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AN INVESTIGATION ON LONG-TERM EXCESSIVE DEFORMATION OF UNDERGROUND RC CULVERTS COUPLED WITH SOIL FOUNDATION

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ABSTRACT

The excessive deflection of underground RC box culverts, which have comparatively smaller thickness of members, has been seen and in some cases, larger cracks are being repaired for water tightness and protection against steel corrosion. This paper aims to investigate the mechanism of the long-term excessive deformation of underground box culverts coupled with soil foundation. Both the settlement of surrounding soil foundation and the moisture gradient over the depth of concrete slabs and walls are taken into account by using the multi-scale hydro-mechanical analysis of structural concrete.

It is experimentally and computationally found that the soil settlement brings about excessive overlay loads to culverts more than the design specification equivalent to the dead weight of soil above the top slabs. Furthermore, the moisture gradient caused by the drying ambient states inside culverts accelerates delayed cracking over 10 years if the smaller slab thickness is provided. Through the sensitivity analyses, it is found that the increased reinforcement ratio may hardly suppress the creep deflection over time, but the control of moisture profile may lead to a substantial impact to the deformation of underground RC culverts.

Keywords: long-term excessive deformation, underground RC culverts, soil foundation, moisture, reinforcement steel ratio.

1. INTRODUCTION

Since the 1990s, the long-term monitoring of the Tsukiyono bridge's deflection has been reported by Hata *et al.* (1993) and the measured deflection is approximately three times larger than the designed values. Recently, excessive deflections of cantilever PC viaducts worldwide have been reported by Bazant *et al.* (2011a, b) as well. Moreover, the long-term excessive deflection of underground RC box culverts, which have comparatively smaller thickness of members, has also been reported and larger cracks are being repaired for water tightness and protection against steel

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corrosion. These facts bring a great concern on the current investigation on long-time excessive deformation of underground RC culverts.

Maekawa *et al.* (2011) points out two main causes of excessive deflection of the PC bridges. One is the non-uniform thermo-dynamic state of moisture inside micro-pores and associated creep, and the other is the delayed average shrinkage of upper and lower flanges in time (Ohno *et al.* 2012). For underground RC culverts, the mechanism of excessive deflection at the top slab is similar with that of PC bridges and the soil-structure interaction is another cause.

This paper aims to investigate the mechanism of the long-term deformation of underground box culverts coupled with soil foundation and to discuss the practical and useful way to control the deflection over the design period. During the analysis, both the settlement of surrounding soil foundation and the moisture gradient over the depth of concrete slabs and walls are taken into account by using the multi-scale hydro-mechanical analysis of structural concrete. The main content of this paper is shown in **Figure 1**.

