

INVESTIGATION AND SHAKING TABLE TESTS OF SUBWAY STRUCTURES OF THE HYOGOKEN-NANBU EARTHQUAKE

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SUMMARY

A detailed reconnaissance survey was conducted at the underground structures such as subways, mountain tunnels, multipurpose underground ducts and other underground structures, etc. around the Hanshin District caused by the 1995 Hyogoken-Nanbu Earthquake. Among them, the Daikai subway station is the first subway structure that completely collapsed due to the earthquake. The damage mechanism of the subway structure, especially at the center column, and the dynamic soil-structure interaction and the dynamic forces acting on the structure were clarified through the scaled model shaking table tests and the simulation analyses. From this study, it was verified that the subway structure collapsed due to lack of the load carrying capacity against shear at the center column.

INTRODUCTION

The Hyogoken-nanbu earthquake of January 17, 1995 caused severe damages to underground structures, such as subway structures and tunnels in Kobe. Among them, a damage to subway structure that completely collapsed due to the earthquake, was one of the astonishing event, because of the fact that underground structures have been considered to be relatively safe from earthquake effect compared to structures constructed on the ground. The author, who belongs to the underground structural engineering group of the Committee of Earthquake Engineering under Japan Society of Civil Engineering (1996), implemented a reconnaissance survey on the damages to the subway structures, and the experimental study on the dynamic behavior and the damage mechanism of the structure, especially at the center column through the shaking table tests and the simulation analyses.

OUTLINE OF DAMAGES OF SUBWAY STRUCTURES

The most serious damage brought to underground structures in Kobe was the damage to those of subway structures, most part of which was constructed by means of cut-and-cover techniques. Six underground stations out of the total 21 subway stations in the Kobe area were severely damaged by the earthquake: the Daikai and Kosoku-Nagata Stations of the Kobe Rapid Transit Line, the Sannomiya, Kamisawa and Shin-Nagata Stations of the Kobe Municipal Subway, and the Nishidai Station of the Sanyo Electric Railway. Also, some sections of running tunnels connecting with the damaged stations and the tunnel section of the Hanshin Railway sustained damages. The Daiichi Station was the most seriously damaged. Figure 1-a shows schematic diagrams of the damages in the longitudinal direction and Figure 1-b shows schematic figure of the damage pattern in the transverse direction. In the station, more than half of the center columns completely collapsed, and the ceiling slab supported by them bent and fell down. Typical damages to the center columns are shown in Photo 1. This

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resulted in subsidence at the surface street with a maximum depth of 2.5 m. At the other stations, as well as the running tunnel, a large number of central reinforced concrete columns cracked. Major factors to have led the cut-and-cover box structures to failure are inferred to be large shear distortion of the box structures induced by shear strains in the surrounding ground during the earthquake, and lack of shear-ductility of the center columns.

SCALED MODEL SHAKING TABLE TESTS OF THE SUBWAY STRUCTURE

The model ground and the model subway structure

The scaled model shaking table tests have been performed to clarify the dynamic behavior and the dynamic forces acted on the structure and the damage mechanism of the subway structure, especially at the center column due to strong earthquake motions.

A new type of soil container has been developed to reproduce the ideal horizontal shear motion in the model ground as shown in Photo 2. The model ground made of fine dry sand (Gifu-Sand) of 1.0m in depth consists of two layers, namely the subsurface layer with 0.4m in depth, and the bearing stratum. 1/30 scaled subway structure model of Daikai Station is set on the bearing stratum. The subway structure model has a box type frame structure with center columns made of polyvinyl chloride resin, with dimensions of 60 cm in length, 60 cm in width, and 24 cm in height. The thickness of the overburden soil is 16 cm, and the joints between the center column and the ceiling and base plates were modeled two types (Type-1 and Type2). Type-1 is a fix-type: , the center column fix on ceiling and base slabs and Type-2 is a hinge-type: the center column hinges on ceiling and base slabs.

Shaking table tests

The measuring points of the shaking table tests are shown in Figure 2. In these tests, the acceleration responses of the structure and the surrounding ground, shear earth pressure acting on the ceiling walls, horizontal earth pressure acting on the side-walls, and the dynamic strains of the center columns and side-walls were measured.

The shaking table tests have been performed as follows. Table 1 shows the items of the tests.

Seismic exploration tests and free vibration tests

The seismic exploration and the damped free oscillations of the model ground estimated the dynamic material properties of the model ground in its lowest natural frequency.

