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Mechanical properties of multiple large-diameter corrugate steel pipes in embankment

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ABSTRACT

Compared with the traditional culverts used in China, corrugated steel pipe (CSP) has many advantages. Due to the limited service duration and construction practices, CSP is still not fully adopted by the Chinese design code. In this paper, a recent study on multiple large-diameter CSPs used in highway embankment is reported. These three parallel CSPs is used to replace a small bridge in a highway project. The earth pressure in such structure was identified by the finite element models (FEM) and compared with the results by the Code formulas and other references. The on-site surrounding load and mechanical performance of CSPs are monitored and analyzed in the study. With the aid of FE methods, suitable models are established for comparison and further factor study. After validation, a parameter study on the models is performed to reveal the influences of some technical factors on CSPs, *e.g*. backfill materials and height of backfill.
Keywords: Corrugated steel pipe (CSP), FEM, earth pressure, mechanical properties, embankment

1. INTRODUCTION

Traditional Culverts used in highway engineering are made by (reinforced) concrete or masonry materials. With the drawbacks of its complexity in design, construction and less adaption to the uneven settlement, corrugate steel pipe (CSP) was introduced and gradually accepted as an alternative from the end of last century in China. Compared with other culverts, CSP has its own advantages in stable mechanical performance, installation, fast construction, *etc.* [Li 2007]. Therefore, it was recognized a potential future structure of highway Engineering in China. However, Due to its limited research and construction experience, CSP is still regards as a new structure and is not fully adopted by the Chinese design code.

Highway is a line-shaped structure across variable landforms. Sometimes, bridge construction can face many difficulties in the desolate area, *e.g*. shortage of electricity

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or water. CSP can be treated as a solution in such situation. However, to replace a bridge, CSP is required to have a large diameter and multiple layout. Previous studies and engineering experience provide rare references for that purpose. Therefore, this project is set up with funding of Beijing Municipal Commission of Transport.

The practical site of the study, Chongyi Bridge, locate at Yingyu highway of Wuan city, in Hebei Province of China, where a girder bridge is replaced by a three parallel CSPs. Each pipe is assembled at site and the final diameter is 6 m, shown in Fig. 1. Fig.2 illustrates the corresponding profile of the CSP. This study is composed by two parts, *i.e.* the on-site construction monitor and the offsite stress analysis. Theoretical solution for calculation of earth pressure above the CSP is sought. A suitable FEM models are established for the comparison purpose. After validation, a parameter study with the models reveals some crucial information of the multiple large-diameter CSPs used in highway embankment. The conclusions drawn by this study can be beneficial for the further application of such type of CSPs in the replacement of small bridges.

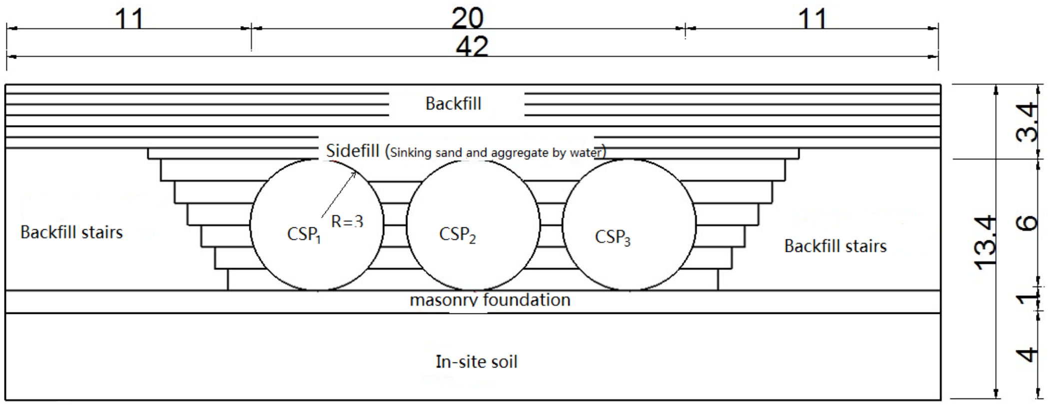


Fig. 1. Plan and schematic finite element model of on-site CSPs in embankment (m)

