Journal of Zhejiang University SCIENCE A
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Study on dynamic response of embedded long span corrugated steel culverts using scaled model shaking table tests and numerical analyses

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Received May 10, 2005; revision accepted Nov. 21, 2005

Abstract: A series of scaled-model shaking table tests and its simulation analyses using dynamic finite element method were performed to clarify the dynamic behaviors and the seismic stability of embedded corrugated steel culverts due to strong earthquakes like the 1995 Hyogoken-nanbu earthquake. The dynamic strains of the embedded culvert models and the seismic soil pressure acting on the models due to sinusoidal and random strong motions were investigated. This study verified that the corrugated culvert model was subjected to dynamic horizontal forces (lateral seismic soil pressure) from the surrounding ground, which caused the large bending strains on the structure; and that the structures do not exceed the allowable plastic deformation and do not collapse completely during strong earthquake like Hyogoken-nanbu earthquake. The results obtained are useful for design and construction of embedded long span corrugated steel culverts in seismic regions.

Key words: Embedded corrugated steel culverts, Shaking table tests, Hyogoken-nanbu earthquake, Dynamic analyses
doi:10.1631/jzus.2006.A0430 **Document code:** A **CLC number:** TU93

INTRODUCTION

On Jan. 17, 1995, the Hyogoken-nanbu earthquake in Kobe, Japan, caused great destructive and damage to underground structures, such as subway structures, mountain tunnels, multipurpose underground ducts and other underground structures, which had previously been considered to be resistant to earthquake effects (JSCE, 1996; ECRHAED, 1998). This earthquake revealed that a number of critical issues should be added in the seismic design and seismic strengthening of underground structures, such as strong seismic motion like that of the Hyogoken-nanbu earthquake has to be considered in the design of underground structure (Iida *et al*., 1996; Matuda *et al*., 1996). It is well known that long span corrugated steel culverts (Fig.1) are widely used in multipurpose underground ducts, when risk of substantial property damage and loss of life is low. But there were few researches on the seismic response of corrugated steel culverts. In order to practically use corrugated culverts for road tunnel, the dynamic behaviors and damage mechanism of corrugated steel culverts due to strong earthquake motions like those of the Hyogoken-nanbu earthquake have to be clarified. A series of shaking table tests and dynamic finite element analyses were conducted to obtain some helpful results to serve as valuable references for seismic design of long span corrugated steel culvert.

This paper describes the results of the scaled model shaking table tests and simulation analyses due to sinusoidal and random strong motions.

SCALED MODEL SHAKING TABLE TESTS OF EMBEDDED CORRUGATED CULVERT MODELS

Shaking table tests were performed to clarify the dynamic behavior and destructive mechanisms of the embedded corrugated culvert models during strong seismic motions.

Fig.1 Corrugated steel culvert

A new soil container was developed to reproduce ideal horizontal shear motion in the ground, which settled 16 sheets of lightweight steel rectangular shear frame bearings on its side walls for free transformations, as shown in Fig.2. The model ground was constructed from fine dry sand (Gifu-Sand, D_{60}=0.35 mm, D_{30}=0.31 mm, D_{10}=0.22 mm) in two layers, a 0.8 m thick subsurface layer (ρ=1.33×10^4 N/m^3) and a 0.2 m thick bearing stratum (ρ=1.57×10^4 N/m^3). Two different types of 1/16-scaled models of the corrugated culvert (model-1 and model-2) were placed on the bearing stratum. Model-1 has two thrust beams on the shoulder, which restrain the deformation of cross section of structure during embedment and model-2 has no thrust beam.

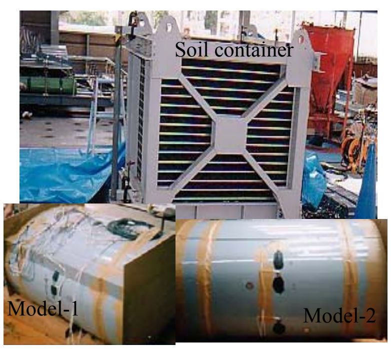


Fig.2 Soil container of shaking table test

The model was an elliptic shell structure of dimensions about 457 mm (short radius)×650 mm (long radius)×800 mm (width) and 2 mm thickness, made from vinyl chloride resin (ρ=1.44×10^4 N/m^3, Young's modulus G=2.94×10^9 N/m^2).

