Shaking table test and numerical simulation of seismic response of subway structures

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Abstract

In order to clarify the dynamic behaviors and damage mechanism of subway structures due to the 1995 Hyogoken-nanbu earthquake, scaled model shaking tests and its simulation analyses were performed. The dynamic responses, dynamic forces (shear earth pressures, lateral earth pressures) acting on the structure and bending strains induced in the center columns were verified due to horizontal and vertical input motions, individually and simultaneously. In case of horizontal input motions, dynamic horizontal forces acting on the structure, and bending strains induced in the center columns were very larger than those in case of vertical input motions. The dynamic responses of the structure and dynamic earth pressures due to simultaneous horizontal and vertical input motions were approximately equal to those by horizontal input motions. The experimental results were verified by simulation analyses using SHAKE (one-dimensional analysis) and TDAP (two-dimensional analysis) programs. From these results, the subway structure collapsed due to strong dynamic horizontal forces mainly acting on the structure.

1 Introduction

On January 17, 1995, the Hyogoken-nanbu earthquake in Kobe, Japan, caused serious damage to underground structures that had previously been considered to be strong to earthquake effects. The most significant damage was caused to subway structures, most of which had been constructed using the cut-and-cover technique. More than half of the center columns at the Daikai station completely collapsed and ceiling slabs failed. Shaking table tests were performed on a 1/30-scaled model of Daikai Station (Photo 2) in Tokyo Metropolitan University...
in August 1995 and verified the dynamic behaviors of subway structure due to horizontal motions between 1995 and 1999 [1,2]. Generally, the vertical seismic forces are considered as smaller than horizontal ones, usually as half of horizontal forces in the existing seismic design standard in Japan [4]. In addition, few studies on vertical earthquake motions have been presented, so after Hyogoken-nanbu earthquake it is important to clarify the dynamic behaviors of the underground structures and the earth pressures acting on structures due to vertical motions. In this paper, in order to determine why the subways in Kobe collapsed, horizontal, vertical, simultaneous horizontal and vertical movements with sinusoidal and random input motions are investigated, by both scaled model shaking table tests and its simulation analyses.

2 Scaled model shaking table tests of the subway structure

2.1 Ground and subway models

A new soil container has developed to reproduce ideal horizontal shear motions in the ground, as shown in Photo 1[3]. The model ground was constructed from fine dry sand (Gifu-Sand) in two layers, a 0.4 m thick subsurface layer and a 0.6 m thick bearing stratum. A 1/30-scaled model of the subway structure was placed on the bearing stratum. The subway model was a box type frame structure with seven center columns (three columns were fitted with a flexible joint, and the remainder with rigid joints) of dimensions 60 mm × 60 mm × 240 mm constructed from polyvinyl chloride resin. The thickness of the overburden soil was 16 cm (Photo 2). A 5 mm thick rubber board was placed between the column and slab to represent the flexible joint [2].

![Photo 1 Soil container of shaking table tests](image1)
![Photo 2 Subway structure model of Daikai station](image2)
2.2 Experimental items

The shaking table tests were performed as follows.

(1) Seismic Exploration Tests and Free Vibration Tests

The dynamic material properties of the model ground were estimated.

(2) White-noise Tests

Seven different accelerations ranging from 10gal, 20gal, 50gal, 100gal, 200gal, 400gal, and 800gal were selected as the horizontal input motions. From these tests, the shear wave velocity (Vs m/s) and the strain-dependency of the soil properties of the ground were evaluated (Figure 4).

(3) Sine Sweep Tests

In case of horizontal input motions, the sinusoidal vibrations with a constant base acceleration and alternating frequency were from 5 Hz to 30 Hz. Five different accelerations of 20gal, 50gal, 100gal, 200gal, and 400gal were selected.

In case of vertical input motions, the sinusoidal vibrations with a constant base acceleration and alternating frequency were from 20 Hz to 50 Hz. Also, five different accelerations of 10gal, 25gal, 50gal, 100gal, and 200gal were selected, which are a half of the horizontal accelerations [4].