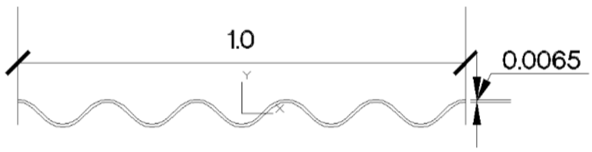


Fig. 2. The profile of CSP (m)

2. EARTH PRESSURE

As the major environmental load, earth pressure plays an important role in the mechanical performance of CSPs. The earth pressure in CSP is influenced by different factors such as the stiffness of pipe, physical properties of soil, height of backfill, *etc*. The pressure can be estimated by different methods in engineering fields [Feng 2010]. Maston [Maston and Andserson 1913] proposed a traditional formula to calculate the earth pressure on a pipe. The Chinese Highway Code [MTC 2007] defines an “earth-pillar” method, where only the factors of soil density (γ) and height of backfill (H) are considered. Compared with the Chinese Highway Code, Chinese Railway Code [MRC 2005] defines an extra parameter (*K*) to consider the influence of diameter. All the calculation formulas defined in the current Chinese codes are based on the rigid concrete pipes, which is far from the mechanical behavior of CSP. Based on definition of Chinese Highway Code and reference of [Feng 2010], the flexibility criterion (*FC*) of CSP can be calculated by Eq. (1). CSP used in the project is easily categorized as flexible. Therefore, Earth pressure is definitely influenced by the present of CSP with different settlement [Kang *et al* 2008].

$$FC = \frac{1000 E_s D(1-\mu)}{E_p A_p \tan(\varphi)} = \frac{1000 \times 80 \times 6000 \times (1-0.26)}{210000 \times 7.664 \times \tan(35)} = 315 > 40 \quad (1)$$

In which, E_s is modulus of soil (MPa); E_p is the Young's Modulus of CSP (MPa); D is the diameter of CSP (mm); A_p is the section area of CSP per unit length (mm^2/mm); μ is the Poison's ratio and φ is the internal friction angle.

In this study, the aforementioned positive buried Maston method [Maston and Andserson 1913], methods of Chinese Highway Code and Chinese Railway Code are used for calculation of earth pressure. Meanwhile, FEMs with or without one CSP are established for comparison purpose. The results are present in Fig. 3. It shows FEM without CSP can predict earth pressure, which complies completely with Chinese Highway code (the earth pillar method). The results of Chinese Railway Code has the highest earth pressure compared with other models. Distribution of earth pressure is uneven above the CSP in a same horizontal line: the crown has the lower values

