involved in examining seismic countermeasures for special levees in urban areas as well as for natural levees. However, the detailed research on nonlinear seismic behaviors for special levees induced by a strong ground motion and liquefaction has not been promoted enough until now. Hence, by dynamic centrifuge experiments we clarified nonlinear dynamic behavior of a special levee and verified the effectiveness of seismic countermeasures for existing special levees. In addition, we improved the models of horizontal load acting onto a seismic countermeasure by comparing the values by current design procedure and the experimental values.

Keywords: special levees of river, liquefaction, seismic countermeasure, dynamic centrifuge test

1 INTRODUCTION

Since we concern about the damage of a levee including a natural levee and a special levee due to liquefaction by large earthquakes in Tokyo Metropolitan areas and Nankai-trough regions, we examine seismic countermeasures for special levees in urban areas as well as for natural levees. However, research on clarification of nonlinear seismic behavior of a special levee due to liquefaction by a ground motion has not been promoted enough until now. In design of a seismic countermeasure to an existing special levee, we have no choice to refer the “Guidelines for Verification of Seismic Performance of River Structures (February 2012, River Improvement and Management Division, Water and Disaster Management Bureau)”ⅳ). Because the guidelines do not show specific examples of seismic retrofit for a special levee, currently, we apply the “Design and Construction Manual for Liquefaction Countermeasure Construction Methods for River Levees (Draft) (October 1997, Public Works Research Institute)”ⅲ) (hereafter referred to as “manual”). Therefore, the current design method of a seismic countermeasure to a special levee is necessary to be improved by clarifying nonlinear seismic behavior of a special levee due to liquefaction by a strong ground motion, and by verifying designed and experimental values of horizontal loads acting on a seismic countermeasure to a special levee.

From the background above, based on analyses of experimental data obtained by dynamic centrifuge testsⅳ)-ⅷ), nonlinear seismic behaviors of a special levee due to liquefaction and effectiveness of a seismic countermeasure corresponding to a solidification body were clarified. In the design retrofit of a special levee, a solidification body is designed for a level 1 ground motion; Natural levees with seismic countermeasure were not almost damage by a level 2 ground motion. We carried out dynamic centrifuge tests for reproducing these damages. For these results, we verified the nonlinear seismic behavior of a special levee and a solidification body subjected to a level 2 ground motion. To reveal those, we analyzed a horizontal seismic coefficient of a solidification body subjected to a level 2 ground motion and modified the models of horizontal load acting on a solidification body.

2 EXPERIMENTAL METHODS

First, we briefly introduce the dynamic centrifuge testsⅳ)-ⅷ) of nonlinear seismic behavior of special levee. The model of foundation ground was manufactured...
with Tohoku silica sand #7. The concrete retaining wall (hereafter referred to as “retaining wall”) is 5[m] high, and made by aluminum. The shape of solidification body was decided by a design on external force of level 1 ground motion. This solidification body was manufactured at with a target design strength of $q_d = 1,000[kPa]$ by using cement-improved soil. We carried out the dynamic centrifuge tests with stressing models by a 50 gravity load. An example of these models is shown in Fig.1. The input acceleration was decided level 2 ground motion (Type I of the 2011 off the Pacific coast of Tohoku earthquake) in seismic design specifications of Highway Bridge on March 2012[8] (Fig.2). These tests were 28 cases (table 1), and these details were shown in the references[5]-7). Unless noted otherwise, all physical quantities indicated hereafter are values actual scale.

![Fig. 1(1). Experimental model and measurement.](image1)

![Fig. 1(2). Experimental model and measurement.](image2)

![Fig. 2. Input acceleration.](image3)

![Fig. 3. Effect by residual displacement of solidification body.](image4)