In case of simultaneous horizontal and vertical input motions, the alternating frequency was from 3Hz to 50Hz. The amplitude of input motions were selected 5 sets (20gal, 50gal, 100gal, 200gal, and 400gal for horizontal components, 10gal, 25gal, 50gal, 100gal, and 200gal for vertical ones). In addition, the phase difference between horizontal motions and vertical ones was varied 0° and 90°.

(4) Random Vibration Tests

Random vibration tests were conducted, wherein the recorded accelerations at Kobe meteorological agency station, during Hyogoken-nanbu earthquake were used as the input motion (Figure 1). In case of horizontal input motions, duration time ranged between five shorting processes (1/1, 1/5, 1/10, 1/20, 1/30) considering the scaling law and maximum acceleration was changed in two cases of 1/2(50%), and 1/1(100%). In case of vertical input motions, duration time ranged 1/1 and maximum acceleration was changed in two cases of 1/2(50%), and 1/1(100%). In case of simultaneous horizontal and vertical input motions, duration time ranged 1/1 and maximum acceleration was changed in two cases of 1/2(50%), and 1/1(100%).

![Figure 1 Kobe marine meteorological observatory record of Hyogoken-nanbu earthquake](image-url)
From tests (3) and (4), the acceleration responses of the structure model and the ground, the dynamic earth pressures acting on the structure (ceiling slab and sidewalls), and the bending strains induced on the center columns and the side-walls were also evaluated. From sine sweep tests, the resonant curves were evaluated.

3 Numerical simulations

3.1 Numerical Method

A schematic of the numerical simulation is shown in Figure 2. The first step is the analysis of the ground's response only, and the second step is the analysis of the combined response of the subway structure and ground.

![Figure 2 Analysis Flow](image)

3.2 Numerical procedure

(1) Earthquake ground response analysis (Step one)
The dynamic responses of the model ground during an earthquake was estimated using the SHAKE program (one-dimensional seismic response analysis using with multiple-reflection theory) (Figure 3), considering the non-linearity of soil properties as equivalent linear properties from G-γ, h-γ curves generated from experimental results (Figure 4) [2,5]. The converged values (shear modulus and damping constants) of the ground were calculated.
(2) Simulation analysis (Step two)
The two-dimensional dynamic response of the subway structure was analyzed using TDAPIII (time domain dynamic analysis program). The ground was modeled using two-dimensional finite elements and the converged values of the soil properties using the results of step one. The structure was modeled as a set of elastic beam elements (Figure 5). The dynamic behaviors of the structure, dynamic forces (shear earth and lateral earth pressures) acting on the structure and bending strains induced in the side-walls and center columns were evaluated, and the results compared with experimental values.

Figure 3 One-dimensional analysis model of the ground

Figure 4 Strain-dependency curves

Figure 5 Two-dimensional analysis model of the subway structure
4 Results

4.1 Dynamic Behaviors of the Ground Model

The simulated resonance curves of the model ground were agreed well with experimental ones. So, the dynamic properties of analytical model (initial shear modulus and damping constants, and $G-\gamma$, $h-\gamma$ relations) were reasonable. The response characteristics of the ground model were determined from the resonant curves (Figures 6,7). The main results are as follows.

(1) In case of horizontal motions, the resonant frequency of the model ground was 20 Hz for weak motion (20 gal) and 8 Hz for large motions (400 gal). The model ground exhibited strong nonlinear properties from low levels of strain.

(2) In case of vertical motions, the resonant frequency of the model ground was 47 Hz for weak motion (10 gal) and 41 Hz for large motion (200 gal). The amplification and resonant frequency did not decrease notably with increasing base acceleration. The model ground did not exhibit strong nonlinear properties.
(c) In case of simultaneous horizontal and vertical motions

Figure 6 Resonant curves of the model ground

(3) In case of simultaneous horizontal and vertical input motions, two resonance points were observed in both cases of phase lag (\( \alpha = 0^\circ & 90^\circ \)). The low resonant point corresponds to the predominant frequency of horizontal motions and the high resonant point corresponds to the predominant frequency of vertical motions. There were no significant differences about dynamic responses between simultaneous and individual input motions. No clear interaction behaviors were identified.

