Centrifuge model tests and elastic FE analysis on seismic behavior of buried culverts

Jun Tohda i), Hiroshi Yoshimura ii) and Katsunori Maruyoshi iii)

i) Guest Professor, Urban Engineering Department, Osaka City University, 3-3-138 Sugimoto, Osaka 558-8585, Japan.
ii) Professor, National Institute of Technology, Anan College, 265 Aoki, minobayashi-choy, Anan 774-0017, Japan.
iii) Engineer, Civil Engineering Group, Nippon Hawer Co., Ltd., 1074-14 Nishihakita-machi, Ako 678-0207, Japan.

ABSTRACT

Sixteen 1/30-scaled static centrifuge model tests and an elastic FE analysis were conducted to investigate the seismic behavior of buried culverts. In the tests, four model culverts (arch-type, box-type, and circular-types with different flexibilities) were buried in different types of model grounds. Distributions of normal and tangential earth pressures acting on the surfaces of the model culverts, as well as those of bending strains produced on their walls were precisely measured during 10 cycles of simple shear deformation of the model ground with the maximum shear strain of 3.2 %. The elastic FE analysis that allows slip and separation at the culvert-ground interface generated results that were in good agreement with the experimental results, confirming the validity of the analysis. On the other hand, the current Japanese seismic design standard using seismic deformation method based on spring model predicted distributions of earth pressures and bending moments on the model culverts that were different from the experimental and the analytical ones, revealing that the standard regards the mechanism of seismic soil-structure interaction incorrectly. Thus, the FE analysis is recommended to be used as an appropriate seismic design method of buried culverts, instead of the problematical current design standard.

Keywords: buried culvert, seismic behavior, centrifuge model test, FE analysis, seismic design

1 INTRODUCTION

The authors have investigated extensively the seismic behavior (earth pressure and deformation) of buried culverts with different shapes and flexibilities through dynamic centrifuge model tests (Tohda et al. 2010a), and the static centrifuge model tests that simulated simple shear deformation of the ground produced by strong earthquakes (Tohda et al. 2013). Special concern was paid in these experiments to measure precisely the distributions of both normal ($\sigma$) and tangential ($\tau$) earth pressures acting on model culverts, because the authors believed that the lack of the precise earth pressure data is a critical obstacle to the understanding of the actual seismic behavior of buried culverts.

Measured results of the dynamic centrifuge model tests were compared with the predicted values calculated according to the current Japanese seismic design standard using seismic deformation method based on spring model (JSWAS 2006). The comparison showed that the current seismic design standard predicts a behavior for the buried culverts which is different from that observed in the experiment. One of the critical differences between the measurement and prediction was the magnitude of the tangential earth pressures ($\tau$) acting on the surfaces of the buried culverts. The measured $\tau$ were always almost null, while the predicted $\tau$ were remarkably greater than the measured $\tau$ (Tohda et al. 2010b). These findings showed the necessity to develop a new seismic design method that can represent the actual behavior of buried culverts.

Thus, the authors applied an elastic FE analysis to the dynamic centrifuge model tests using four types of model culverts (Tohda et al. 2010b), as well as an elastic continuum model analysis of the static centrifuge model tests using circular-type model culverts (Tohda et al. 2013). The FE analysis allowed slip and separation at the interface between the soil and culvert. The elastic continuum model analysis allowed slip at the soil-culvert interface, but did not allow separation there. Both analyses generated results that were in good agreements with the measured results in most cases, while several inconsistencies between the analyses and experiments were seen in several exceptional cases. An examination for these inconsistencies proved that the following obstacles existed in both analyses:

1) The FE analysis for the dynamic centrifuge model tests could not avoid errors in the input horizontal

http://doi.org/10.3208/jgssp.JPN-106
deformations at the lateral boundaries of the model ground, which were calculated by double integrations in relation to the elapsed time \( T \) of the horizontal acceleration waves that were measured by several accelerometers installed at different depths in the vicinity of the lateral side of the model ground. The analysis also involved difficulties in determining dynamic elastic moduli of soils that depend on the level and rate of the strain.

2) The continuum model analysis could not deal with the separation at the soil-culvert interface. Also, its application was limited to the circular-type culvert case.

In the present paper, the measurement in the static centrifuge model tests and the predictions of the FE analysis were compared, because this comparison overcomes the obstacles described above, as follows:
1) The static centrifuge model tests do not have the errors in the horizontal displacements at the lateral boundaries of the model grounds. The tests also avoid the difficulties in determining the dynamic elastic moduli of soils.
2) The FE analysis can be applied to any type of culvert.