### Table 1. Experimental cases.

<table>
<thead>
<tr>
<th>Ground structure</th>
<th>Support conditions</th>
<th>solidification body</th>
<th>Ground structure</th>
<th>Liquefiable layer</th>
<th>Solidification body</th>
<th>Retaining wall (W)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Layer thickness</td>
<td>Width (m)</td>
<td>Height (m)</td>
</tr>
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<td>Concrete retaining walls (W)</td>
<td></td>
<td></td>
<td></td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
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<tr>
<td>Bearing pile (B)</td>
<td>Without solidification body (N)</td>
<td>[All layer] Bearing layer</td>
<td>Non (ANL)</td>
<td>-</td>
<td>-</td>
<td>W-B-N-ANL(C7)</td>
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<td>Bearing pile (B)</td>
<td>Solidification body in front (standard) (FS)</td>
<td>[2-layer]</td>
<td>All (AL)</td>
<td>16.5</td>
<td>-</td>
<td>W-B-SL-LFS(C12)</td>
</tr>
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<td>Without solidification body (N)</td>
<td>Upper layer: Liquefiable layer</td>
<td>Large (LL)</td>
<td>7.1</td>
<td>-</td>
<td>W-B-N-LC(C2)</td>
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<td>Lower layer: Bearing layer</td>
<td>Large (LL)</td>
<td>7.1</td>
<td>-</td>
<td>W-B-N-LC(C13)</td>
</tr>
<tr>
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<td>Without solidification body (N)</td>
<td>Alternate-layer (3-layer)</td>
<td>Small (SL)</td>
<td>2.1</td>
<td>-</td>
<td>W-B-N-RS(C22)</td>
</tr>
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<td>Solidification body in front (standard) (FS)</td>
<td>Upper layer: Non-liquefiable layer, Center layer: Liquefiable layer, Lower layer: Bearing layer</td>
<td>Large (LAL)</td>
<td>5.1</td>
<td>-</td>
<td>W-B-N-LAL(C23)</td>
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<td>Solidification body in front (narrow) (FN)</td>
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<td>7.1</td>
<td>W-B-FS-LF(C11)</td>
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<td>Solidification body in rear (standard) (RS)</td>
<td>[2-layer]</td>
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<td>7.6</td>
<td>W-B-RS-LFS(C10)</td>
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<td>[3-layer]</td>
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<td>9.0</td>
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<td>W-B-RS-LFS(C10)</td>
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<td>Sheet pile walls (P)</td>
<td>Without solidification body (N)</td>
<td>[All layer] Liquefiable layer</td>
<td>All (AL)</td>
<td>-</td>
<td>-</td>
<td>P-B-N-ANL(C7)</td>
</tr>
<tr>
<td>Sheet pile walls (P)</td>
<td>Solidification body in front (standard) (FS)</td>
<td>[2-layer]</td>
<td>Small (SL)</td>
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<td>-</td>
<td>P-B-SL-LFS(C12)</td>
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<td>Large (LL)</td>
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<td>12.0</td>
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<td>Lower layer: Bearing layer</td>
<td>Large (LL)</td>
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<td>6.0</td>
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<td>[3-layer]</td>
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<td>9.5</td>
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<td>[4-layer]</td>
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<td>11.0</td>
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<td>Solidification body in front (standard) (FS)</td>
<td>[6-layer]</td>
<td>4.0</td>
<td>8.0</td>
<td>7.6</td>
<td>P-B-FS-LF(C27)</td>
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</tbody>
</table>
3 DYNAMIC RESPONSES OF SOLIDIFICATION BODY

Fig. 3 shows residual displacement of retaining wall. We were able to confirm an effect of seismic countermeasure by comparison between with solidification and without solidification. This residual horizontal displacement was less mostly than 2[m], except for case 1, case 2 and case 13. And this residual vertical horizontal displacement was less mostly than 1[m], except for case 1.

Next, we compared experimental values with design values by dynamic responses of solidification body. Fig. 4 shows comparison between design values and experimental values about physical indices of solidification body in case 12. These experimental values calculated by experimental data, and these design values calculated by manual\(^3\). When we calculated design value and experimental value, this model of horizontal load was shown Fig. 5. The subscript of “d” is design value, and the subscript of “e” is experimental value. From Fig. 4, when it is about 35[s] after vibration each horizontal loads increased by response of input acceleration, residual horizontal displacement increased at same time, too. And we calculated active earth pressure, passive earth pressure, inertia force of solidification body, inertia force of upper soil on solidification body and bottom friction force of solidification body of each case. These results of comparison between design values and experimental values were shown Fig. 6.

![Fig. 5. Model on horizontal load.](image)

![Fig. 4. Dynamic responses of solidification body.](image)

![Fig. 6(1). Comparison between experimental value and design value of horizontal load Solidification body.](image)

Design value
$P_d^{AH} = 1043$

Design value
$P_d^{PH} = -434$

Design value
$P_d^{AF} = 0$

Design value
$H_d = 129$

Design value
$Q_d = 1927$
From Fig. 6, experimental values were almost same as design values of each horizontal load. For the cases with 3 alternation layers (C24, C25, and C28), almost design value of passive pressure was a few smaller than other experimental value. This factor is that weight of non-liquefaction layer upon liquefaction layer was loaded during ground motions with dynamic component of earth pressure. In wide cases (C21 and C25), design value is bigger than experimental value. This factor is that rocking motion of solidification body in experiment did not occur. Almost design value of active pressure was a few bigger than other experimental value, and almost design value of active pressure was a few smaller than other experimental value. This factor is that bearing layer did not liquefaction.

We calculated limit value of horizontal seismic coefficient ($k_{d_{hcr}}$). Limit value of horizontal seismic coefficient is calculated when safety factor of sliding is 1.0. And, we compared experimental values with design values of limit value of horizontal seismic coefficient. These results were shown Fig. 7. Experimental values of limit value of horizontal seismic coefficient were calculated by Eq. (2).