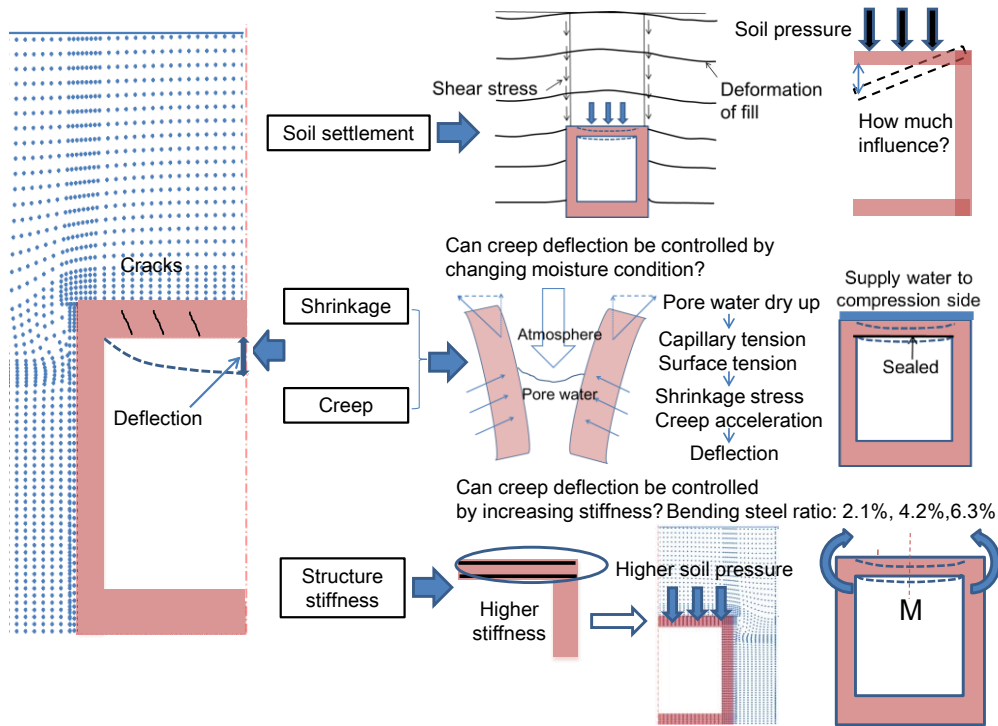


Figure 1: Overview of the investigation on underground RC culverts in this study

2. FINITE ELEMENT MODE

Figure 1 gives the shape of profile of the underground RC culvert consisting of RC members. The culvert has an outer dimension of about 4m width and 4.35m height. The wall thickness is 0.35m. The thickness of the top slab is 0.35m and 0.4m for the bottom one. The reinforcement ratio of whole section is assumed to be 1.2% and the bending reinforcement ratio is 0.6%. The deformed soil is set as dry sand with the frictional angle of 45° and the initial shear stiffness and the density are shown in **Table 1**. Because of symmetry, the half model can be used in the two-dimensional

analysis. Joint elements are set at the culvert-soil interface and soil-elastic interface. The downward-forced settlement applied to the soil boundary simulates the settlement of the backfill soil which takes place in the early decades. The downward displacement is set as 7.65 cm within 2 days after 28 days curing and it is kept constant.

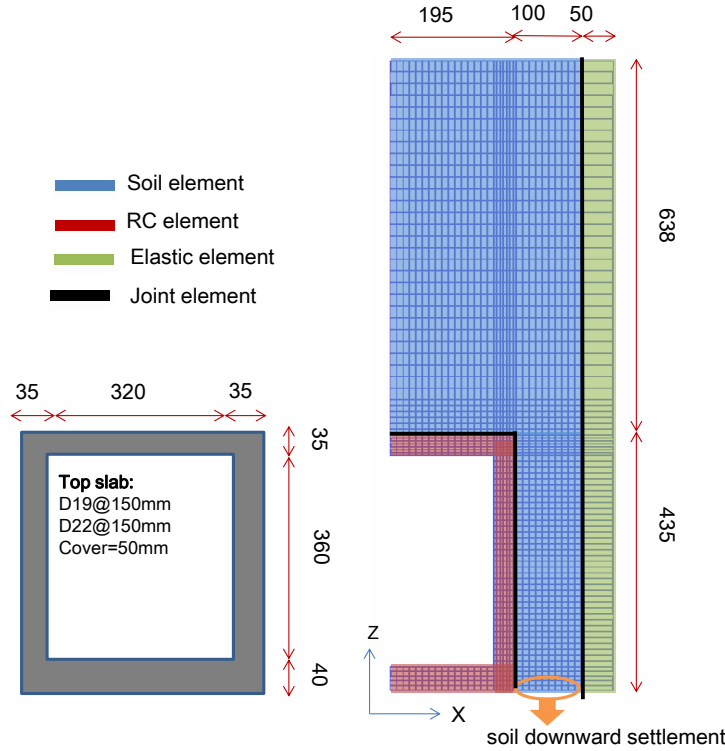


Figure 2: The model of the underground RC culvert

Table 1: Material properties used in analysis

Soil(sand)		Reinforced Concrete	
Initial shear stiffness	22.3MPa	Compressive	24.5MPa
Unit weight	16.7 KN/m ³	Tensile strength	1.4MPa
Friction angle	45°	Steel Young's modulus	210GPa
Relative density	90%	Steel yield stress	363MPa

3. CONSTITUTIVE MODELING

In the analytical simulation of this study, the DuCOM-COM3 (Maekawa *et al.* 2008) system is used. This is a multi-scale analysis code that links the thermo-chemo-physics platforms DuCOM (Maekawa *et al.* 1999, 2008) and COM3 (Maekawa *et al.* 2003) as shown in **Figure 3**. DuCOM is an integrated thermo-hygro analysis code that includes cement hydration in concrete mixture, micro-pore structure formation and mass transport models for concrete ranging from 10^{-3} to 10^{-9} meter scales of micro-voids, while COM3 is a 3D finite element analysis platform for structural concrete with and without cracks. As a result, DuCOM-COM3 is capable of predicting the change in concrete material properties from casting to dismantling of entire structures and taking this material development into account for predicting the response of structural concrete.