The comparison led to good agreement without any exception as expected, proving the validity of the FE analysis. On the other hand, the prediction on the basis of the current seismic design standard led to poor agreement with the measured results, similarly to that presented in the same literature.

Figure 2 shows the model configuration. The model was scaled to 1/30 of the prototype. The model culverts were buried in model grounds with a cover height \( H \) of 9 cm or 18 cm \( (H/D=1 \text{ and } 2) \). The internal front and and tangential \( (\tau) \) earth pressures acting on the culvert surfaces, as well as bending strains \( (\varepsilon) \) produced on the walls of the culverts, were measured. The structure of the model culverts and their instrumentation were detailed in past literature (Tohda et al. 2010a). High accuracy in earth pressure measurement was confirmed in all the tests through the good agreement obtained between the measured bending strains and the bending strains calculated under the measured earth pressure conditions, in addition to the fulfillment of the external forces equilibrium, similarly to that presented in the same literature.

Figure 2 shows the model configuration. The model was scaled to 1/30 of the prototype. The model culverts were buried in model grounds with a cover height \( H \) of 9 cm or 18 cm \( (H/D=1 \text{ and } 2) \). The internal front and

| Table 1. Dimensions and elastic properties of model culverts. |
|------------------|-----------------|-----------------|----------------|
| Type of culvert  | \( D \) (mm)    | \( t \) (mm)    | \( E_p \) (GPa) | \( v_p \)     |
| A-type           | 90              | 3.3             | 71             | 0.33         |
| B-type           | 90              | 3.3             | 71             | 0.33         |
| C-type R-pipe   | 90              | 3.5             | 74             | 0.33         |
| F-pipe           | 90              | 0.95            | 74             | 0.33         |

| Fig. 1. Model culverts (unit: mm). |
|-----------------------------------|

| Fig. 2. Model configuration (unit: mm). |
|----------------------------------------|
back walls of the container, as well as the internal surfaces of the lateral plates, were lubricated by means of two sheets of rubber membrane with silicon grease. A sheet of water resistant sand paper was pasted on the bottom of the container.

The properties of the model grounds are shown in Table 2. Two types of soils, dry silica sand (S0) and decomposed granite (S16), were used in the tests. Loose and dense S0-grounds (S0L- and S0D-grounds) were constructed by dry pluviation, and loose S16-ground (S16L-ground) was constructed by compaction.

At a centrifugal acceleration field of 30 \( g \) (gravitational acceleration), the lateral plates were rotated in parallel, for ten cycles, first to the left and next to the right, until simple shear strain (\( \gamma \)) of the model ground reached 3.2 %. The value of \( \gamma =3.2 \% \) was determined as the average value of relative shear strains produced between the bottom and top of the culverts that were buried in the different model grounds under resonant conditions due to level-2 seismic motions.

### 3 ELASTIC FE ANALYSIS FOR THE EXPERIMENT

Figure 3 shows an example of the FE mesh used in the analysis. The analysis was carried out under plain strain condition. Both soil and culvert were assumed as isotropic elastic bodies. Table 3 shows the elastic properties (deformation modulus \( E_s \) and Poisson’s ratio \( \nu_s \)) of the soils, obtained through \( K_s\)-compression tests using a rectangular box (Tohda et al. 2001). According to the test results, \( \nu_s \) was independent of the axial stress level, while \( E_s \) was dependent on the stress level. Therefore, different values of \( E_s \) were assigned to the soil elements according to their ground stress levels, as shown in Figure 3 and Table 3.

Centrifugal acceleration of 30 \( g \) was applied as load condition. Horizontal displacement corresponding to simple shear strain \( \gamma =3.2 \% \) and free vertical displacement were applied to the lateral ground boundaries. Both horizontal and vertical displacements were fixed at the bottom of the model ground.

A curved parabolic joint element was inserted at the soil-culvert interface to achieve the semi-smooth boundary condition with separation, frictional slip and failure (Tohda et al. 1994). The initial values of the normal \( (k_n) \) and tangential \( (k_t) \) stiffnesses attributed to the joint element were 98 MPa and 0.29 MPa. The calculation was repeated until the normal \( (\sigma_n) \) and shear \( (\tau_j) \) stresses in the joint element converged through the followings: 1) where \( \sigma_n \) was tensile (separation range), \( k_n=k_t=0 \), 2) where \( \tau_j < \tau_p \) (frictional slip range), the initial values of \( k_n \) and \( k_t \) were maintained, and \( \tau_p \) is the shear resistance calculated through \( \tau_p = c_p + \sigma_n \tan \phi_p \) \( (c_p \) and \( \phi_p \) : frictional resistant parameters on the culvert surface measured by a direct shear apparatus), and 3) where \( \tau_j \geq \tau_p \) (failure range), \( k_a \) was reduced by multiplying \( \tau_p/\tau_j \) to satisfy \( \tau_p \geq \tau_j \).

