A SEISMIC DESIGN OF THE UNDERGROUND BOX-TYPE RC STRUCTURE CONSIDERING THE THREE-DIMENSIONALITY

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ABSTRACT

A seismic evaluation method is proposed for determination of planar shear deformation of a shear wall, considering the three-dimensionality, which is an underground box-type structure such as screen chamber and pump chamber of intake facilities in large-scale energy power plants. In underground box-type structures, as results of large-scale ground motion side walls that are perpendicular to the direction of ground motion is pushed by the ground, hence earth pressure acting on the side wall center is reduced by the deformation occurred due to the decrease in the rigidity. On the other hand, earth pressure acting on the side wall end and the shear force acting on the shear wall surface is increased, resulting in in-plane shear deformation of the shear wall, which can lead to cases where critical breakage of the entire structural system occurs. In this case, a method for calculating the limit value of deformation angle “limit deformation angle” is proposed by applying the index of structural member’s deformation angle to the damage index of the shear wall of an underground box-type structure, and the validity of this method is verified by utilising it in a seismic evaluation.

Keywords: Underground RC structure, Numerical analysis, Damage index, Centrifuge experiment, three dimensionalities

1. INTRODUCTION

This paper proposes the new seismic design procedure considering the three-dimensionality of the underground box-type RC structure subjected to seismic motion, based on the results of centrifuge model vibration test and 3D nonlinear dynamic analysis. As a performance-based earthquake engineering, it is to purpose of performing seismic evaluation of an underground box-type structure, such as screen chamber and pump chamber of intake facilities in large-scale energy power plants with each side wall surrounded by soil. This box type structure is connected to multiple culvert and a structural joint is given between the two, and there is an opening on the first floor as shown in Figure 1. Two-dimensional analysis by two-dimensional sliced cross section has been carried out until now, but seismic design method considering three-dimensionality is proposed in this paper.

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2. CENTRIFUGE EXPERIMENT

2.1 Outline of experiment

A centrifuge model vibration test is performed to confirm 3D seismic behavior of underground box type structure and the load acting on each member of the structure, as shown in Figure 2. The box type structure, which is 1/50 scale model with an opening on lower part of one of its side wall surface, was made of aluminum and the wall thickness is 12 mm. The outer dimensions of the model are 250 mm × 350 mm in planar shape and 350 mm in height (actual size scale, planar shape 12.5 m×17.5 m, height 17.5 m). Here, the material physical properties of the aluminum material are elastic modulus E=7.00×10^7 kN/m^2, Poisson's ratio ν_A=0.30, yield stress σ_y=1.00×10^5 kN/m^2. It is put in the central part of the shear soil tank in the centrifuge apparatus.

Upper layer of ground is a sand and lower layer is a cement improved soil. The sand layer is made of Gifu's No.7 silica sand (G_s=2.645, γ_{max}=1.529 g/cm^3, γ_{min}=1.184 g/cm^3) and aimed at a relative density of 70% (γ_d=1.406 g/cm^3) by compacted, which is C=50.1 kN/m^2, φ=36.0°, according to the consolidated non-drainage (CU) triaxial compression test (JGS 0523) of the soil.

The cement improved soil was formed in the lower layer of the shear soil tank, and the thickness was 150 mm with the same height as the load cell. The uniaxial strength q_u of the cement improved soil is 1.51 MN/mm^2, and the modulus of elasticity is 3.24×10^6 kN/m^2.

Input waves are the sign waves of 100 Gal, 200 Gal, and 400 Gal, inputted from undersurface of the shear soil tank. Accelerometers, displacement gauges, earth pressure gauges, shear stress meters and load cells were used as the measurement of the experiment.

2.2 Experiment results

2.2.1 Classification of applied load

As the results of experiment, increase of the applied load and its convergence situation due to gradual increase of the input waves has been revealed by classifying the load acting on each structural member, as shown in Figure 3.

Front-back earth pressure force and circumferential shear force, which are main loads except inertia force, show the little increase rate from 200 Gal to 400 Gal against increasing tendency until 100 Gal. Here, the front-back earth pressure is taken as the sum of earth pressure on the two side walls perpendicular to the input wave direction.
The circumferential shear force tends to converge first comparing with front-back earth pressure force and inertial force. The inertial force increases approximately linearly as the input acceleration amplitude increases. The ratio of the inertial force to the total horizontal force is approximately 20% or less, and its ratio is small like general underground culvert structure. In the ratio to the total horizontal force, the front-back earth pressure was the largest, and the circumferential shear force was the second.