With this integration, the long-term structural response under actual ambient conditions can be predicted in a realistic manner. **Figure 3** illustrates the code linkage for computing the nonlinear, time-dependent responses of reinforced concrete.

A nonlinear path-dependent constitutive model for soil mainly depends on the shear stress-shear strain relation, which is extended to three-dimensional generic states. In this study, soil is mechanically idealized as an assembly of a finite number of simple elasto-perfectly plastic elements connected in a parallel pattern as shown in **Figure 3** (Maekawa *et al.* 2003; Towhata 2008).

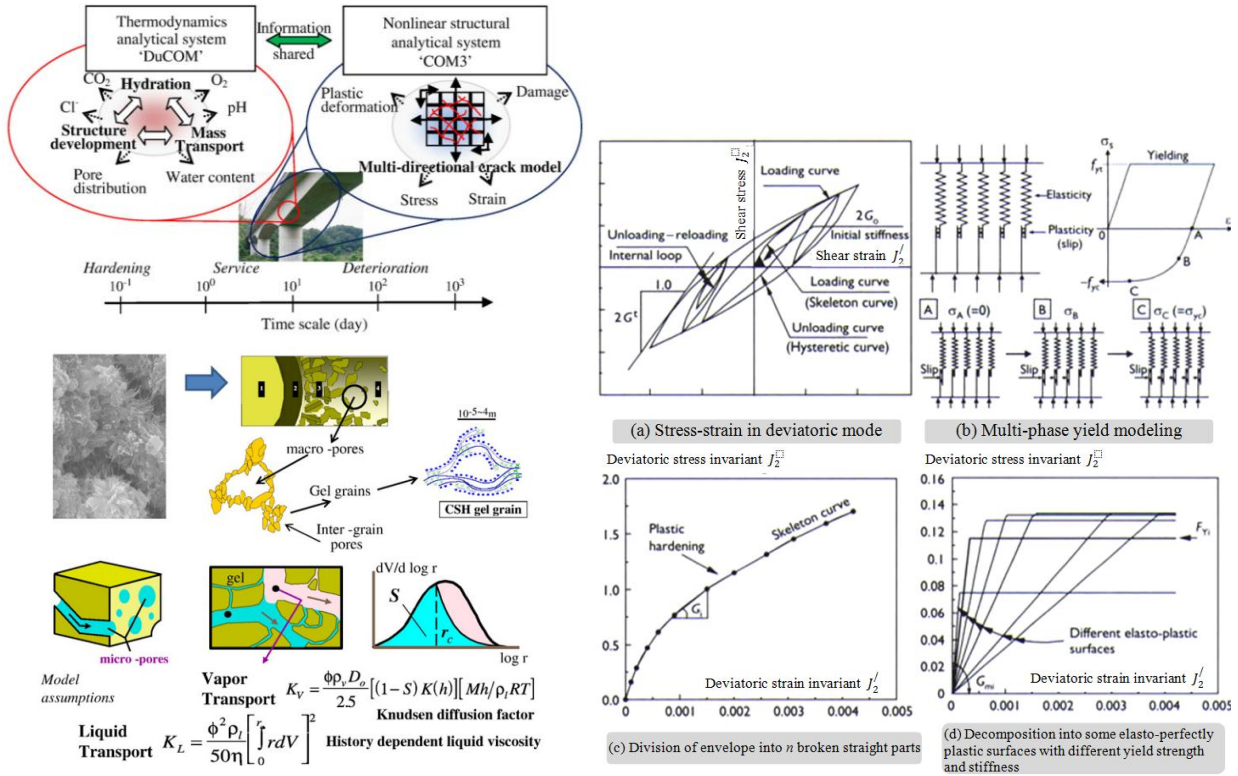


Figure 3: The multi-scale integrated analytical system and soil multi-spring model

4. ANALYTICAL RESULTS

The factors including soil settlement, moisture gradient and structure stiffness are investigated in the following analysis. The deflection in this study is defined at the mid-span of the top slab and the time length of the analysis is almost 7,000 days (about 19 years).

