SEISMIC RESPONSE OF UNDERGROUND REINFORCED CONCRETE STRUCTURE —CENTRIFUGE MODEL TEST AND ITS ANALYSIS—

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A centrifuge model test with similitude of 1/20 is carried out to clarify the inelastic response characteristics of reinforced concrete members in the culvert type of underground structure. Numerical analysis simulating the centrifuge model test is carried out to confirm the applicability of numerical procedure considering the material non-linearity. It is concluded that the reinforced concrete member in miniature is similar to the actual member in mechanical properties and yielding of reinforcing bars was found in the centrifuge model test under the applied strong motions. The present numerical procedure had the possibility of predicting the inelastic response of soil-structure interaction during strong earthquakes.

Key Words : *centrifuge model test, underground structure, seismic response, numerical analysis*

1. INTRODUCTION

On the seismic design of underground and foundation structure, the importance of seismic performance considering the non-linearity of both structure and ground during strong earthquake has been increased after the experience of the 1995 Hyogoken Nanbu Earthquake^{1), 2)}. Concerned with the numerical analysis related to the inelastic response of underground reinforced concrete structure (hereafter, RC), some of the sophisticated procedures have been employed considering the non-linearity of both RC member and ground^{3), 4)}.

These sophisticated procedures will make it possible to design the underground structure rationally on the seismic capacity design considering the material non-linearity of both structure and surrounding ground in soil-structure interaction.

The large-scale shaking table tests especially focussing on the inelastic behavior of both underground structure of RC and surrounding ground have

been conducted under 1G gravity field. The relationships of inelastic response between the RC member and the ground are gradually appreciated⁵⁾.

On the other hand, the shaking table test of the RC structure under centrifuge gravity field, which is expected more suitable than 1G gravity field in the actual and mechanical sense, has not been conducted in the past because of its complexity.

In this study, firstly, preparing technique for the miniature specimen of RC member with similitude of 1/20 is presented. The technique is employed to the centrifuge model test of the underground structure. Secondly, the characteristics of inelastic response of RC member are presented and discussed, based on the results of centrifuge model test.

Finally, numerical procedure considering directly the material non-linearity of RC member and ground is employed to simulate the results of centrifuge model test, and its applicability is verified to estimate the inelastic response of soil-structure interaction during strong earthquake.

Fig.1 Culvert type of underground structure

2. MINIATURE OF RC SPECIMEN

(1) Specification

The dimension of RC culvert type of underground structure aimed on the centrifuge model test is shown in Fig.1. The model ground is made by completely dry sand because the level of ground water is assumed to be below the RC culvert. The similitude of specimen is set to 1/20 resulting from the dimensional restriction of rigid soil container used in the centrifuge model test. The two types of dynamic response analysis have been conducted previously, the one is analysis for a ground with a free field boundary and another is analysis for a ground with a rigid boundary. These analyses have confirmed that the boundary condition of soil container less affect the seismic response of RC culvert.

The RC culvert type of underground structure is installed at the overburden of 3m, the configuration of inner space is 4m times 4m and the thickness of sidewalls is 0.5m. Based on the similitude of 1/20, the thickness of overburden is 150mm, the inner space is 200mm times 200mm and the thickness of sidewalls is 25mm. For the RC member composed of reinforcing bar and concrete, the diameter of reinforcing bar is consequently ranged from 1mm to 2mm (hereafter, D1 and D2) and the diameter of coarse aggregate is almost equal to 1mm.

The thickness of upper and lower slab is set to 45mm so as to make the behavior of slab in elastic manner through the centrifuge model test.

(2) Specimens

The RC specimen for bending test shown in Fig.2 is prepared on the basis of sidewall of underground RC structure. It is composed of the fine reinforcing bar of D1 and the concrete with 1/20-scaled-down fine and coarse aggregates employed to the centrifuge model test (hereafter, micro-concrete)⁶⁾.