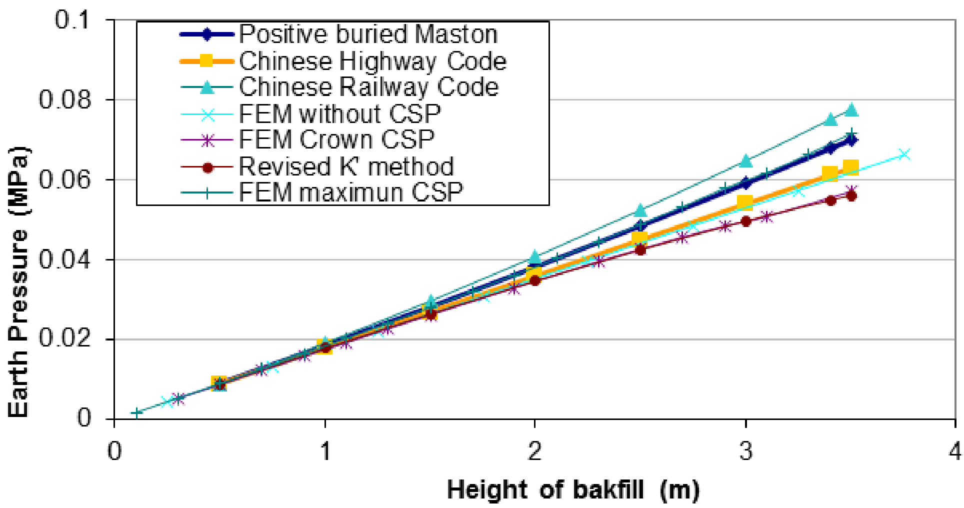


Fig.3 Earth pressure comparison with different method and models

compared with other location above CSP; the region near about one radius of CSP away of crown has the highest value. The maximum earth pressures revealed by the FEM can be estimated by the positive buried Maston method. As the crown earth pressure is critical for the mechanical performance of CSP, a revised method (named as "the revised *K′* method") on the approach of Chinese Highway Code is proposed using regression method. The relationship between K' and K is present by Eq. (2). The analytical results by this method comply quite well with the results of FEM simulation.

$$K' = f(K) = 1 - 2(K-1)^2 \tag{2}$$

3. ON-SITE MONITOR

For monitoring of the real mechanical performance of CSP, 34 pressure cells and 40 strain gages are installed around three sections of the CSPs. The layout of pressure cells and strain gages in one section are illustrated in Fig. 4. The instruments are installed before or during the backfilling construction based on the schemata. The readings are recorded with the progress of construction. Fig. 5 presents the strain development of