4.1. The effect of soil settlement

For the safety, it is meaningful to check how much the soil settlement influences the long-term deflection of underground culverts. The soil pressure is also an important parameter for designing related to serviceability limit state.

In the following analysis, two groups with different moisture conditions, which are wet and dry group separately, are investigated. One of the dry groups is set with soil settlement and the other is

set without soil subsidence. The relative humidity of the dry case is kept 50% and 40% outside and inside, separately. The difference in their response reflects the influence of soil settlement. The wet group is set as a contrast group to show how the moisture conditions influence on the creep deflection caused by the soil settlement. The relative humidity of the wet groups is kept 99% both outside and inside.

The surface of the outside and inside of the culvert is kept under a temperature of 20°C and 40°C, respectively. And the settlement of the backfill soil in the early time is 7.65 cm downward displacement within 2 days, then kept constant.

The left one of **Figure 4** shows that the soil downward settlement has a strong influence on the deflection of the top slab. When the soil settlement is considered, the time-dependent deflection increases and the growth is 0.4 cm in the dry case and 0.2 cm in the wet one. It is because the soil settlement brings about excessive overlay loads on the top slab. Then, the soil pressure increases and it has also been proved by the experiments (Tadros et al. 1989; Bennett et al. 2005; Kuwano and Ebizuka 2010). When the backfill soil settles down, the soil settlement speed above the culvert is slower than the side soil and the shear stress occurs as shown in the right one of **Figure 4**. Then, the soil pressure above the culvert becomes higher.

Compared to the wet and dry cases, it is also found that the moisture condition influences on the creep deflection caused by the soil settlement. As shown in the right of **Figure 4**, the soil pressure value is almost the same for the dry and wet cases with the same soil settlement, but the creep deflection caused by the soil subsidence in the dry condition is greater than that of the wet state. The main cause of this difference is the relative humidity. The relative humidity (RH) of the dry case is low and associated shrinkage occurs easily, then the creep deformation is accelerated. This result means that the environmental conditions of the culvert in terms of the relative humidity can also influence on the creep deflection caused by soil settlement.

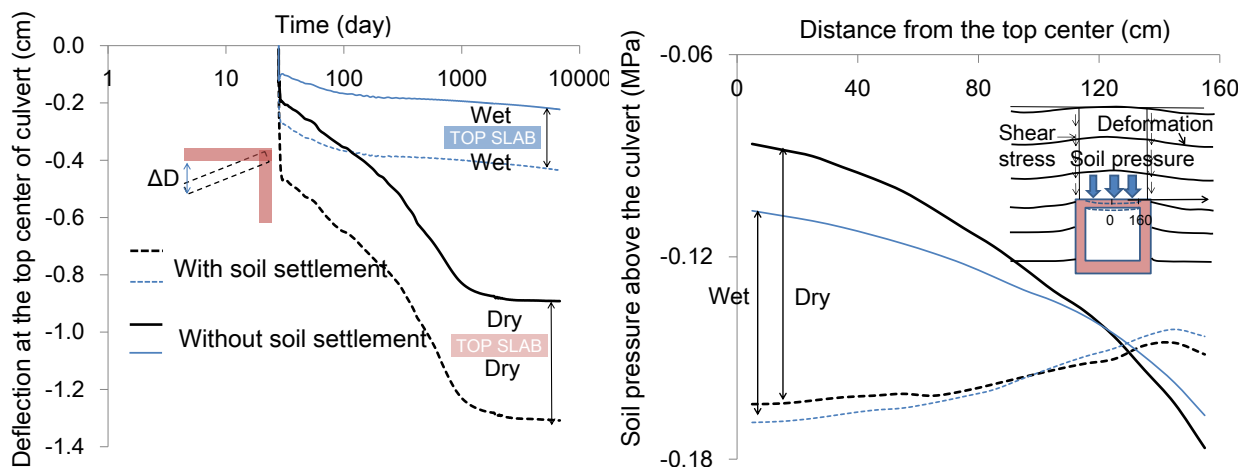


Figure 4: The effect by soil settlement under different moisture conditions

4.2. The effect of moisture condition

In order to understand the effect of moisture condition, three cases with different relative humidity are investigated. The difference in their response reflects the influence of moisture condition.