The bending test of RC specimen is conducted so as to verify the structural performance compared with

Fig.2 RC specimen for bending test

Fig.3 RC specimen for centrifuge test

the actual RC member and the monotonic loading test is employed under 1G gravity field.

The culvert type of RC specimen shown in Fig.3 is prepared in the same way on the basis of full type of underground RC structure. It is employed to the centrifuge model test so as to confirm the seismic response of RC culvert in the inelastic region. The specimen is composed of three RC culverts, one is main culvert with outer length of 400mm and the others are dummy culverts of 190mm, so as to eliminate the friction between RC specimen and outer walls of rigid container.

(3) Materials

For preparing the miniature specimens of RC

Table 1 Chemical component of reinforcing bar

Component (%)	C	Si	Mn	P	S
JIS regulation (SD345)	≤0.27	≤0.55	≤1.60	≤0.04	≤0.04
Manufacture (Steel S45C)	0.43	0.24	0.720	0.017	0.007

Table 2 Configuration of reinforcing bar

Name		Width of rib b (mm)	Outer diameter D (mm)	Height of knot h (mm)	Interval of knot Ln (mm)
D1	Target	$b \leq 0.5$	$D \approx 1.2$	$0.05 \leq h \leq 0.1$	$Ln \leq 0.8$
	Manufacture	0.16	1.22	0.096	0.77
D2	Target	$b \leq 0.9$	$D \approx 2.2$	$0.1 \leq h \leq 0.2$	$Ln \leq 1.6$
	Manufacture	0.41	2.10	0.11	1.54

Table 3 Tensile test of reinforcing bar

Name	Nominal diameter ¹⁾ (mm)	Nominal section ¹⁾ (mm ²)	Tensile strength (N/mm ²)	Fracture strength (N/mm ²)	Yield strength ²⁾ (N/mm ²)	Elastic modulus (N/mm ²)	Stretching (%)
D1	1.13	1.00	401	313	284	103000	15.4
D2	2.07	3.36	499	383	360	190000	15.1

1) Obtained from the weight per unit volume and its specific gravity.

2) Averaged with three specimens obtained by offset method at yield strain of 0.2%.

Table 4 Arrangement of micro-concrete

W/C (%)	s/a (%)	Weight per unit volume (kg/m ³)				
		W	C	S	G	SP
57	42	250	439	613	838	8.78

member, the manufacturing of fine reinforcing bar of D1 and D2 and the design of arrangement with micro-concrete are previously conducted.

a) Fine reinforcing bar

The fine reinforcing bar prepared is out of application consequently compared with JIS G3112 reinforcing bar for RC. On manufacturing the fine reinforcing bar of D1 and D2, chemical components, mechanical properties and configuration are also arranged so as to keep in range of JIS regulation as possible. The chemical components of reinforcing bar is shown in **Table 1**, and the configuration, the rib parallel and the knot transverse to axial direction of bar, is shown in **Table 2**, respectively.

The result of tensile test with fine reinforcing bar of D1 and D2 is shown in **Table 3**, and the relationship between stress and strain with fine reinforcing bar of D1 is shown in **Fig.4**.

b) Micro-concrete

The fine and coarse aggregates used are rearranged in grain size based on the similitude of 1/20. As the fine aggregate, silica No.7 sand mined in Vietnam is used. As the coarse aggregate, the standard sand is rearranged and used under maximum grain size 1.2mm, which is generally employed in the compressive strength test of cement manufactured by

Fig.4 Relationship between stress and strain with reinforcing bar of D1 **Photo.1** Arrangement of reinforcing bars for main culvert type of specimen

Japanese Cement Association. With use of the above-mentioned aggregates, the regular Portland cement and AE recede mixture in high performance, the arrangement of micro-concrete is consequently determined as shown in **Table 4**. It is required so as to be mobilized the compressive strength of 24N/mm² prescribed for 28 days, elastic modulus in mechanical properties and workability in operation.