2.2.1 The distribution of front earth pressure

The distribution of earth pressure acting on the front wall at the time, when the largest load in the historical data is calculated, is shown in Figure 4. The earth pressure of the opening side and the central part, due to deformation of the structure against the deformation of the ground, has little change even if the input acceleration is increased. Especially, the earth pressure of the central part is 50% or less compared with earth pressure at the end of the front wall.

On the other hand, earth pressure at the end of the front wall increases due to the rigidity of the structure and the response displacement of the surrounding soil. Earth pressure at the end of the front wall approaches to static passive earth pressure \( \sigma_p=K_s \cdot \sigma_v \), where \( K_s=\tan^2(\pi/4+\phi/2) \), \( \sigma_v \): effective weight of the ground kN/m\(^2\) in 400 Gal. This is because the deformation of the shear wall is small and the relative displacement between the ground and the structure increases.

![Figure 3. Relationship between acting force and ground response displacement of each case](image)

2.2.3 Deformation of the entire structure

Planar maximum deformation of the front wall and the shear wall is summarized as shown in Figure 5(a). The relationship between the out-of-plane deformation angle of the front-back wall and the in-plane deformation angle of the shear wall, and the relationship between the out-of-plane deformation angle of the front-back wall and the torsional deformation angle of the shear wall are shown in Figure
5(b). For the out-of-plane deformation angle of the front-back wall and in-plane deformation angle of the shear wall, it was confirmed that the approximate straight line was \( y = 0.38x \), and in-plane deformation of the shear wall occurred. As the results, in the case of concrete wall members, because out-of-plane fracture (limit value of deformation angle of out-of-plane bending interlayer :1.0%) and in-plane fracture (limit value of deformation angle of in-plane shear strain of RC wall:0.4%) is 1: 0.4, it is assumed that the shear wall and the front-back wall are destroyed almost at the same time. For the out-of-plane deformation angle of the front-back wall and the torsional deformation angle of the shear wall, the approximate straight line is \( y = 0.33x \), and even if the input wave’s direction is one direction, the torsional deformation was proved to be occurring, we found that it was necessary to always consider deformation in both directions (out-of-plane, in-plane) in the shear wall. In seismic performance evaluation, it is necessary to select an analysis method that can take three-dimensional deformation into consideration.

![Graph](image)

(a) Maximum deformation of planar view  

(b) Relationship of deformation angle

Figure 5. Relationship of deformation angle between front wall and shear wall

### 3. 3D-Numerical Analysis

#### 3.1 Experimental verification analysis

Detailed time history dynamic analysis by 3D FEM model was carried out to confirm the reproducibility of the experiment. The finite element analysis program "FINAL-GEO" developed by Obayashi Corporation was used. This analysis program has many verification results in the concrete material constitution model and also has a modified GHE model as a structural model of the ground. In addition, the computational speed has dramatically increased from the conventional speed by using simultaneous equation solving method suitable for large-scale high-speed operation. Geometric nonlinearity is not considered in the analysis. The calculation method of dynamic analysis applies the Newmark-\( \beta \) method.

In the analysis model, the structure is a shell element, and the ground is a hexahedral solid element. The number of elements of the structure is 1870, and the number of elements of the ground is 74500. Also, the shell element has 5 degrees of freedom, and the hexahedral solid element has 3 degrees of freedom. Repeated triaxial tests were carried out to determine the deformation characteristics of the ground material for silica sand No.7 (Dr=70%), and the fitting by the H-D model which is the skeleton curve of the modified GHE model was performed. The nonlinear relationships between stiffness (G/G₀), damping ratio (h) and strains in the upper layer of ground are modelled by the modified GHE model. Relationship between the dynamic shear coefficient and the damping constant of the ground used for the modified GHE model (G-\( \gamma \), h-\( \gamma \)) is shown in Figure 6. The history law can satisfy arbitrary G/G₀-\( \gamma \) relation, h-\( \gamma \) relation and strength characteristic (upper limit value of shear stress) by
improving the Masing rule.