The dry case is kept under a RH of 50% and 40% at the surface of outside and inside, respectively. One of the wet cases is kept wet outside and 40% inside, and the other one is kept wet outside and sealed inside. In the three cases, the surface of outside and inside of the culvert is kept under a temperature of 20°C and 40°C. The computationally forced soil settlement is 7.65 cm downward displacement within 2 days, and consequently kept constant.

Figure 5 shows that time-dependent deflections of the top slab under different moisture conditions drew apart as the time passed. The deflection in the dry case is larger than that of the wet cases. This is because the low RH accelerates the drying and capillary tension becomes high, then the associated shrinkage of the flange of the top slab occurs easily, and the creep is also accelerated. By supplying water to the upper compression side of the top slab, the capillary tension will release and the shrinkage and creep are controlled. For the wet case with the seal inside, deflection is the smallest. That is because the water may penetrate the pavement through fine paths and it keeps the top slab of the culvert wet. Then, the shrinkage and creep can be controlled better.

According to the analytical results, it can be considered that shrinkage is the main driving force of the excessive deflection of the top slab of RC culverts, and it is a possible way to control excessive deformation of RC culvert by non-mechanical methods which are to supply water to the compression side of the top slab and keep sealed at the inside face.

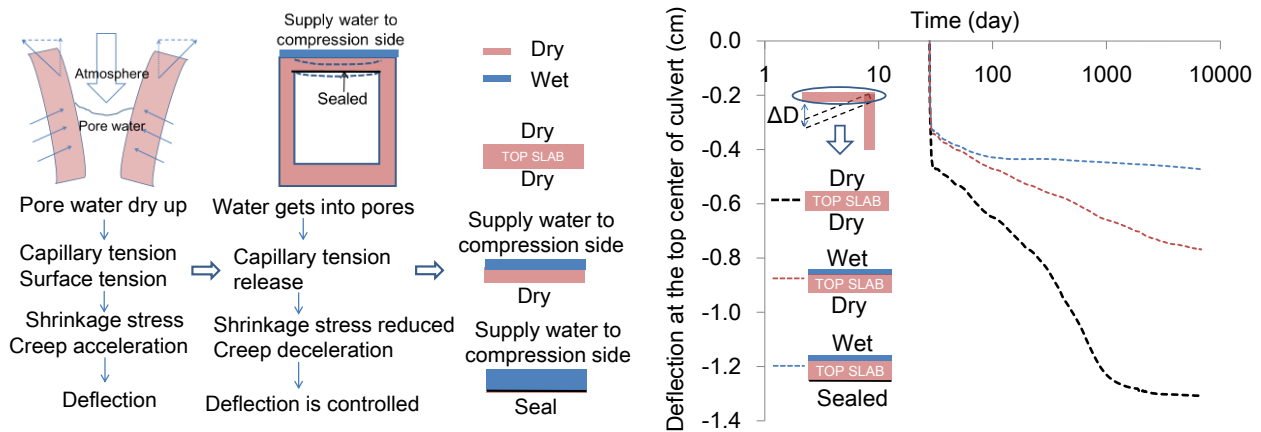


Figure 5: Mechanism of controlling deflection by changing moisture condition

4.3. The effect of increasing stiffness

In present design codes, it is a practical way to control the deformation by increasing in the structural stiffness. The stiffness of RC culverts can be improved by increasing the reinforcement ratio. The analytical cases with different steel ratios at the top slab are analyzed and the reduction of deflection can reflect the effect by increasing the reinforcement ratio.

The whole sectional steel ratio of the top slab is set 1.2%, 2.4% and 3.6% respectively, and the other properties are set the same. The relative humidity on the surface of the outside and inside is set 50% and 40% and the temperature outside and inside is kept 20°C and 40°C. The settlement of the backfill soil in the early time is 7.65 cm downward displacement within 2 days, then kept constant.

