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Numerical Study for Seismic Stability of Box Culvert and Arch Culvert Using FEM

J.H. Hwang[1], H.S. Shin[1], K. Kishida[2] and M. Kimura[3]

Summary

In this study, Finite Element analyses have been carried out to investigate the seismic stability of an arch culvert comparing to that of a box culvert, and the mechanical behavior of the box culvert and arch culvert with filling embankment has been discussed. The arch culvert is a new type of structure consisting of a series of two-hinge arch structure made of precast concrete members, and its applicability to road embankment structures instead of box culvert has made it attractive. However, in a seismically active area like Japan, it is necessary to study the dynamic behvior of arch structures. Based on the analytical results obtained this analyses, seismic endurance of the arch culvert has higher stability than box culvert based on soil-structure interaction.

Introduction

The applicability of arch culverts is increasing compare to box culvert because they have advantages which are of economical and mechanical benefit. Box culverts are constructed by cast-in-place; nevertheless, arch culvert is an embankment filling structure made of precast concrete members, namely, the vault, side walls and invert. An important characteristic of the arch culvert structure is that it can behave flexibly due to expecting horizontal subgrade reaction. However, since this precast arch culvert system was originally developed to resist dead and live loads, verification of the degree of attained with the precast arch culvert system was an important consideration in applying the system in Japan, a seismically active country.

The 1995 Hyogoken-Nanbu earthquake caused a few damage in the reinforced concrete underground structures, which had not been experienced in the past. Since the earthquake, modules of design have become more developed. Therefore input ground motions were adopted based on Hyogoken-Nanbu earthquake level 2 ground motion in this study (Design Codes of Japan Highway, 2002; Design Codes for Foundations and Earth-Retaining Structures of Japan Railway, 2000). In the field of precast arch culverts, a few studies have been done through both experiments and numerical analyses. Adachi *et al.* (2001) conducted an experimental test on a single-arch culvert in order to investigate the mechanical behavior. Saitoh *et al.* (1998) carried out an experimental study of a 2

[1]Underground Structure Research Division, Korea Institute of Construction Technology, Korea
[2]Department of Urban Management, Kyoto University, Japan
[3]Innovative Collaboration Center, Kyoto University, Japan

hinge-arch culvert by using a model of 1/2 of scale subjected to static-cyclic horizontal loading test. Nonetheless, arch culverts subjected to seismic ground motion have never been studied, particularly, the arch culvert compared to box culvert under level 2 ground motion. Therefore, in this study, the stability of a box culvert and an arch culvert has been examined under level 2 seismic conditions by Finite Element Method.

Analytical Conditions

The constitutive model for sands (ground and embankment) adopted in the present study is the original t_{ij} sand model developed by Nakai *et al.* (1989). Nakai *et al.* proposed the t_{ij} sand model based on the concept of SMP (spatially mobilized plane), in which the influence of the intermediate principal stress can be properly evaluated. The model has been verified through many true triaxial tests on normal sand in generalized stress paths. The t_{ij} sand model can predict the mechanical behavior of soil well, such as the stress-strain-dilatancy relation under generalized stress conditions. The nonlinearity of reinforced concrete is also considered by the AFD model (2002, Zhang and Kimura), which is considered the axial-force dependency according to the variable axial force of the structure.

In this study, a total of three cases of embankment without structure, box culvert and arch culvert were modeled by 3D finite element method. However, the numerical analysis only considered the length of 1m to Y-axis aspect. The embankment's height, filling the top of structure is 1.5 m and the width and height of domain of analysis are 400.0 m and 35.5 m respectively, as shown in Figures 1 and 2. The reinforced concrete of the structure was modeled with beam elements defined through stiffness evaluation assuming the effectiveness of the entire cross section. The road embankment and ground consisted of homogeneous Toyoura sands. Table 1 shows the parameters of the used model in this study. The input ground motion used in the analysis, which is an artificial wave; one period of sin wave with a maximum acceleration of 600 gal, was determined by frequency characteristics based on the Hyogoken-Nanbu earthquake.

Table 1: Parameters of model road embankment, ground and structure

Embankment and Groud		Reinforced concrete	
$R_f = (\sigma_1/\sigma_3)_{cri}$	4.7	Elastic modulus of concrete (E_c)	1.5×10^7 kN/m^2
Poisson's ratio (ν)	0.2	Compressive strength of concrete (f_c)	4.0×10^4 kPa
Density (ρ)	1.5×10^3 kg/m^3	Tensile strength of concrete (f_t)	2.69×10^3 kPa
Coffecient of earthpressure at rest (K_0)	0.6	Elastic modulus of reinforcement (E_s)	2.0×10^8 kN/m^2
C_e	0.60×10^{-2}	Yield strength of reinforcement (f_y)	4.0×10^5 kPa
C_t	0.84×10^{-2}	Density of reinforcement (r)	2.5 t/m^3
Damping coffecient (h)	0.05	Damping coffecient (h)	0.02