Figure 6. Analysis model of soil and structure system

3.2 Confirmation of reproducibility

The time history analysis was carried out in good convergence. Overall deformation is shown in Figure 7. Relationship between displacement and horizontal force is almost the same as the above tests results as shown in Figure 8. The comparison of deformation of planar view is shown in Figure 9, as the results, the both results are almost the same. The load and the deformation of an underground box-type structure computed by the dynamic analysis are confirmed to become almost the same as the above tests results. It was confirmed that in-plane deformation and torsional deformation of the shear wall occurred.

Figure 7. Overall deformation (200Gal)  
Figure 8. Relationship between displacement and force  
Figure 9. Deformation of planar view
4. A NEW DESIGN METHOD CONSIDERING 3-DIMENSIONALITY OF STRUCTURE

4.1 A new design method considering three dimensionalities

Dynamic analysis of 3D FEM model takes a lot of time and cost, so it is difficult to evaluate all the designed ground and structure systems. Therefore, we propose a new design method considering three-dimensionality. Design flow of the new design method for an underground box-type structure is shown in Figure 10. Earthquake resistance assessment is performed by using detailed nonlinear dynamics below seat of 3D FEM model. The method for calculating the index of "critical deformation angle" applied in the design method is introduced in next section. The maximum response deformation angle of the shear wall is obtained by acting the seismic wave of coupled analysis. And finally, it is a value smaller than the critical deformation angle. It is a simple checking method to compare the critical deformation angle and the maximum response deformation angle.

![Figure 10. Design flow of an underground box-type structure](image)

4.2 Calculation method of “limit deformation angle”

For the various assumed load distributions, the critical deformation angle of the shear wall of the box type structure was calculated as shown in Table 1, by load control gradual increase analysis by the three-dimensional laminated shell model. We changed the load distribution in the depth direction to the front wall and the shear wall to parametric in the examination series of K1 ~ K6. The relationship between the horizontal load and the shear deformation angle of the shear wall is determined in this analysis. When the wall member reaches the horizontal yield strength (maximum value) in the in-plane direction and undergoes in-plane shear deformation, it becomes brittle (sharply decreasing the horizontal yield stress). The deformation angle at the time when the horizontal yield strength is reached is calculated as the critical deformation angle. It is possible to obtain the minimum critical deformation angle of the box type structure with respect to the shear wall, and it can be a threshold value of the damage index used in the seismic evaluation. The method of calculating the critical deformation angle is proposed by the following study.

Table 1 shows the results of determining the critical displacement angle of each case. The load -
displacement curves of each case are shown in Figure 11 and Figure 12. In-plane shear deformation of the shear wall preceded by the load distribution of the lower triangle (K3-3) with the load of only the peripheral shear stress, resulting in the smallest shear deformation angle (=0.462%). From this, we propose a case where circumferential shear force acts on the shear wall with a lower triangular distribution as a method for finding the minimum value of the critical deformation angle.