Measurement points

The measurement points of the tests are shown in Fig.3. Five accelerometers were set in the ground and seven were set on the structure to measure the acceleration response of the ground and structure. Eight seismic soil pressure gages and four shear seismic soil pressure gages were set on the structure along the circumferential direction to measure the dynamic seismic soil pressures acting on the structure. Sixteen strain gages were set on the inner and outer part of the structure to measure bending and normal strains independently. And four displacement gages were set on the outside of the soil container to measure the horizontal displacement of the ground.

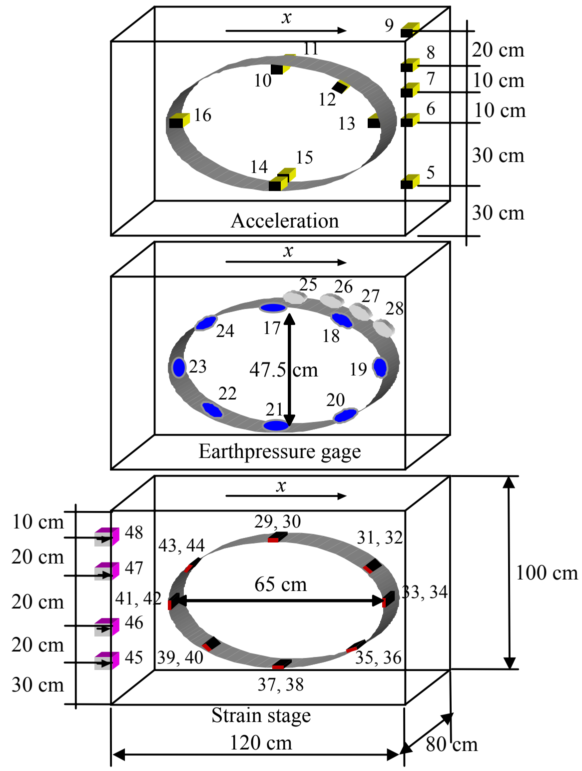


Fig.3 Measurement points

Results of the shaking table test

(1) The dynamic material properties of the model ground at its lowest natural frequency were estimated by pulse impact tests, free vibration tests, white-noise tests, and sine sweep tests.

The shear velocity of the model ground was measured by the test of shear velocity, which was 70 m/s on the ground and 100 m/s in the bearing stratum. The densities of the model ground were obtained as 1.33×10^4 N/m^3 before shaking, and 1.54×10^4 N/m^3 after shaking of the subsurface layer, and that of the bearing stratum was 1.57×10^4 N/m^3.

The nonlinear properties of the model ground were evaluated by strain-dependency curves (shear modulus (G)-shear strain (γ) and damping (h)-(γ) relations) (Fig.4). The results of shaking table tests showed well agreement with the approximate curves of the Modified Hardin-Drnevich model (Kokusyo and Iwatate, 1979). And the model ground exhibited strong nonlinear properties from low levels of strain. In Fig.4, G/G_0 is shear modulus ratio, $G/G_0=(1+\gamma/\gamma_t)^{-1}$; h is damping ratio, $h=\frac{4}{\pi}\left[\frac{G}{G_0}\left\{\frac{\gamma_t}{\gamma}-\left(\frac{\gamma_t}{\gamma}\right)^2\right\}\ln\left(1+\frac{\gamma_t}{\gamma}\right)-\frac{1}{2}\right]+0.02$; γ is criterion strain ($=3.5\times10^{-4}$); G_0 is initial shear modulus.