White-noise tests and sine sweep tests

The white-noise vibration tests were performed. In this case, seven different accelerations ranging from 10 gal, 20 gal, 50 gal, 100 gal, 200 gal, 400 gal, to 800 gal were selected as horizontal input motions. The sinusoidal vibrations with constant base acceleration and alternating frequency were from 5 Hz to 30 Hz. Also, five different accelerations ranging from 20 gal, 50 gal, 100 gal, 200 gal, to 400 gal were selected as horizontal input motions. From these tests, the resonant curves and acceleration responses of the underground structure model and the surrounding ground were evaluated.

Random Vibration Tests

The random vibration tests were conducted wherein the recorded horizontal accelerations at the station of Kobe Meteorological Agency during the Hyogoken Nanbu Earthquake (Ko-motion) were used as input motion. In these tests, the duration time of the data ranged to five shorting processes (1/30, 1/20, 1/10, 1/5 and 1/1) considering the scaling law, and the maximum acceleration amplitude was changed in two cases, ranging 1/2 (50%) and 1/1 (100%). From these tests, the dynamic responses of the structure and the surrounding ground were also evaluated.

SIMULATION ANALYSES OF SHAKING TABLE TEST

Simulation analyses of the shaking table tests are conducted through the two-step analyses as follows:

Simulation analyses of the ground

As first step in order to examine the dynamic response of the model ground during an earthquake, onedimensional seismic response analysis was conducted by the program SHAKE considering non-linearity of soil properties by the equivalent linear method. In this analysis, the acceleration response of the ground subjected to horizontal sweep sinusoidal motions and random motions were evaluated.

Simulation Analysis of the Subway Structure

As second step in order to examine the dynamic response of the subway structure, two-dimensional seismic response analysis was conducted by TDAP (Time-domain Dynamic Analysis Program).

In this analysis, the ground is modeled into two-dimensional finite element (Figure 3) and the soil properties of the ground were the converged values obtained from the first step simulation, and the structure is modeled into an elastic beam. The acceleration response of the structure and the dynamic forces (shear earthpressure and lateral earthpressure) acting on the structure and the strain induced in the structure were evaluated.

RESULTS

Dynamic material properties of the model ground

- (1) The shear wave velocity (Vs) of the model ground determined by seismic exploration was 90m/sec 100m/sec.
- (2) The strain-dependency of soil properties of Gifu-sand was estimated from the tests. The obtained shear modulus (G) vs. shear strain (γ) curve, and damping (h) vs. (γ) curve for strain ranged more than 10^{-6} that agreed well with theoretical ones proposed by Kokusho-Iwatate (1979) are shown in Figure 4.
- (3) The resonant curves of model ground with base accelerations of 20 gal and 400 gal, are shown in Figures 5a, and 5-b, are experimental results, and Figures 5-c and 5-d are calculated ones, respectively.

(4) The acceleration responses of the ground subjected to sinusoidal motions with base accelerations of 20 gal and 400gal, and Ko-motion with 1/10 time shorting process and maximum amplitude 100% in shown in Figure 6. In this figure, the solid lines are test results and the dotted lines are calculated ones.

The decrease in amplification and the resonant frequency of the ground with increase of base acceleration are shown in these figures. The model ground exhibits strong nonlinear properties from low strain level.

Dynamic responses of the subway structure

- (1) Figure 7 shows the acceleration responses of the structure and the surrounding ground subjected to Komotion with 1/10 time shorting processes and the maximum amplitude 50% (Case-A) and 100% (Case-B). Comparing the dynamic motions of the structure and the ground, in Case-A, the difference in acceleration amplitude and phase lag between the structure and the ground were observed slightly and the amplitude and vibration mode coincide well with each other. The structure moves in shearing mode predominantly. On the other hand, in Case-B, the difference in amplitude and phase lag between the two was observed more remarkably. The structure model moves predominantly not only in shearing mode but also in rocking mode.
- (2) Figure 8 shows the maximum dynamic lateral earth pressure, dynamic shear earth pressure, and bending strain distributions of the subway structure at the resonant frequency subjected to the sinusoidal motions with base accelerations 20 gal and 400 gal, and Ko-motion (100%), respectively. In this figure the solid lines are test results and the dotted lines are the calculated ones. Both results agree well with each other.
- (3) The distribution of the lateral earthpressure acting on the side-walls have different effects on the shear deformation of the structure. In the case of weak motion (20 gal), the lateral earth pressure acted to resist the shear deformation of the structure, but in the case of strong motion (400 gal, Ko-100%), it did not resist the shear deformation of the structure.
- (4) Figure 9 shows the distributions of maximum dynamic shear earth- pressures acted on the ceiling slab at the

resonant frequency subjected to the sinusoidal motions with base accelerations 20 gal, 100 gal and 400gal. In this figure the solid lines are test results and the dotted lines are the calculated ones. Both results agree well with each other. The distribution of the shear earthpressure varies with the intensity of input motion. In the case of low-level input motions (20 gal to 100gal), the distribution shape is almost uniform, but in the case of strong input motion (400 gal), the distribution shape is a concavity, the center is smaller than the both edges. From these results, a slide and an exfoliation phenomenon occurs in the case of 400 gal.