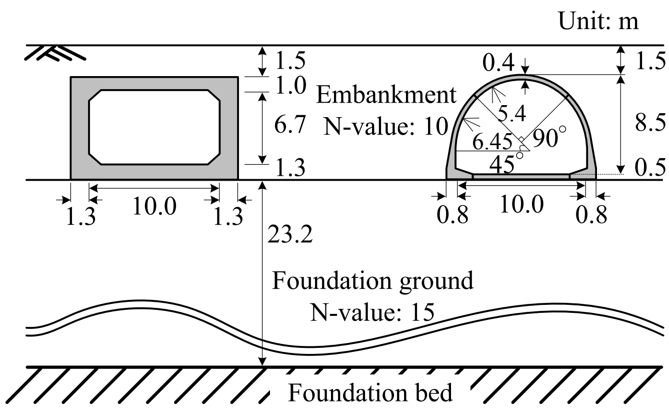

Figure 1: Dimensions of box culvert and arch culvert

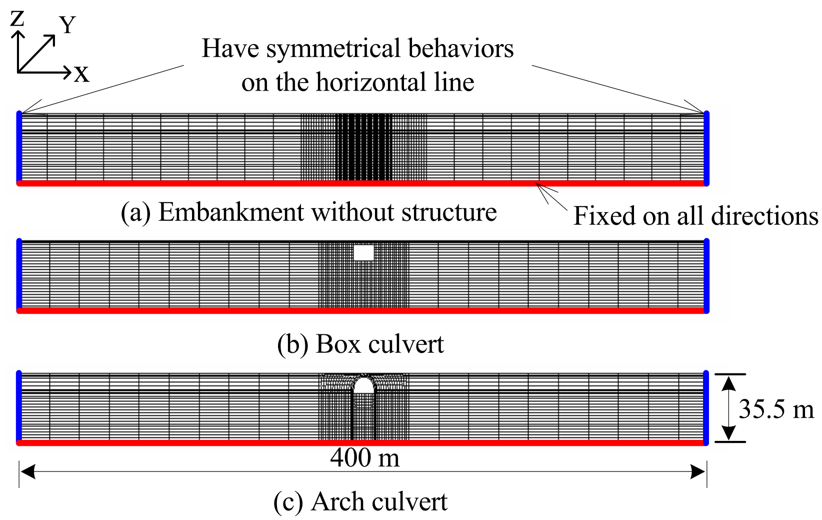

Figure 2: Finite element mesh for seismic simulation

Seismic Evaluations of Box Culvert and Arch Culvert

Figure 3 shows the variable maximum acceleration to depth structures and near the structures. In the bottom of structure, response of the box culvert and arch culvert is smaller than the embankment without structures. The reason behind this is that hysteresis damping occurred in the structures appears to change the structure to plastic state. In the top of the structure, the response acceleration is increased at the box culvert, however, it is decreased at the arch culvert. This means that the dynamic energy is spread out in the arch culvert. On the contrary, the dynamic energy is concentrated in the box culvert. In the vicinity of the structure at a distance of 3 m; the dynamic energy is concentrated on the surface in the case of arch culvert.

Figure 4 shows the time histories of relative displacement between top and bottom of structures. In the box culvert, larger relative displacements are observed. Time histories of relative displacements have the same trend as those of the acceleration responses. Furthermore, it was observed that the arch culvert behaves more analogous to the embankment without structure than the box culvert.