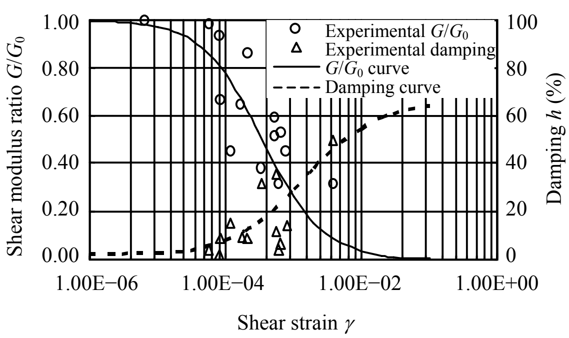


Fig.4 Strain-dependency curves (G/G_0-γ and h-γ relations) of model ground

The seismic soil pressures acting on the structure and the strains of the structure were evaluated by the sin-sweep tests and random vibration tests using the recorded horizontal accelerations at the station of Kobe Meteorological Agency during the Hyogoken-nanbu earthquake (maximum acceleration=818 gal, the duration time of data was 1/15 that of shorting processes, according to the scaling law) (Iwatate *et al.*, 2000).

Static soil pressures and static strains of the model (measured before and after excitations) caused by overburdened soil were evaluated (Figs.5 and 6).

Fig.7 shows the distributions of lateral seismic soil pressure acting on model-1 and model-2 at resonant frequency with base acceleration of 200 gal. Comparing these results with static ones, the maximum values were almost equal. But the distribution modes were different from each other remarkably, the modes were non-symmetric. The maximum values

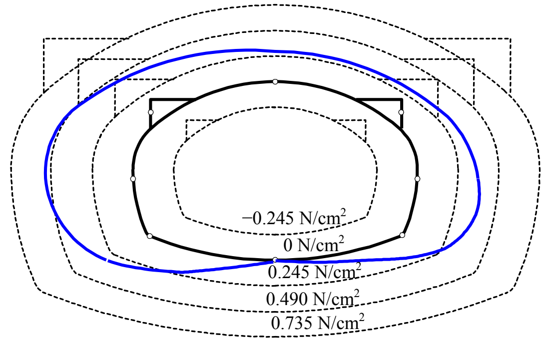


Fig.5 Static soil pressures acting on model-1

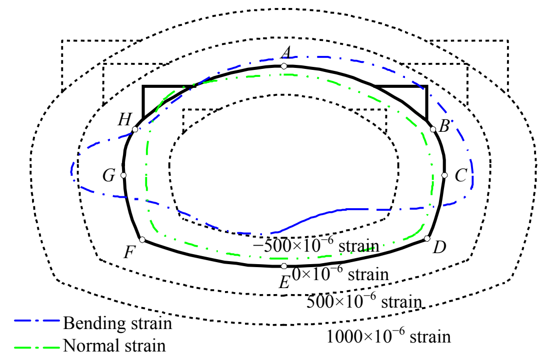


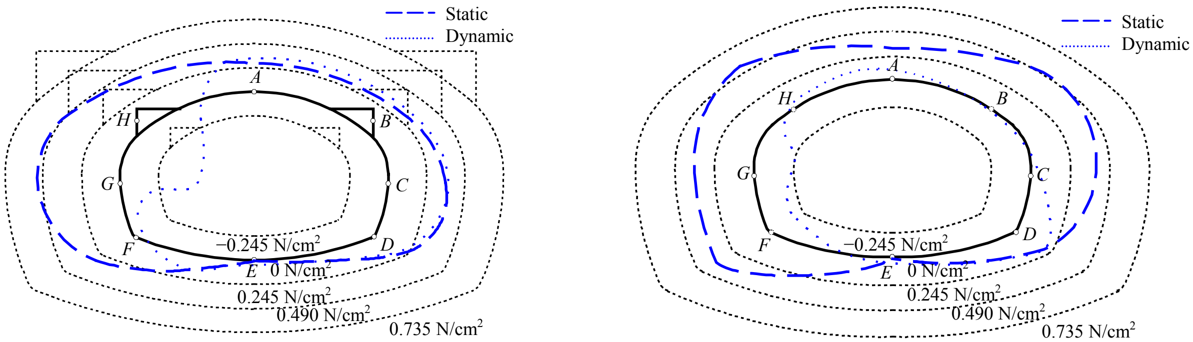
Fig.6 Static strain of model-1 (Bending strain and normal strain)

occurred at both sides (point G is compression and point C is tension), and those at the top (point A) and bottom (point E) were small.