Figure 6 shows that improving the steel ratio does not have much effect on reducing the excessive deflection. That is because the soil pressure above the culvert and mid-span bending moment also increases with the improvement of culvert stiffness. When the stiffness of culvert is improved, the settlement of the soil above the culvert becomes more difficult especially the soil above the center of culvert, so the soil pressure becomes larger correspondingly and the center pressure is the largest as shown in **Figure 7**. Because of the increase in the soil pressure, the tensile steel at the top slab has to undertake more loads and the tensile steel force level is also elevated proportionally. The mid-span moment also becomes bigger and the deflection is enlarged.

Compared with the effect of changing moisture condition, the effect of increasing structure stiffness is limited to control the excessive deflection of culvert.

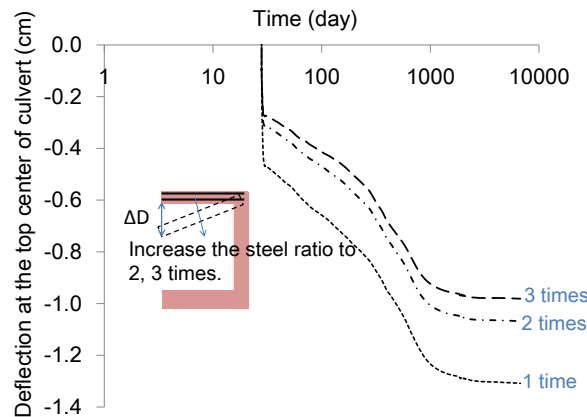


Figure 6: Deflection of the top center of culvert with different stiffness

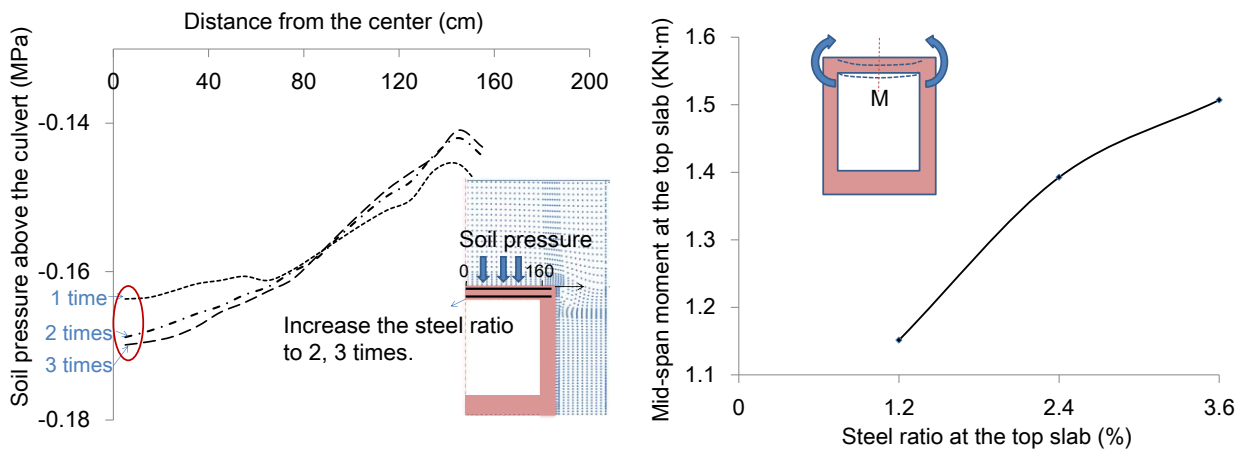


Figure 7: Soil pressure above the culvert and mid-span moment under different stiffness

5. CONCLUSIONS

This paper presents discussion into long-term deformation of underground RC culverts over the design criterion coupled with soil foundation, and the effect of factors as soil settlement, moisture conditions and structure stiffness are investigated by simulation analysis. The approaches to control excessive deformation are proposed as well. The conclusions are lined up as follows.

(1) The soil downward settlement has a strong influence on the increase of excessive deflection at the top slab and the moisture condition influences the creep deflection caused by soil settlement. The creep deflection caused by soil settlement in the wet condition is smaller than that of dry condition.

(2) Environmental control inside and outside of culverts is a possible way to control deflections. According the analysis results, supplying water to upper compression side of the top slab and keep sealed on the surface of inside is a better way to control excessive deflections of underground RC culvert.

(3) The effect by increasing the structural stiffness is limited to reduce the excessive deflections beyond the design requirement, because the soil pressure above the culvert and mid-span bending moment of the top slab also increase with the improvement of the culvert stiffness.

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