- (5) Figure 10 shows the relation between input acceleration and the shear earthpressure acting on the ceiling slab evaluated by the simulation analyses. In this figure, the solid line is the shear pressure acting on the center of the slab and the dotted line is that acting on the edge of the slab. From this figure, a slide phenomenon occurs at the center of the slab over 100 gal.
- (6) Table 2 shows the maximum bending strains induced in the center column and the side-wall compared with Case -1 (fixed-type) and Case-2 (hinged-type). The strain at the center column was about five times larger than that of the side-wall in the case-1. In case-2, the strain of center column is about 1/5 ∼ 1/7 times smaller than that in Case-1. From these results, hinged-type joint is useful to reduce the damage of center column.
- (7) Figure 11(a) and 11(b) show the calculated time histories of the dynamic earthpressures (lateral earthpressure and shear earthpressure) acting on the joint element of the ceiling slab and the side-wall subjected to sinusoidal input motion of 20 gal and 400 gal respectively. From these figures, a slide and an exfoliation phenomenon occurs at 400 gal.

CONCLUSION

The main results of this study are as follows:

1. The subway structure was subjected to strong horizontal forces (shear earth pressure and lateral earth pressure) acting on the structure from the surrounding ground, which caused the shear deformation of the structure. A slide phenomenon occurs around the structure due to the seismic motion over 100 gal.

2. The strain of the center column was five times larger than that of side-walls. The hinged-type joint is useful to deduce the damage of center column.

3. The center column collapsed due to lack of the load carrying capacity against shear resulting to failure of the ceiling slab.

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Table 1 Items of shaking table to	ests
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Test Items	Test Contents					
(a)Seismic Exploration	Vs of model ground					
(b)Free Vibration Test	Damping constant of model ground					
(c)White Noise Tests	Input Acc 10gal.20gal.50gal.100gal.200gal.400gal.800gal					
(d)Sine Sweep Tests	Sweep Range 5Hz.30Hz					
	Input Acc 20gal.50gal.100gal.200gal.400gal					
(e)Random Vibration Tests	Time Scale 1/1.1/5.1/10.1/20.1/30					
Ko-Motion	Input Acc 818gal (100%).409gal(50%)					



Figure 1-a Schematic figure indicating damage of the ceiling slab and the center column



Column 10

Figure 1-b Schematic figure showing the damage patterns in the transverse direction



Photo 1 Collapse of center column of the Daikai station



Photo 2 Soil container of shaking table tests



(b)Subway structure model

Figure 2 Measuring points of the shaking table tests



Figure 3 2-dimensional FEM model



(a) Test results(Base Acc 20gal)



(c) Calculated results (Base Acc 20gal)







Figure 4 The strain-dependency of soil properties Gihu-sand



(b) Test results (Base Acc 400gal)



(d) Calculated results (Base Acc 400gal)



Accelerationigalj Figure 7 Maximum acceleration responses of model ground and the structure subjected to Ko-motion with maximum input acceleration 100% and 50% and shorting process

input Acc Sinuscinal input Acc Random input Motion 0 jal 400gal Ko-Motion 100 " Ko-motion (I'=

Figure 5 The resonance curves of model ground (Sine sweep tests)

<Ceiling Slab>



Figure 8 The dynamic lateral and shear earth pressure acted on the structure and bending strains of induced in the structure subjected to sinusoidal motion and Ko-motion



earth pressure acted on the ceiling slab subjected to sinusoidal motion



Figure 10 Relation between shear earthpres- sure acted on the ceiling slab and input acceleration

Table 2	Maximum bending strain of the stru-
ctı	re subjected to sinusoidal motion
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Input Motion	Joint	Center Co	olumn()	Side-Wall()			
		Calculation	Test	Calculation	Test		
Sinusoid	Fix	52	204	16	39		
20gal	Hinge	9	39	16	36		
Sinusoid	Fix	452	952	137	177		
400gal	Hinge	76	122	141	168		
Ko-Motion	Fix	606	963	179	194		
100%	Hinge	103	141	189	179		



(a) 20gal



Figure 11 Calculated time histories of the dynamic earthpressure acted on the joint element of the ceiling slab and side-wall subjected to sinusoidal input motion