Table 1. Evaluation result of critical deformation angle*

<table>
<thead>
<tr>
<th>No.</th>
<th>Structure</th>
<th>Load type</th>
<th>Loading place</th>
<th>Load distribution</th>
<th>Limit deformation angle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.621</td>
</tr>
<tr>
<td>K2-1</td>
<td>Acceleration</td>
<td>All walls</td>
<td>Uniform distribution</td>
<td></td>
<td>0.853</td>
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<tr>
<td>K2-2</td>
<td>Front and back</td>
<td>Front back wall</td>
<td>Uniform distribution</td>
<td>Upper triangular distribution</td>
<td>0.644</td>
</tr>
<tr>
<td>K2-3</td>
<td>Back earth pressure</td>
<td></td>
<td>Lower triangular</td>
<td>Lower triangular distribution</td>
<td>0.650</td>
</tr>
<tr>
<td>K3-1</td>
<td>Circumferential</td>
<td>Shear wall</td>
<td>Uniform distribution</td>
<td></td>
<td>0.787</td>
</tr>
<tr>
<td>K3-2</td>
<td>Shear force</td>
<td></td>
<td>Uniform distribution</td>
<td>Upper triangular distribution</td>
<td>0.956</td>
</tr>
<tr>
<td>K3-3</td>
<td>Lower triangular</td>
<td></td>
<td>Uniform distribution</td>
<td>Lower triangular distribution</td>
<td>0.462</td>
</tr>
<tr>
<td>K4-1</td>
<td>Opening</td>
<td>All walls</td>
<td>Lower triangular 75%</td>
<td>Lower triangular 50%</td>
<td>0.625</td>
</tr>
<tr>
<td>K4-2</td>
<td>Circumferential</td>
<td>All walls</td>
<td>Lower triangular 50%</td>
<td>Lower triangular 50%</td>
<td>0.760</td>
</tr>
<tr>
<td>K5-1</td>
<td>Front and back</td>
<td>The lower half of all walls</td>
<td>Uniform distribution 75%</td>
<td>Lower triangular 50%</td>
<td>0.691</td>
</tr>
<tr>
<td>K5-2</td>
<td>Back earth pressure</td>
<td></td>
<td>Uniform distribution 25%</td>
<td>Uniform distribution 25%</td>
<td>0.565</td>
</tr>
<tr>
<td>K6</td>
<td>Response displacement method</td>
<td>All walls</td>
<td>Ground spring + Response displacement</td>
<td>Uniform distribution 50%</td>
<td>0.491</td>
</tr>
</tbody>
</table>

* Calculated by the three-dimensional laminated shell model

Figure 11. Relationship between shear deformation angle and load (K1, K2, K3)
4.3 Case study in actual structure

4.3.1 Analysis condition

3D nonlinear dynamic analysis of a box type structure only, which is a structure of real size with an opening, simulating real structures, is performed. The target structure is a two-story box-shaped structure, the outer shape is 23.9 m (side wall width perpendicular to the direction of the input horizontal seismic wave) × 32.1 m (side wall width parallel to the direction of the input horizontal seismic wave) × 29.0 m (height), as shown in Figure 13. The structure has an opening on the lower first floor of one side wall having four walls. As a coupled model, the structure and the ground were hexahedral solid elements (number of elements: 37060, number of nodes: 59740).

The structure is a foundation structure which is directly installed on the rock (CM class), and the ground constituent law is based on the rock under the structure as an elastic body. For the upper layer of soil, a modified GHE model that can account for the nonlinearity of the ground is applied.

The analysis software is a large-scale, high-speed nonlinear finite element method program "FINAL-GEO" which can greatly shorten the calculation time.
4.3.2 Analysis results

In the underground box-type structure, as the results of large-scale ground motion, front-back walls that are perpendicular to the direction of ground motion is pushed by the ground, hence earth pressure acting on the front wall centre is reduced by the deformation occurred due to the decrease in the rigidity. On the other hand, acting earth pressure on the front wall end and the shear force acting on the shear wall surface is increased, resulting in in-plane shear deformation of the shear wall, which can lead to cases where critical breakage of the entire structural system occurs.

Input seismic waves are shown in Figure14. Input range of analysis is 30.0s to be shorten analysis times. In original input wave, overall deformation and crack graph of the structure are shown in Figure15. Maximum deformation angle of shear wall occurs in 8.4s of input range to analysis. Then, the large strain of rebar and minimum principal strain of concrete occur in the lower end of front-back wall and lower of shear wall as shown in Figure16 and Figure17. In 3 times input wave, compression softening in lower of shear wall is expended as shown in Figure18.

Figure14. Input wave motions (NS-dir., UD-dir., original)

<table>
<thead>
<tr>
<th></th>
<th>Overall deformation</th>
<th>Crack graph</th>
</tr>
</thead>
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<tr>
<td>5.0s</td>
<td><img src="image" alt="Overall deformation 5.0s" /></td>
<td><img src="image" alt="Crack graph 5.0s" /></td>
</tr>
<tr>
<td>8.4s</td>
<td><img src="image" alt="Overall deformation 8.4s" /></td>
<td><img src="image" alt="Crack graph 8.4s" /></td>
</tr>
<tr>
<td>Max deformation angle</td>
<td><img src="image" alt="Overall deformation Max deformation angle" /></td>
<td><img src="image" alt="Crack graph Max deformation angle" /></td>
</tr>
<tr>
<td>15.0s</td>
<td><img src="image" alt="Overall deformation 15.0s" /></td>
<td><img src="image" alt="Crack graph 15.0s" /></td>
</tr>
</tbody>
</table>