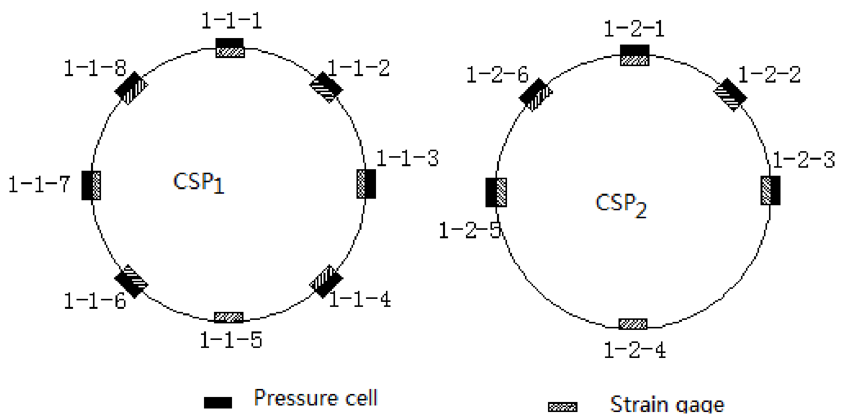


Fig.4 The layout of pressure cells and strain gages in a section of CSPs

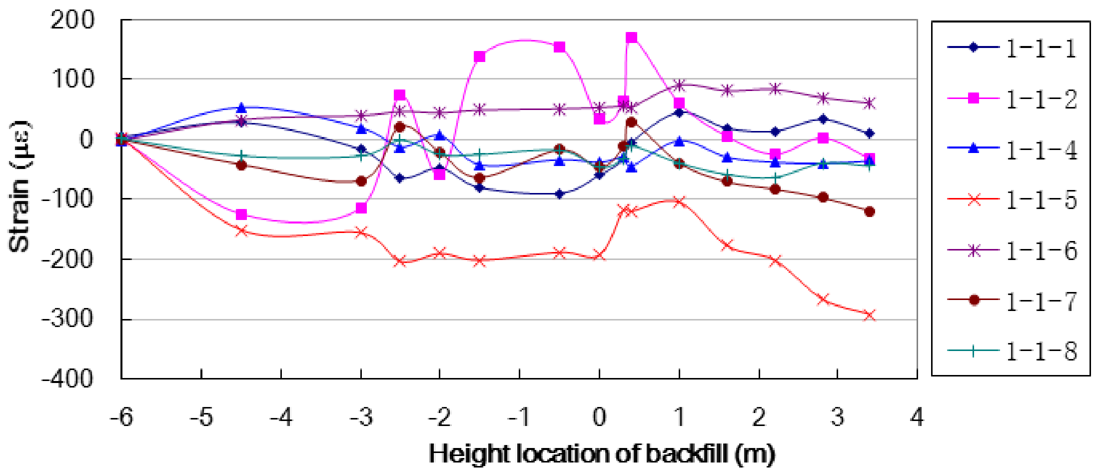


Fig. 5 Strain development of deferent location of CSP_1 with backfill process

different locations on the CSP_1 circle with construction progress. It shows the strain increases with increasing of backfill height. The whole development can easily divided into two stages: side-filling stage and top-filling stage. The strains of all location zigzag increase at the first stage. However, all the strains have a tendency to be linearly stabilized and tend to be compressive. Bottom point (invert) has the highest compressive stress. The results from CSP_2 show a similar tendency, *i.e*. two strain development stages. It seems the backfilling process can reduce the divergency of strain and will be beneficial to the further mechanical performance.

4. NUMERICAL SIMULATION

Based on the profile of on-site embankment of Fig. 1, a 2D FEM is established to analyze the mechanical performance of CSPs under different influences. The real construction process is simulated by the loading steps in FEM. The materials properties of different components are listed in Table 1. The CSP is modeled using the curved beam elements, whose section properties are based on the real one per unit meter of CSP.

Table 1 Materials properties of different conponents of enbankment in FEM

Parameter / Materials	Modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Cohensive force (kPa)	Inner friction angle (°)
CSP	2.1e5	0.3	7850	-	-
Backfill	25	0.35	1800	35	20
Sidefill	80	0.26	1900	12	35
Backfill stairs	25	0.35	1800	35	20
Masonry foundation	300	0.25	2200	5	60
In-site soil	20	0.36	1800	35	26

4.1 Basic results

Figure 6 shows the final deflection of embankment after the backfill construction. It shows the deflection is perfectly symmetry based on the vertical center axial of CSP_2. The backfill stair has the maximum deflection zone of embankment. Backfill deflection is significantly influenced by the present of CSPs. They generally reduces the deflection of backfill, which is partly similar as the concrete pipe. However, the deflection is unevenly

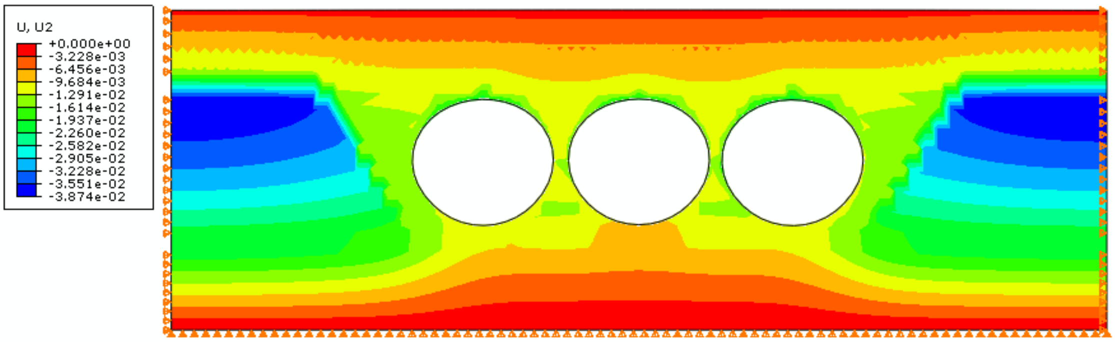
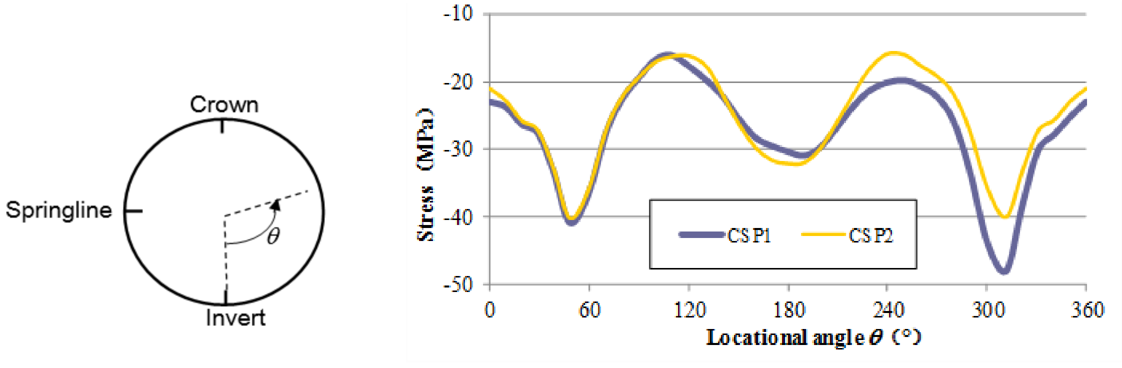