Fig.8 shows the distributions of dynamic bending strains of model-1 and model-2 at resonant frequency (6 Hz) subjected to sinusoidal input motion with 200 gal. In both models, the bending strains were concentrated at both sides (points B, C, D and F, G, H), the top (point A) and the bottom (point E) were negligibly small, but maximum values did not exceed allowable strain. Moreover, the bending strains were about 5 times those of normal strains.

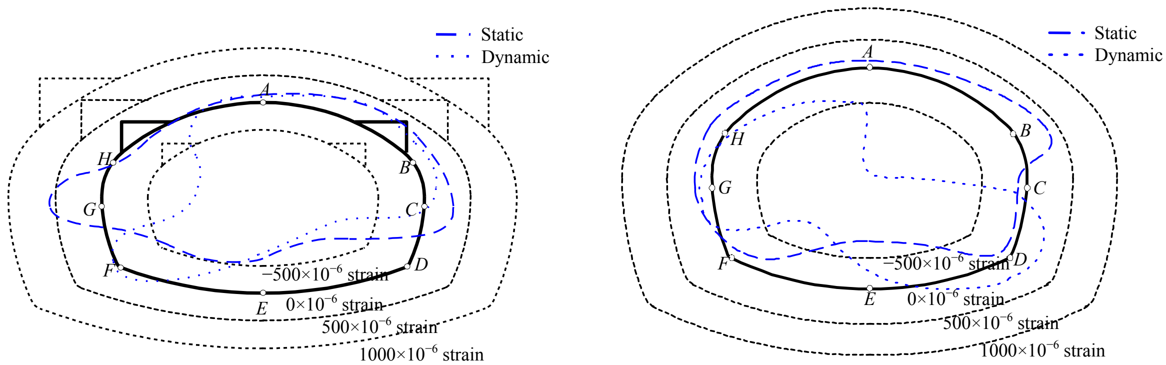
Figs.9a and 9b show the distribution of maximum lateral seismic soil pressure acting on the model-1 and dynamic bending strain of the model-1 subjected to Kobe-motion, respectively. The maximum seismic soil pressure and bending strain were almost equal to static ones.

From this result, the culvert model did not exceed the allowable plastic deformation and did not collapse when subjected to strong earthquake motions, like those of the Hyogoken-nanbu earthquake.



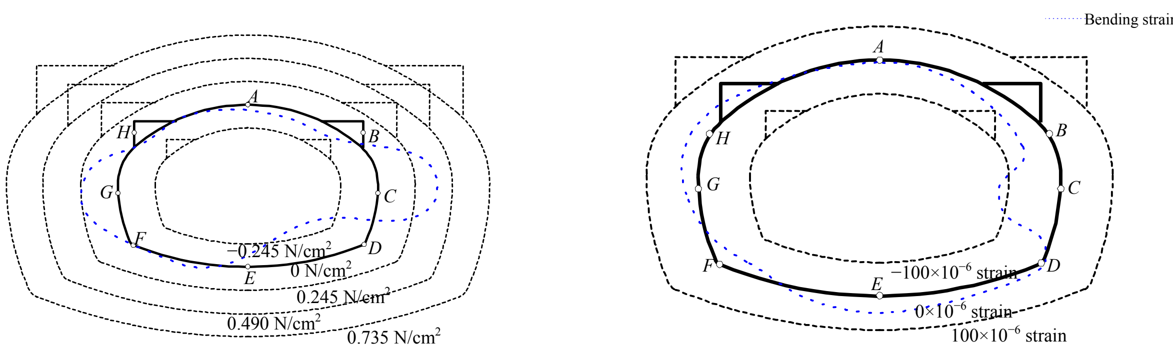
(a) (b)

Fig.7 Distributions of the maximum dynamic soil pressures subjected to sinusoidal motion with 200 gal
(a) Model-1; (b) Model-2



(a) (b)

Fig.8 Distributions of the maximum dynamic strains subjected to sinusoidal motion with 200 gal
(a) Model-1; (b) Model-2



(a) (b)

Fig.9 Distributions of the maximum lateral seismic soil pressures of model-1 (a) subjected to Kobe-motion and (b) subjected to Kobe-motion