Figure15. Analysis results (Deformation, Crack)

Section[1]  Section[2]

Figure16. Rebar strain distribution (t=8.4s)

Section[1]  Section[2]

Figure17. Minimum principal strain distribution (t=8.4s)
4.3.3 Seismic safety judgment of structure system

The evaluation is based focusing on "shear deformation angle of shear wall". In this case, a method for calculating the limit value of deformation angle, which is “limit deformation angle”, is proposed by applying the index of structural member’s deformation angle to the damage index of the shear wall of an underground box-type structure. As the results, Figure 19 shows the result of obtaining the member deformation angle of the time history from the response displacement of the three-dimensional coupled analysis. Here, the horizontal axis is the shear deformation angle of the shear wall of the whole-time history, and the vertical axis is the horizontal load applied to the lower end of the shear wall at that time. In the case of seismic wave 6 times the limit deformation angle occurred and the deformation angle exceeded. The deformation angle ($\theta_{\text{max}}=0.695\%$) at the response load peak shows a value larger than the critical deformation angle ($\theta_u=0.365\%$) which was analysed as the proposed method by using the structure model of hexahedral solid elements, which is the verification of the applicability of the critical deformation angle calculation method.

The response maximum deformation angle of the shear wall and front-back wall that was obtained by loading original, 3 times and 6 times seismic waves of coupled analysis, as shown in Table 2 and Table 3. In case of 3 times seismic waves, the breakage of the shear wall was occurred first and the deformation angle of shear wall became a larger value ($Sd/Rd = 1.03$) than “limit deformation angle”.

<table>
<thead>
<tr>
<th>Table 2. Evaluation result of shear wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input wave</td>
</tr>
<tr>
<td>Maximum deformation angle, Sd</td>
</tr>
<tr>
<td>Limit deformation angle, Rd</td>
</tr>
<tr>
<td>Examination result, Sd/Rd</td>
</tr>
<tr>
<td>Judge</td>
</tr>
</tbody>
</table>

![Figure 18. Crack graph at maximum interlaminar deformation](image)

![Figure 19. Relationship between "Out-of-plane deformation angle of member" and "Horizontal load at lower end of wall"](image)
Table 3. Evaluation result of front and back wall

<table>
<thead>
<tr>
<th>Input wave</th>
<th>Original</th>
<th>3 times</th>
<th>6 times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deformation angle, Sd</td>
<td>0.220</td>
<td>0.559</td>
<td>1.554</td>
</tr>
<tr>
<td>Limit deformation angle, Rd</td>
<td></td>
<td>0.996</td>
<td></td>
</tr>
<tr>
<td>Examination result, Sd/Rd</td>
<td>0.22</td>
<td>0.56</td>
<td>1.56</td>
</tr>
<tr>
<td>Judge</td>
<td>OK</td>
<td>OK</td>
<td>NG</td>
</tr>
</tbody>
</table>

5. CONCLUSION

(1) As the results of the centrifuge model vibration test and the detailed time history dynamic analysis by 3D FEM model, we confirmed that it was necessary to select an analysis method that can take three-dimensional deformation into consideration in seismic performance evaluation.

(2) In designing RC structure, in-plane shear failure of the shear wall is a brittle fracture that causes a sharp drop in the horizontal yield strength. Therefore, to grasp the damage mode preceding such fracture, it is necessary to evaluate by a simple method in advance. The deformation and failure modes of the entire structure can grasp easily by evaluating the inspection of the entire structure and the out-of-plane and in-plane destruction of each member with one index of only the deformation angle. It is necessary to grasp the macro response of the whole structure and it is considered that the proposed method will be useful.

(3) The proposed seismic evaluation method is a simple checking method to compare the critical deformation angle and the maximum response deformation angle. We expect it to be carried out by actual seismic performance evaluation in the future. The evaluation results and the proposed method in this paper are the result of examination by a box type structure with a simplified structure assuming horizontal stratification ground, and it is necessary to pay attention to the scope of its application.

6. REFERENCES


Japan Society of Civil Engineers (2005), Guideline and recommendation for seismic performance verification of underground reinforced concrete structures in nuclear power stations.