Fig. 6 Contour plot of the final deflection of embankment (m)



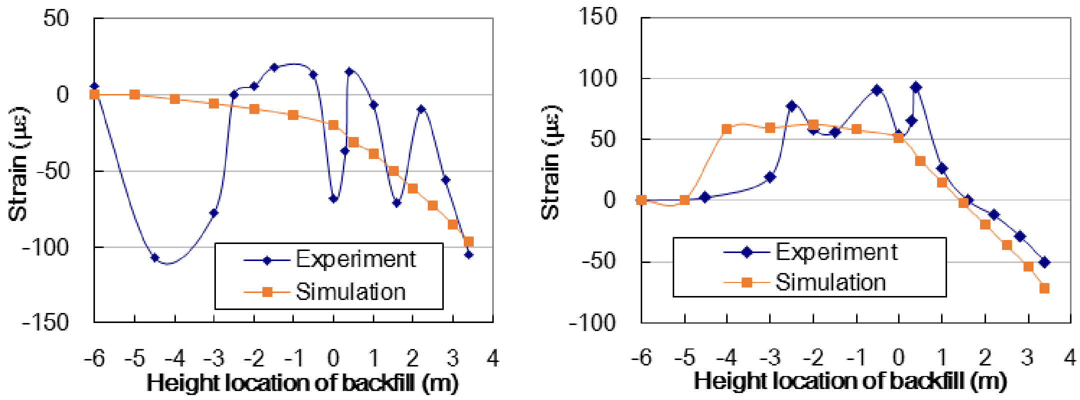
(a) (b)

Fig. 7 (a) illustration of locational angle (θ) and (b) its corresponding stress of CSP_1 and CSP_2

distributed near a single CSP in the same horizontal line. The deflection value is has a maximum one at the crown point of CSP, which is also illustrated in section 2 in this paper. Taking the advantage of symmetry, Only CSP_1 and CSP_2 is used for comparison study. The hoop stress of two pipes along a locational angle (θ), illustrated in Fig. 7(a), is plotted in Fig. 7(b). It shows hoop stresses of both pipes are in compressive in the final stage of construction. The stress of CSP_2 is almost symmetric based on the vertical axial through invert point. Compared with CSP_2, CSP_1 has a stress concentration in the region between out-springline and invert.