From this result, design values of cases with 3 alternation layers (C24, C25, and C28) and wide cases (C21 and C25) were bigger than experimental values.

$$k_{d_{hcr}} = \frac{PH_H + PH_P - PH_{d}}{WE + WE} \cd (1)$$

$$k_{e_{hcr}} = \frac{AY}{\theta} \cd (2)$$

Where $PH_H$ is horizontal active earth pressure, $PH_P$ is horizontal passive earth pressure, $PH_{d}$ is bottom friction force, $k_{hcr}$ is limit value of horizontal seismic coefficient, and $AY$ is acceleration of solidification body.
4 IMPROVEMENT OF MODEL ON HORIZONTAL LOAD

The difference of experimental value with design value was effect as follows:
1) The weight of non-liquefaction layer upon liquefaction layer was loaded during ground motions with dynamic component of earth pressure.
2) The rocking motion of solidification body in experiment did not occur.
3) The bearing layer did not liquefaction.
And, horizontal seismic coefficient of solidification body was shown Fig.8. From Fig.8, experimental values of horizontal seismic coefficient of solidification body for the level 2 ground motions were equal to be about 0.2. From this result, we confirmed that horizontal seismic coefficient of solidification body for the level 2 ground motion was almost same as horizontal seismic coefficient of current manual3).

Based on these results, we studied on revision to horizontal loads of solidification body. This image was shown Fig.9. We revised as follows:
1) The weight of non-liquefiable layer upon liquefiable layer in case of 3 alternation layer (C24, C25 and C28) is loaded on solidification body during ground motions with dynamic component of earth pressure10) (Eqs. (3) and (4), Fig.10).
2) The bottom friction force of wide case (C21 and C25) is reduced about 0.7 times than standard case.

Next, we calculated limit value of horizontal seismic coefficient by these two revisions (Eq. (5)). This result was shown Fig.11. From Fig.7 and Fig.11, design value of limit value of horizontal seismic coefficient is almost same as experimental value, and two revisions of design limit values of horizontal seismic coefficient gave good agreement with experimental limit values of horizontal seismic coefficient. As these results, we were able to confirm that two revisions were effective.

\[
\text{(Non-liquefaction layer)} \quad p_{d_{\text{dw}}}^{dm1} = \frac{7}{8} \gamma_t \cdot k_h \cdot \sqrt{(H_{NL} + H_L)z} 
\]

\[
\text{(Liquefaction layer)} \quad p_{d_{\text{dw}}}^{dm1} = \frac{7}{8} \gamma_{\text{sat}} \cdot k_h \cdot \sqrt{(H'_{NL} + H_L)z_w} 
\]

\[
k_{d_{\text{hr}}} = \frac{p_{d_{\text{hr}}}^{dm1} + 0.7p_{d_{\text{hr}}}^{dm1} - p_{d_{\text{hr}}}^{d1}}{W_f + W_e} 
\]

Where \(p_{d_{\text{dw}}}^d(\gamma_t)\) is extension dynamic water pressure at depth \(z_w\) of under water level, \(k_h\) is horizontal seismic coefficient, \(\gamma_t\) is unit of slurry weight, \(h_t\) is thickness of liquefaction layer, \(p_{d_{\text{hr}}}^{dm1}\) is active earth pressure where \(p_{d_{\text{dw}}}^d(\gamma_t)\) is reflected, and \(p_{d_{\text{hr}}}^{d1}\) is passive earth pressure where \(p_{d_{\text{dw}}}^d(\gamma_t)\) is reflected. And, because experimental value of case 20 is poor measurement, this is reference value.
5 CONCLUSIONS

In this research, the effect of solidification bodies was confirmed, and we compared experimental values with design values by dynamic responses of solidification body. The model horizontal loads of solidification body were revised by comparison between design values and experimental values. We show these results.

(1) We were able to confirm an effect of seismic countermeasure by comparison between with solidification and without solidification. This residual horizontal displacement was less mostly than 2[m]. And this residual vertical horizontal displacement was less mostly than 1[m].

(2) Experimental values of horizontal seismic coefficient of solidification body for the level 2 ground motions were equal to be about 0.2. We confirmed that horizontal seismic coefficient of solidification body for the level 2 ground motion was almost same as horizontal seismic coefficient of current manual.

(3) The difference of experimental values with design values were effects as follows:
1) The weight of non-liquefaction layer upon liquefaction layer was loaded during ground motions with dynamic component of earth pressure.
2) The rocking motion of solidification body in experiment did not occur.
3) The bearing layer did not liquefaction.

And, we confirmed to improvement points of model of horizontal load on solidification body as follows:
1) The weight of non-liquefiable layer upon liquefiable layer is loaded on solidification body during ground motions with dynamic component of earth pressure.
2) The bottom friction force of wide case is reduced about 0.7 times than standard case.

REFERENCES

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