(4) Processing of reinforcing bar and micro-concrete

The hook and the bending inner diameter for the fine reinforcing bar are processed by the bender apparatus specially manufactured in order to satisfy the standard concrete regulation. In conjunction with each fine reinforcing bar, the intersection is tightened up with the fine strings. The arrangement of fine reinforcing bars for the main culvert type of specimen is shown in **Photo.1**.

On arranging and operating the micro-concrete, sufficient compaction is installed at the outer face of frame with a wooden hammer and a small size of vibrator, and at inner with a micro-vibrator.

(5) Bending test

The reinforcing bar and lateral reinforcing bar of

Fig.5 Relationship between load and displacement (HD4)

Fig. 6 Relationship between load and displacement (HD2)

specimens are composed of D1 as shown in Fig.2. The ratio of tensile reinforcing bar P_t and of shear reinforcing bar P_w are set to 0.38% and 0.22%, respectively. The bending tests are carried out for two types of specimens, the ratio of shear span H/D of 4 and 2, respectively (hereafter, HD4 and HD2 specimen, H : shear span, D : thickness).

The relationships between load represented by sum of applied loads and displacement at center of specimen are shown in Figs.5 and 6 on HD4 and HD2 specimens, respectively. The results from prediction analysis are also shown in Figs.5 and 6.

In the prediction, the laminate beam element is on the hypothesis of being kept in plane with fiber model. As a constitutive model for the RC member under monotonic condition, the Modified Ahmed model for concrete in compressive side, the Izumo model for concrete in tensile side and the Modified Menegotto-Pinto model for reinforcing bar are employed ⁷⁾. The mechanical test result of micro-concrete is shown in Table 5.

Table 5 Mechanical test of micro-concrete

Compressive strength	Elastic modulus	Tensile strength
30.2 N/mm ²	23600 N/mm ²	2.87 N/mm ²

Fig.7 Model configuration

Photo.2 Installation of RC culverts

3. CENTRIFUGE MODEL TEST

(1) Specification

The model configuration and the location of main transducers used are shown in Fig.7. On preparing of the supporting ground, silica No.6 sand is compacted up to relative density of 100% with a vibrator in each

thickness prescribed. For the surrounding ground, relative density of 84% and dry mass density of 1.46t/m³ are obtained from the air pluviation with silica No.6 sand.

Resulting from the measurement of bender element

Fig.8 Time histories
(Experiment for input acceleration of 20G)

Fig.10 Maximum strain of reinforcing bar
(Experiment for input acceleration of 20G)

Fig.9 Time histories
(Experiment for input acceleration of 25G)

Fig.11 Maximum strain of reinforcing bar
(Experiment for input acceleration of 25G)

employed under 20G centrifuge gravity field, before the centrifuge model test conducted, shear wave velocity of 200m/s is obtained at the depth of 295mm, which is the center of ground ⁸⁾.

The initial shear modulus ratio of G/G_0 is almost equal to 1.0, where G is initial shear modulus of the prototype of RC culvert obtained from the push-over analysis previously conducted, and G_0 is obtained from mass density and shear wave velocity of surrounding ground. The apparent mass density of RC culvert is $1.09t/m^3$.

The installation of RC culverts in the rigid soil container is shown in **Photo.2**. In the centrifuge model test, the sinusoidal type of input acceleration

with frequency of 60Hz, wave number of 20 and amplitude of 2G, 5G, 10G, 20G and 25G is employed. The maximum amplitude is set to 25G sufficient to obtain the inelastic behavior of RC culvert in the centrifuge model test.

(2) Results

The time histories of mean acceleration averaged with ATN and ATS of the shaking table, relative displacement of DT between the upper and the lower slab, relative displacement of ground subtracted DG4 from DG2, and the outer and the inner strains of reinforcing bar at both the ends of left sidewall are shown in **Figs.8** and **9**, respectively. These results

Fig.13 Time histories
(Prediction for input acceleration of 20G)

Fig.15 Maximum strain of reinforcing bar
(Prediction for input acceleration of 20G)

Fig.14 Time histories
(Prediction for input acceleration of 25G)

Fig.16 Maximum strain of reinforcing bar
(Prediction for input acceleration of 25G)

two-dimensional finite element method (hereafter, FEM), is conducted to simulate the response of the centrifuge model test scaled up to the configuration of prototype as shown in **Fig.12**. On numerical analysis, input acceleration of 20G and 25G is employed continuously in the form of mean acceleration averaged with ATN and ATS of the shaking table so as to recognize the evolution of yielding of reinforcing bar.