4.2 Comparison with experimental results

The simulation results can be compared with the ones by the on-site monitor to illustrate the reliability of numerical simulation. Fig. 8 and Fig. 9 show the developemtn of strain of two selected points in the CSP_1 and CSP_2 with construction of backfilling, respectively. Despite some deviation by experimental measurement, the results by FEM simulation comply quite well with results by the on-site monitor. Experimental results



(a) (b)

Fig. 8 Comparison of strain development of (a) θ=90° and (b) θ=0° in CSP_1 with construction of backfilling

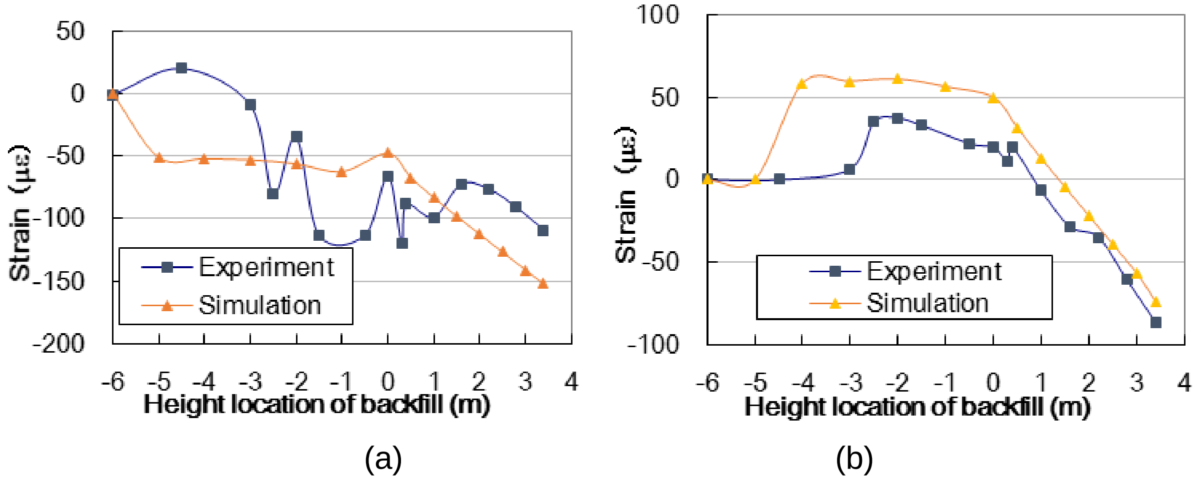


Fig. 9 Comparison of strain development of (a) θ=180° and (b) θ=270° in CSP_2 with construction of backfilling

show more zigzag compared with simulation results. It may due to the experimental complications, which is easily influenced by manual factors, for instance. In general, the whole development of strain can easily divided into two stages: side-filling stage (below height location 0) and top-filling stage (above height location 0). In the first stage, side-fill loading dominates the initiation of strain. Strains in some locations of pipe are developing in tensile. But in the latter stage, compressive strain is linearly developing with increasing of backfill. Comparison study shows the established FEM models are generally validated. Later on, these models can be used for other parameter study, e.g. influence of backfill materials, influence of height of backfill, *etc*.

4.3 Influence of height of backfill

Height of backfill can be widely different in engineering application, which is determined by the design documents. But it has a high relevance with mechanical performance of CSP as the backfill is the main loading. For this sake, the influence of height of backfill (*H*) is studied by the validated FEM model. Fig. 10 illustrates the