### 4 COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

Figure 4 (S0L-ground and \( H/D=1 \)) and Figure 5 (S0D-ground and \( H/D=1 \)) show typical comparisons between experimental and analytical results. The data in the figures correspond to those obtained at \( \gamma =3.2 \% \) when the ground was deformed to the left-hand side. In the figures, the normal and tangential earth pressures \( (\sigma \) and \( \tau \)) acting on the culvert surfaces, as well as the bending moment \( (M) \) produced on the culvert walls, are illustrated in prototype scale. The marks and the thin lines correspond to the data measured at \( N=1, 2, 5, \) and 10 \( (N) \) : number of repetition times for ground shear). The thick lines of \( \sigma, \tau \) and \( M \) show the analytical results. Compressive \( \sigma \) and counterclockwise \( \tau \) are counted as positive. Positive \( M \) corresponds to the case where the internal surface of the culvert is under tension.

Measured results indicate that: 1) \( \tau \) is always close to null, 2) \( \sigma \) tends to concentrate on the first and third quadrants of the rigid culverts (A-type, B-type and

---

| Ground   | \( G_s \) | \( D_{\text{max}} \) (mm) | \( E_s \) (MPa) | \( \nu_s \) | \( \rho_{\text{max}} \) (g/cm\(^3\)) | \( \rho_{\text{min}} \) (g/cm\(^3\)) | \( \rho_d \) (g/cm\(^3\)) | \%Uc | Gs |
|---------|----------|----------------|----------------|---------|----------------|----------------|----------------|-------|------|
| S0L     | 2.65     | 1.4            | 0              | 1.75    | 1.58           | 1.32           | 1.43           | 0      | S0L  |
| S0D     | 2.65     | 1.4            | 0              | 1.75    | 1.58           | 1.32           | 1.55           | 0      | S0D  |
| S16L    | 2.71     | 2.0            | 16             | 70      | 1.92           | 1.42           | 1.50           | 10     | S16L |

Table 2. Properties of model grounds.

Table 3. Elastic properties of soils.

| Ground | \( H/D \) | \( E_s \) (MPa) | \( \nu_s \) |
|--------|----------|----------------|---------|
| S0L    | 1        | 0.8~3.5        | 0.37    |
| S0L    | 2        | 0.8~4.1        | 0.37    |
| S16L   | 1        | 0.5~1.2        | 0.33    |
| S0D    | 1        | 1.4~7.6        | 0.35    |

Fig.3. FE mesh (A-type, S0L-ground and H/D=1, unit: cm).

---

Input content is about the analysis of the behavior of soil-culvert interfaces under seismic loads. The analysis involves the use of finite element (FE) methods to simulate the interaction between the soil and the culvert, considering factors such as shear and normal stresses, and the behavior of the joint elements. The properties of the model grounds, including their density, are shown in Table 2. The analysis is performed under resonant conditions due to level-2 seismic loads, with the ground accelerated by a centrifugal field of 30 \( g \). The FE mesh used in the analysis is shown in Figure 3. The elastic properties of the soils used in the analysis are shown in Table 3. The analysis results are compared with experimental results to validate the model.
Fig. 4. Comparison between experimental and analytical results (S0L-ground and $H/D=1$).

Fig. 5. Comparison between experimental and analytical results (S0D-ground and $H/D=1$).
Prediction was carried out by applying the design procedures of RC box-culvert, RC-pipe and FRPM-pipe to B-type, R-pipe and F-pipe, respectively. Prediction for A-type was omitted, because the standard does not specify it. Inertia forces acting in the culverts were ignored. Spring coefficient \(k\) of the ground were determined in accordance to the design standard by using \(E_s\) and \(\nu_s\) at the stress level of the mid-height of the culverts measured in the \(K_0\)-compression tests. \(\tau_0\) were obtained by substituting these \(E_s\) and \(\nu_s\), as well as \(\gamma=3.2\%\), in the equation: \(\tau_0=E_s\gamma/(2(1+\nu_s))\).