As a constitutive model for the RC member expressing the material non-linearity under cyclic condition, the one-dimensional relationship between stress and strain considering the hysteresis effect is adopted similar with the bending test previously employed⁹⁾. As a constitutive model for the ground,

the cyclic elasto-plastic relationship between stress and strain considering the hysteresis effect is adopted under plane-strain condition.

In prediction, the laminate beam element for the RC member, in which the rigid region is provided at both the end of sidewalls and slabs, is on the hypothesis of being kept in plane with fiber model. At the interface between the RC member and the surrounding ground, the joint element considering the effect of separation and sliding is employed with a constitutive model in the type of Mohr-Coulomb. The mechanical property of sliding on the joint element, so-called the frictional angle between the wall and the ground, is set to be equal to the frictional angle of ground, which is reflected the interface

characteristics of tangential and normal stresses obtained from the centrifuge model test.

The mechanical properties for the RC member and the surrounding ground adopted in the numerical analysis are shown in **Table 6**. The properties of concrete and reinforcing bar are determined from the results of mechanical test, and those of surrounding ground are approximately determined from the results of mechanical test with Toyoura sand under almost the same relative density with the centrifuge model test conducted.

(2) Results

The time histories for the input acceleration of 20G and 25G are shown in **Figs.13** and **14**, respectively. The relative displacement between the upper and the lower slab, the inner and the outer strains of reinforcing bar of sidewalls are determined at the same location with the centrifuge model test.

For the input acceleration of 20G, the relative displacement between the upper and the lower slab is gradually increased up, which is similar with the results of DT observed in the centrifuge model test shown in **Fig.8**. The strains of reinforcing bar are also non-stationary oscillated, which is not strictly coincident with the tendency of evolution observed in the centrifuge model test, so it is recognized that the maximum values are almost the same with the results of centrifuge model test.

For the input acceleration of 25G, the relative displacement between the upper and the lower slab is stationary oscillated, which is similar with the results of DT observed in the centrifuge model test shown in **Fig.9**, except for the residual displacement accompanying with drift. The strains of reinforcing bar are also stationary oscillated, unlike for the input acceleration of 20G, which is coincident with the tendency of evolution observed in the centrifuge model test. It is recognized that the maximum values are almost the same with the results observed in the centrifuge model test, except for the reinforcing bar of LWI3 severely yielded.

The maximum strains of reinforcing bar and the location of yielding generated are illustrated in **Figs.15** and **16** obtained from the input acceleration of 20G and 25G, respectively. The response plastic ratio determined from the maximum strain of reinforcing bar divided by yield strain of 2800μ is almost equal to 1.2 and these results obtained from the numerical analysis are slightly less than the results of centrifuge model test.

For more precise prediction, re-estimating the mechanical properties of RC member and ground is expected so as to confirm the applicability of numerical procedure compared with the results of centrifuge model test conducted.

5. CONCLUSIONS

A centrifuge model test concerned with the culvert type of underground structure composed of actual reinforced concrete member is conducted under the similitude of 1/20, and the subsequent numerical analysis based on FEM considering the material non-linearity of both the reinforced concrete and the ground is carried out. The main conclusions obtained from this study are as follows.

(1) The reinforced concrete member in miniature is almost similar to the actual member in mechanical properties and yielding of reinforcing bars was found in the centrifuge model test under the applied strong motions.

(2) The present numerical procedure considering the material non-linearity of both the reinforced concrete structure and the surrounding ground had the possibility of predicting the inelastic response of soil-structure interaction during strong earthquakes.

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