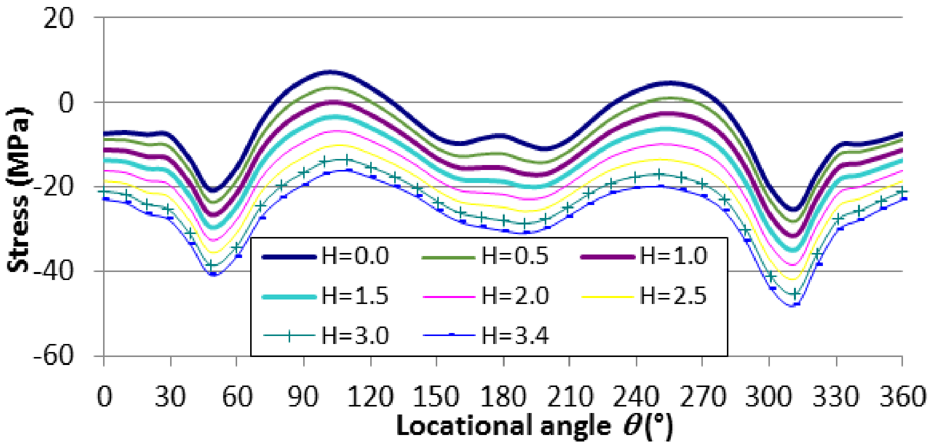


Fig. 10 Hoop stress of CSP_1 with different height of backfill

development of hoop stress of CSP_1 with height of backfill. It shows the stress of CSP_1 in all location is linearly development after side-filling stage, which can also expected by Fig. 8 and Fig. 9. The stress in top-filling stage is generally developed in compressive despite the initial value. The conclusions drawn from current model can be influenced by the limitation of height of backfill. For the construction of CSP in a high embankment, the stress performance should be further verified by a new model.

4.4 Selection of backfill materials

Backfill material is the material used to bury CSP (including side, boundary, and top). The selected material can influence mechanical performance of CSP and their interaction, but also the construction requirements. Four types of popular construction materials, listed in Table 2, are selected in the study. Table 2 shows the properties of these four types of materials. Basically, the mechanical properties are getting stronger from materials 1 (fine sand) to materials 4 (concrete).

Figure 11 illustrates the final hoop stress of CSP_1 with different backfill materials. In general, the stress patterns of four models have similar distribution. However, the stress levels are different. Models with unbounded backfill materials (material 1 to material 3) have higher hoop stress. CSP1 with the strongest material, *i.e.* concrete, has lower compressive stress, while tensile stress can be found in some regions. It may due

Table 2 Materials properties of four types of construction materials

Parameter / Materials	**Modulus (MPa)**	**Poisson's ratio**	**Density (kg/m^3)**	**Cohesive force (kPa)**	**Inner friction angle (°)**
1.Fine sand	40	0.35	1800	10	32
2.Graded sand and rock	80	0.26	1900	12	35
3.Stablized sand	200	0.23	2000	90	15
4.Concrete	30000	0.17	2500	-	-