(a) Horizontal motion  
(b) Vertical motion

Figure 7 Relationship between acceleration and the maximum amplitude of the input motions

4.2 Dynamic Behaviors of the Subway structure

(1) Behaviors of the subway structure

The subway structure was deformed significantly in shear and rocking modes and large strains induced in the center columns at the resonant frequency due to horizontal input motions. These vibration modes can also observed at the same resonant frequencies due to simultaneous horizontal and vertical motions. But, shear and rocking modes did not occurred, and no shear deformation of structure induced at the resonant frequency due to vertical input motions (Figure 8).
(2) Dynamic earth pressures acting on the structure (Figure 9)

a) Dynamic shear earth pressures acting on the ceiling slab

In case of horizontal motions, the dynamic shear earth pressures increased with input level. The distribution of shear earth pressures varied with the input motions. In case of a weak input motion (20 gal & 100 gal), the distribution shape was approximately uniform, but in case of a strong motion (400 gal & Ko-motion), the distribution was not uniform. From test data, a slide and exfoliation phenomena occurred at center of slab when the input motion was greater than 100 gal [5]. But in case of vertical input motions, the dynamic shear was negligible. In case of simultaneous horizontal and vertical motions, the dynamic shear earth pressures tended to increase with input level at the horizontal resonant frequency for both phase lags. The distribution shape showed maximum values at the edges. Comparing the results of the two cases, the phase lag did not influence.

b) Lateral dynamic earth pressure acting on sidewalls

The lateral earth pressure increased with input level, and the distributions shape were out of phase because of rocking vibration of the structure were occurred in case of horizontal input motions. In case of vertical motions, the lateral earth pressure was negligible. In case of simultaneous horizontal and vertical input motions, the lateral earth pressures were almost the same as those in case of horizontal input motions at the horizontal resonant frequency.

(3) Bending strain induced in center columns and sidewalls

In case of horizontal input motions, bending strain in the center column was approximately five times larger than that in the sidewalls when a rigid connection was used. However, when a flexible joint was used, the strain was 1/6 ~ 1/10 of that for the rigid connection. In case of vertical input motions, the bending strains induced in the center column and sidewalls were negligible. The axial strains induced in the center columns were 1/5 of the bending strains by horizontal input motions. In case of simultaneous horizontal and vertical input motions, the results were as for the horizontal input motions (Figure 10).

5 Conclusions

From the scaled model shaking tests and simulation analyses, the dynamic behaviors of the subway structure and the dynamic earth pressures acted on the structure were clarified as follows.

(1) The results of the numerical simulations agree well with experimental ones.
(a) In case of horizontal motions

(b) In case of vertical motions

(c) In case of simultaneous horizontal and vertical motions

Figure 9 Dynamic earth pressures on the structure
(2) The earth pressures acting on the structure and the bending strain induced in the center columns by vertical input motions, were negligible in comparison with those induced by the horizontal input motions.

(3) The bending strain in the center column due to horizontal input motions was five times larger than which at the sidewalls, and the bending strain of center column with flexible-type joint, was about 1/5 smaller than that with fixed-type joints. The flexible-type joint between center column and ceiling slave would have reduced the level of damage to the center column.

(4) In case of simultaneous horizontal and vertical input motions, dynamic responses and dynamic earth pressures (shear forces, lateral forces) at resonant frequency approximate those of the horizontal motions. Therefore, it is concluded that vertical earthquake motion did not have a significant effect on the structure and the subway structure collapsed due to strong dynamic horizontal forces and insufficient shear capacity of the center columns.

References