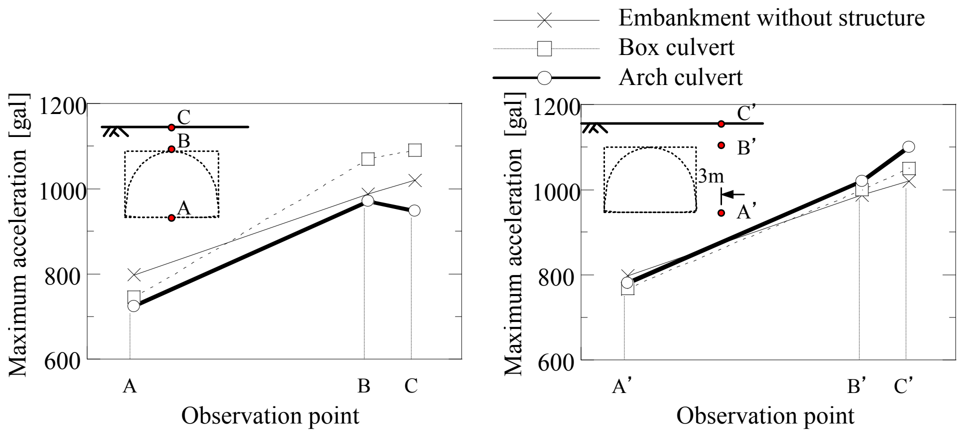

Figure 3: Variable maximum acceleration nearby structures

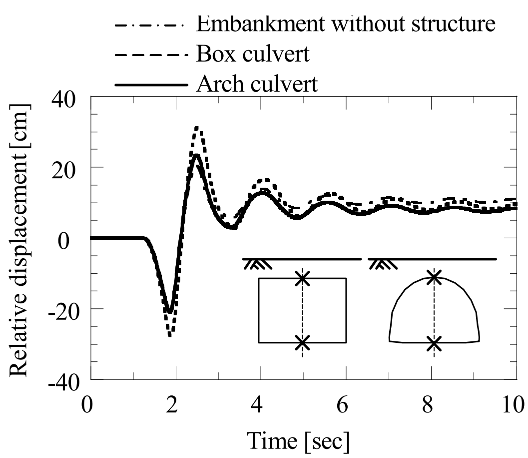

Figure 4: Time histories of relative displacement of the top and the bottom

Figure 5 shows the relations of moment-axial force, *Mc*, *My* and *Mu* (Crack, Yield and Ultimate moment of reinforced concrete) at the bottom of side walls. The maximum sectional force by transversal wave happens at the bottom of sidewalls. In the box culvert, the moment is exceeded *Mu* when the part is on tensile state. The reason is not only inadequate tension reinforcement but the larger tensile strength occurred in the box culvert compared to the case of arch culvert.

Figure 6 shows the deformation of finite mesh when the maximum bending moments occurred in the case of box culvert and arch culvert. The scale of deformation was 5 times the real scale. Uniform settlements with the structure with filling embankment were observed in the case of arch culvert; nevertheless, differential settlement was occurred by stiffness of side walls in the case of box culvert. It seems to affect the increase in shear stress between structure and soils.

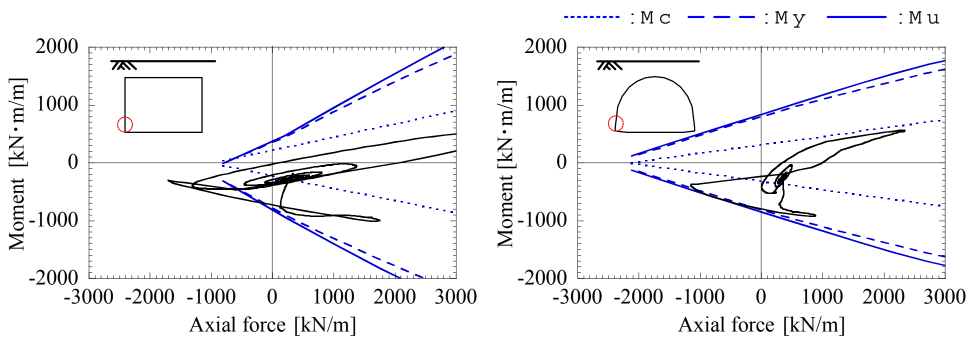

Figure 5: Relation of moment-axial force at the bottom of the side walls

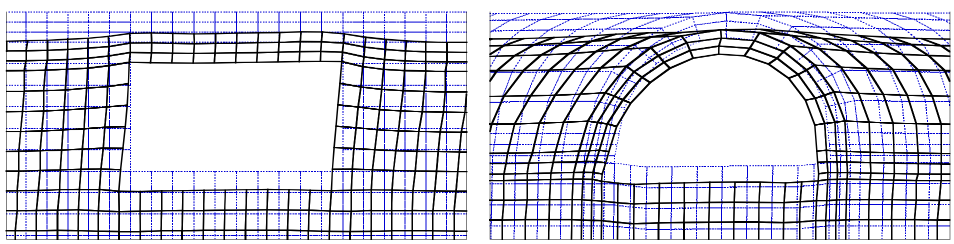

Figure 6: Deformation and displacements when the vibration was stopped

Conclusions

This paper reported the results of FEM numerical analyses on the behavior of road embankments built with box culvert and arch culvert, when they are subjected to seismic ground motions. The following conclusions can be drawn based on the results of this study:

1. The dynamic energy are spread out nearby the arch culvert, however, they are concentrated in the box culvert. Therefore, the seismic behavior of box culvert is more violent than arch culvert.
2. In the relation of moment-axial force, the moment exceeded M_u when a concrete member is on tensile state in the box culvert, however, it does not reach the failure when the maximum moment occurs.
3. It is observed that in case of the arch culvert, uniform settlement with the structure with filling embankment occurs, however, differential settlement was occurred by stiffness of side walls in the case of box culvert. Such a

settlement is likely to be a reason for the increase of shear stress between structure and soils.

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