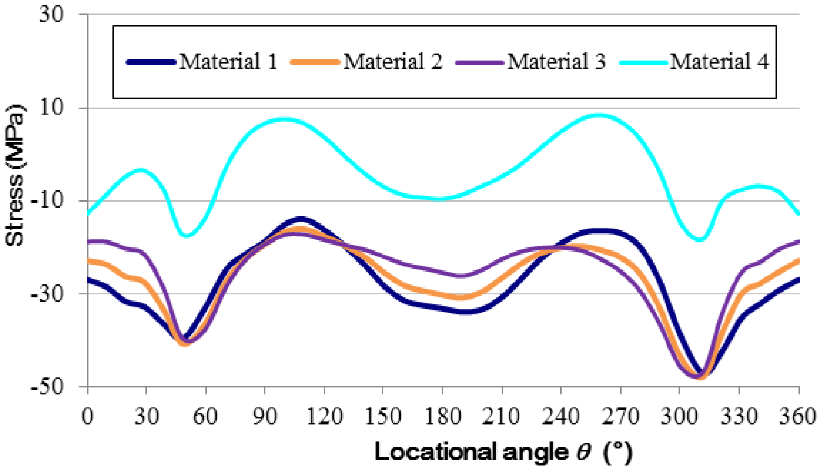


Fig. 11 Hoop stress of CSP_1 with different backfill materials

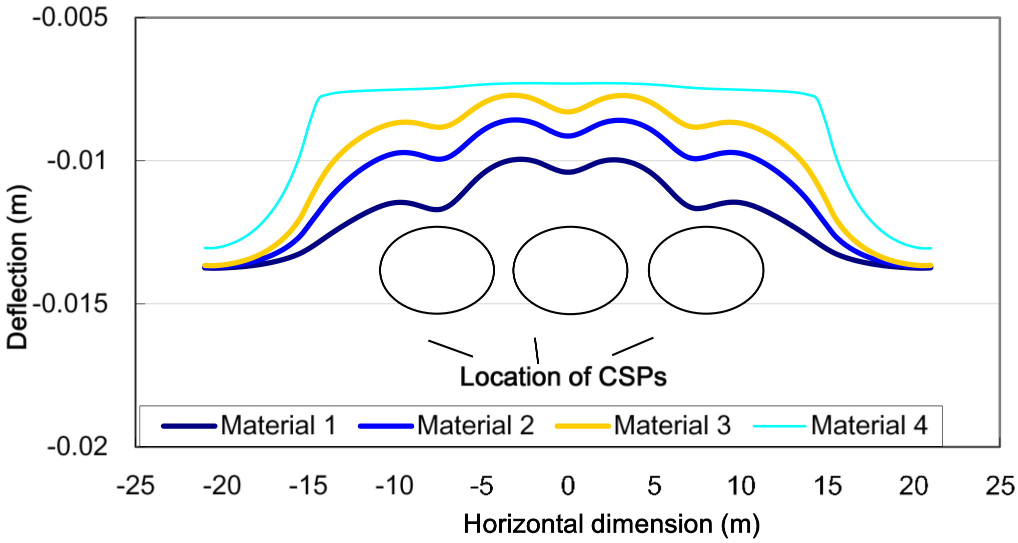


Fig. 12 Along the road deflection of embankment with different backfill materials

to the loading has been well distributed and bore by the backfill material. A lower level of loading has been transferred to inner pipe in such model. From this point of view, strong backfill material is beneficial for reduction of stress level of CSP. However, the material selection should be judged from various aspects. Fig. 12 presents the deflection distribution of embankment with different backfill materials. It shows material properties has a heavy impact on the deflection of embankment. Stronger backfill material can leads to a wide deflection difference to the adjacent pavement and results a greater uneven settlement. Uneven settlement is a challenge problem, *e.g*. bump at bridge-head, which should be avoid in the pavement engineering. Therefore, the selection of backfill material should be considered comprehensively. A proper backfill materials should share proportional part of loading with CSP, but also should reduce the uneven settlement in the embankment.

5. CONCLUSIONS

CSP is a relatively new but promising structure to replace rigid culvert or small bridge in some difficult construction occasions in China, *e.g.* with weak foundation, in limited construction conditions. However, many technical specifications are still remain uncertain due to limited engineering and research experiences. In this paper, a real project of embankment with three parallel large diameter CSP was selected for the study. Some technical problems, *e.g*. the earth pressure, stress, selection of backfill material, influence of height of backfill, *etc*., are focused through theoretical, on-site experimental and FEM simulation approaches. Some conclusions can be drawn based on this study:

(1)The distribution of earth pressure above CSP is different compared with traditional rigid culvert. It is mainly due to the flexibility of CSP. CSP can be categorized as flexible. Distribution either by Chinese Highway Code or Chinese Railway Code can precisely predict the distribution of earth pressure above CSP. FEM simulation shows that within the same level of backfill, the pressure are unevenly distributed. Near region about one radius of CSP away from crown has the highest value, while the Crown Point has a lower value. The highest values can be well predicted by the positive buried Maston method. A revised method (named as "the revised K' method") based on the Chinese Highway Code is proposed in this paper.

(2) On-site monitor show the development of strain of CSPs can be divided into two stages: side-filling stage and top-filling stage. It seems the backfilling process can reduce the divergency of strain and be beneficial to the mechanical performance.

(3) A proper 2D FEM model can be established, which is validated by the comparison with the results of on-site experiments. The model can be further used for the parameter study.

(4) It shows the stress of CSP in all location linearly develop with increasing of backfill height after side-filling stage.

(5) Backfill materials has a close relevance to the mechanical performance of CSP. Selection of material should considered comprehensively. A proper backfill materials should share proper part of loading with CSP, but also should reduce the uneven settlement in the embankment.

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