Figure 7 shows a typical comparison between the predicted and experimental results for SOD-ground and \(H/D=1\). Similar tendency in comparison was obtained under other test conditions. Figure 7 indicates that:

1) In any culvert, the predicted \(\tau\) is not only remarkably greater than the measured \(\tau\), but also greater than the predicted \(\sigma\) in wide areas. Similar results were obtained in the former dynamic centrifuge model tests. These results indicate that the occurrence of the predicted \(\tau\) is impossible.

2) In the rigid culverts (B-type and R-pipe), the predicted \(\sigma\) is concentrated on their first and third quadrant surfaces, except that the predicted \(\sigma\) on the upper plate of B-type is uniform. In their second and fourth quadrants, there are wide areas where the predicted \(\sigma\) is tensile stress. If this is true, separation must occur there to generate null earth pressures.

3) The predicted \(M\) in B-type and R-pipe are considerably greater than the measured \(M\). This difference between the predicted \(M\) and the measured \(M\) is caused by the impossible predicted earth pressures (the remarkably great \(\sigma\) and the tensile \(\sigma\)).

4) In F-pipe, distribution of the predicted \(\sigma\) has symmetric axes differing by 90° from those of the measured \(\sigma\).

5) The difference in the magnitude of the predicted and the measured \(M\) in F-pipe is slight, because the modes of \(M\) produced by the predicted \(\sigma\) and \(\tau\) are opposite so as to cancel each other’s magnitude.

The differences between the prediction and the experimental results shown in Figure 7 are caused by the following problems related to the design standard:

1) Earth pressures on Box-culvert and FRPM-pipe are calculated using both \(\delta_{GH}\) and \(\tau_G\). This commits a double count for an identical shearing phenomenon.

2) The slip and separation at the soil-culvert interface are ignored. According to the valid interpretation for soil-structure interaction, the stress and deformation of the ground at the infinite ground boundaries produced by earthquakes must change at the vicinity of culverts, so as to satisfy the interface boundary condition with the slip and separation.

3) The spring coefficients of the ground can not be
determined at all, because they are not inherent coefficients of soil. JSWAS has published a revised guideline of the design standard in 2014 (JSWAS 2014), although the details of the design procedure have not yet been revealed to public. According to the revised guideline, however, the main changes are as follows: 1) the method to calculate the value of $k$ has changed, and 2) $\sigma$ and $\tau$ acting on RC-pipe are calculated by the sum of earth pressures due to $\delta_{GH}$ and $\tau_{G}$, similarly to the other culvert cases. It is clear, therefore, that these changes do not eliminate the problems described above.

6 CONCLUSIONS

Static centrifuge model tests that simulated simple shear deformation of ground produced by strong earthquakes generated precise measurements in normal and tangential earth pressures on different types of buried culvert. The elastic FE analysis that allows slip and separation at the culvert-soil interface conformed well to the experimental results. However, current seismic design standard predicted a culvert behavior that was different from the experimental and the analytical ones, revealing that the standard regards the mechanism of the seismic soil-structure interaction incorrectly. Thus, the FE analysis is recommended to be used as an appropriate seismic design method for buried culverts, instead of the problematical current design standard.

REFERENCES

1) JSWAS (Japanese Sewage Works Association) (2006): Earthquake-resistant measures guidelines and commentary of sewer facilities (in Japanese).
2) JSWAS (Japanese Sewage Works Association) (2014): Earthquake-resistant measures guidelines and commentary of sewer facilities, Revised Edition (in Japanese).
3) Tohda, J., Li, L., and Yoshimura, H., (1994): FE elastic analysis of earth pressure on buried flexible pipes, Centrifuge 94, 727-732.
4) Tohda, J. and Yoshimura, H. (2001): A new design method for buried pipes, Proc. of the 15th ICSMGE, 1319-1322.
5) Tohda, J., Yoshimura, H., Ohsugi, A., Nakanishi K., Ko, H.Y., and Wallen, R.B. (2010a): Centrifuge model tests on dynamic response of sewer trunk culverts, ICPMG 2010, 651-656.
6) Tohda, J., Yoshimura, H., Inoue, Y., and Mukaichi, H. (2010b): Centrifuge model tests and FE analysis on seismic response of sewer trunk culverts, Journal of JGS (Tsuki-to-kiso), 58(2), 18-21 (in Japanese).
7) Tohda, J., Yoshimura, H., and Martuyoshi, H. (2013): An elastic continuum model for interpretation of seismic behavior of buried pipes as a soil-structure interaction, Proc. of the 18th ICSMGE, 1777-1780.