NUMERICAL SIMULATIONS

In order to clarify the dynamic behaviors and dynamic forces, 2D time domain analyses were conducted. The nonlinear properties of the ground were estimated by G-γ and h-γ curves from the experimental results, as shown in Fig.4, which is calculated from 1D seismic response analysis using multiple-reflection theory (Kumar, 2000; Shawky and Maekawa, 1996; Wakai *et al*., 1997). The analytical model is a 2D FEM model (Fig.10). The ground was modelled as 2D finite elements in which the aforementioned converging values of the soil properties were used. The structure was modelled as a set of elastic beams elements. The sinusoidal sweep excitations with 5 different constant base acceleration and the recorded NS accelerations at the Kobe Meteorological Agency Station during the Hyogoken-nanbu earthquake were used. The dynamic behaviors of the structure and the dynamic forces (shear and lateral seismic soil pressures) acting on the structure and the strains of the structure subjected to sinusoidal and random earthquake motions were evaluated, and the results compared with experimental values.

Numerical results

(1) Fig.11 shows the distribution of the static and dynamic soil pressures acting on the structure (Model-2) subjected to sinusoidal motion with 200 gal (at resonant point). The shear-mode deformation of the structure was clearly shown due to horizontal excitations, so that the distributions between static and dynamic seismic soil pressures (lateral stress) showed different forms. On the other hand the maximum values of static and dynamic seismic soil pressures were almost the same.

(2) Fig.12 shows the distributions of the static and dynamic normal force and the bending moment subjected to sinusoidal motion with 200 gal (at resonant point). In both case of static and dynamic strains, the maximum strains were at the side of θ=45° and 135°. On the other hand the maximum values of static and dynamic normal force and bending moment were almost the same. Moreover, the bending strains were about 3~4 times that of normal strains.

These results verified that the numerical model and method can reasonably estimate the dynamic behavior of the corrugated culverts, and that the models did not collapse due to strong earthquake motions like those of the Hyogoken-nanbu earthquake.

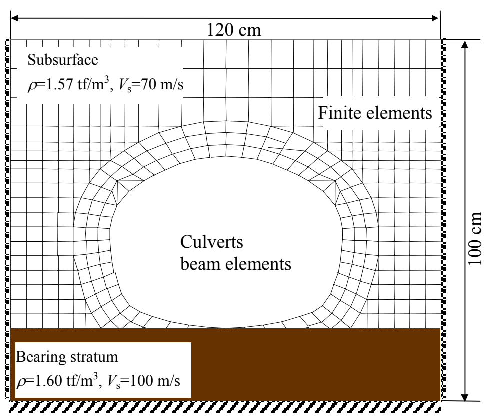


Fig.10 Ground-structure models

CONCLUSION

The dynamic behaviors of the embedded corrugated culvert, the seismic soil pressures acting on the structure and dynamic strain of the structure were verified through the scaled model shaking table test and its simulation analyses.

(1) The corrugated culvert model was subjected to dynamic horizontal forces (lateral seismic soil pressure) from the surrounding ground, which caused the large bending strains of the structure. But normal strain of the structure was negligibly small.

(2) The absolute maximum seismic soil pressures subjected to Kobe-motion were almost equal to

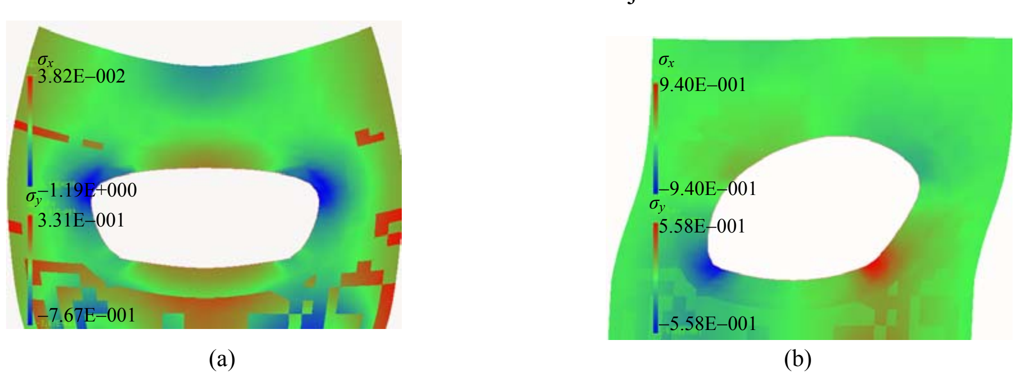


Fig.11 Distributions of the dynamic seismic soil pressures acting on the model (Model-2). (a) Static soil pressures; (b) Dynamic seismic soil pressures subjected to sinusoidal motion with 200 gal (At resonant point)

