A Case Study of Roadway Embankment Construction Over Existing Sewers in Montreal, Canada

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Abstract. This paper presents a case study of the influence of a roadway embankment on existing sewers with diameter or width of approximately 3.3 to 4.3 m. The proposed embankment would be constructed directly above the existing sewers, which would induce an additional load. Traditional analysis methods cannot account for the structural/soil interaction and the benefit of the lateral supporting characteristics of the soils. In order to evaluate the loading of the proposed embankment on the existing sewers, a structural/soil interaction analysis using a two-dimensional finite element computer program was performed for various loading cases. The sensitivity of soil parameters was also considered in the analysis. From the analysis, the loadings on the sewers including axial force, bending moment and shear force were obtained and then the structural capacity of the existing sewers was checked. Light-weight sand fill or expanded polystyrene (EPS) geofoam was considered to reduce the additional vertical and horizontal loads on the sewers. The EPS geofoam or a structural protection system consisting of a concrete slab supported by concrete piles was considered to eliminate any incremental vertical and horizontal loads on the sewers. These mitigation methods were compared. It is found that the light-weight sand fill is most economic material to reduce the additional loads on the sewers, the EPS geofoam is most suitable material to eliminate incremental loads on the sewers for a lower embankment, and the structural protection system is only option to eliminate incremental loads on the sewers for a higher embankment.

1 Introduction

Redevelopment of roadway systems is a frequent occurrence in urban centers as infrastructure ages and as our reliance on transportation networks increases. A roadway embankment was proposed to replace an existing roadway viaduct in the downtown area of Montreal, Canada. The height of the embankment is up to 9 m. There are numerous challenges associated with roadway embankment construction in urban areas, such as the construction impact on existing utilities, nearby buildings, etc.

This paper presents a case study of the construction influence of a roadway embankment on existing sewers with a diameter or width of approximately 3.3 to 4.3 m. The proposed embankment would be constructed directly above the existing sewers, which would induce an additional load onto the existing sewers. Traditionally,

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Marston-Spangler theory (Spangler and Handy 1982) is used for the analysis of buried culverts/sewer pipes. However, this method cannot account for the benefit of the lateral supporting characteristics of the embedment soils. In order to evaluate the loading of the proposed embankment on the existing sewers, a soil/structure interaction analysis using a two-dimensional finite element computer program was performed for various loading cases. The sensitivity of soil parameters was also considered in the analysis. From the analysis, the loadings on the sewers, including axial force, bending moment and shear force were obtained and then the structural capacity of the existing sewers was checked. If the existing sewer could not take the additional loads, mitigation methods to reduce or eliminate the additional vertical and horizontal loads on the sewer were considered.

To reduce the additional vertical and horizontal loads, consideration was given to using light-weight sand fill and expanded polystyrene (EPS) geofoam, which are more compressible than conventional fill, to induce positive arching above the sewer. To eliminate any incremental vertical and horizontal loads, consideration was given to use of ultra-lightweight fill (i.e. EPS geofoam) to replace the conventional backfill, or use of a structural protection system consisting of a concrete slab supported by concrete piles to pick up the embankment weight. These methods were compared and the most economical or suitable method was proposed.

2 Site Conditions and Roadway Embankment Construction

The site of the proposed roadway embankment is located in Montreal, Canada. In the study area, a new embankment with an approximate width of up to 70 m and with a height up to approximately 9 m needs to be constructed to replace aging and severely deteriorating roadway viaducts. As the proposed embankment would be constructed directly above the existing sewers, an additional load will be imposed on the existing sewers. These sewers ("Collecteurs") were installed between 1963 and 1990 and were not designed for the additional surcharge. Figure 1 shows a typical cross section of existing sewers and viaducts, along with the proposed new roadway embankment.

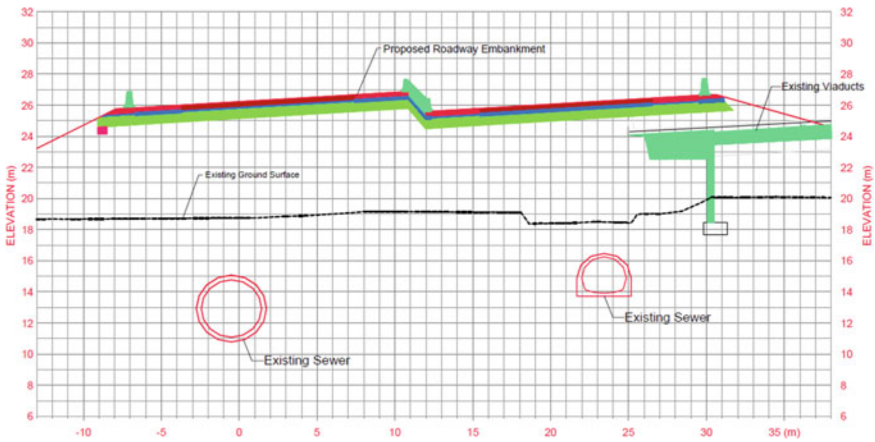

Fig. 1. Existing condition and proposed roadway embankment relative to existing grade