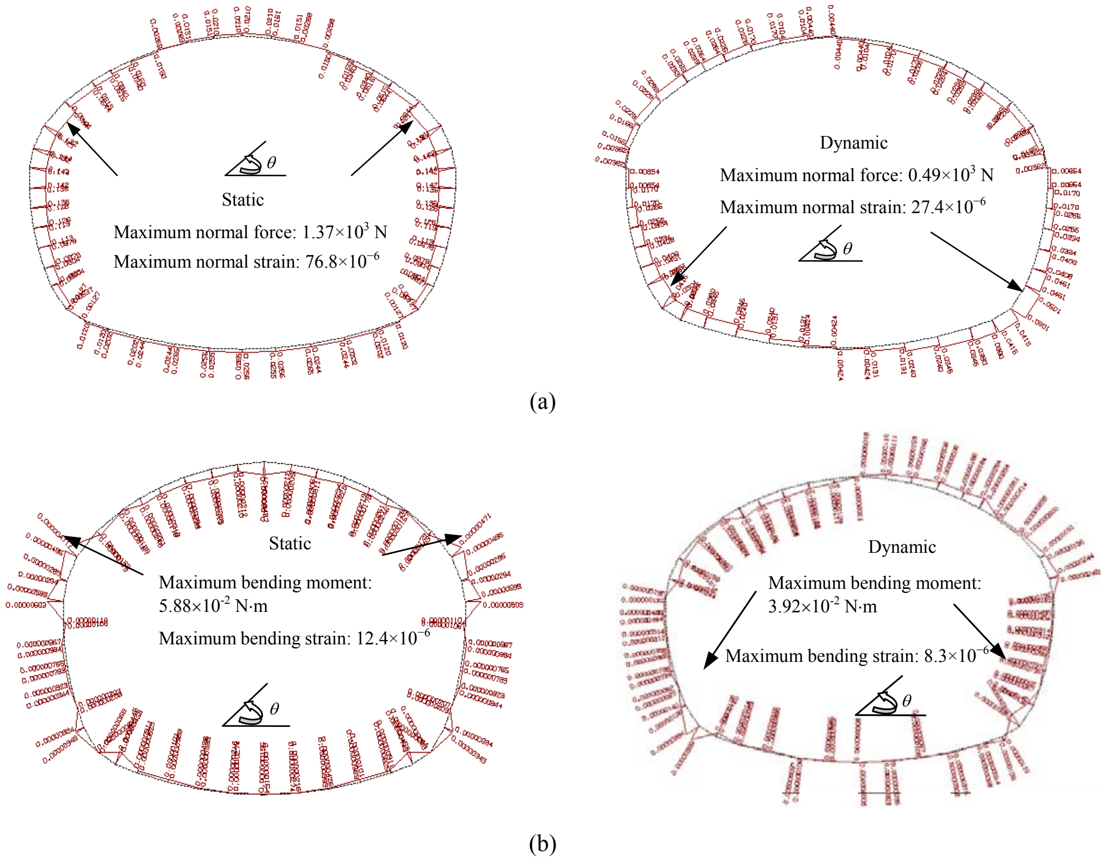


Fig.13 Distribution of the normal force (a) and bending moment (b) of the structure subjected to sinusoidal motion with 200 gal (at resonant point) (Model-2)

those of static seismic soil pressure by overburdened soil.

(3) The maximum bending strain of the embedded corrugated culverts subjected to Kobe-motion did not exceed the allowable strain of the structure.

(4) The embedded corrugated culvert models did not exceed the allowable plastic deformation and did not collapse completely during strong earthquake like the Hyogoken-nanbu earthquake.

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