The existing sewers used in the case study includes two types: (1) circular type of concrete pipe with an inside diameter of 3.6 m and thickness of 350 mm; and (2) horseshoe type of concrete pipe with an inside diameter of 2.7 m and thickness of 203 mm to 305 mm.

A geotechnical investigation, including borehole drilling, standard penetration tests (SPT), pressuremeter tests and laboratory testing of soil index parameters, was carried out to support the design of the embankment.

The investigation revealed subsurface soils consisting of: loose to compact fill over very loose to loose sandy silt to silty sand, interbedded with marl, which is in turn underlain by dense to very dense glacial till of sand to sandy silt. Limestone bedrock was encountered at depths of 6.2 to 11.6 m (El. 12.6 to 6.7 m) below the existing ground surface. Piezometric levels were measured at depths of 1.9 to 3.2 m (El. 15.9 to 14.2 m) below the existing ground surface.

Based on the subsurface information encountered in the boreholes, the existing sewers were founded in the dense to very dense glacial till of sand to sandy silt or bedrock.

3 Review of Design Approach for Buried Sewers

The traditional design methods for assessing the capacity of buried sewers are based on the Marston-Spangler theory developed in the 1910's (Spangler and Handy 1982). The buried conduit has been divided into two categories: (1) flexible and (2) rigid. Independent analysis and design approaches have been developed for each. When designing rigid pipes (i.e. concrete pipes), it is customary to assume that the pipe is affected mainly by a vertical pressure caused by soil and traffic; a horizontal reacting pressure is generally negligible. For flexible pipes, the vertical load causes a deflection of the pipe, which in turn results in a horizontal supporting soil pressure. The load on buried conduits consists of earth loads and live loads, both of which depend on the relative stiffness of the soil and conduit. Conduits can be classified as being constructed: (1) in-trench, (2) positive projecting, (3) negative projecting, (4) imperfect trench, and (5) in-tunnel.

It is likely that the existing concrete sewers would have been initially designed for a trench condition, which is relatively narrow ditch dug in undisturbed soil and then covered with compacted backfill to the ground surface. The load on the sewers is a function of the unit weight, height and width of the backfill, and the friction between the backfill and native soil, without consideration of soil cohesion. The load on the rigid pipe is less than the total weight of trench above the conduit due to the soil friction. Based on the calculated load on the pipe and determined bedding factor, the required pipe three-edge bearing strength was then selected for an appropriate factor of safety.

After construction of the roadway embankment, resulting in additional grade raise above the original, the negative projecting condition needs to be considered for the existing sewers. The load on the sewers will be higher than that for the trench condition. Obviously, the existing sewers were not designed for the additional load.

Although the traditional design methods have been the standard practice since the early 1900's, research and field monitoring have confirmed that such approaches are overly conservative due to assumptions associated with limited knowledge on soil-pipe interaction, especially the inability to account for the benefit of the lateral supporting characteristics of the embedment soils (Smeltzer and Daigle 2005). Research on soil-structure interaction with the application of the finite element (FEM) method over the past thirty years has led to the development of an enhanced design method (i.e. a direct design method) for rigid concrete pipe and its embedment systems. The direct design method determines the actual moments, thrust and shears in the buried pipe. Furthermore the direct design method based on the FEM analysis enables the evaluation of various installation conditions (time-history) as part of the design analysis. A standard installation design method was developed by the American Concrete Pipe Association (ACPA 1998) based on a large number of FEM model simulations and field studies of four standard installations. The American Society of Civil Engineers (ASCE) adopted a standard installation design method through ASCE 15-93 (ASCE/ANSI 1993). Canadian Standards Association (CSA) includes a standard installation design method for the design and installation of buried structures in the Canadian Highway Bridge Design Code (CSA S6-06 2006).

This project required the load on the existing sewers to be reviewed based on CSA S6-06 (2006). The earth load determined from the unit weight of overfill soil over the top of the sewer and its effect were determined by an analysis of soil-structure interaction based on the characteristics of the installation based on CSA S6-06 (2006).

For a circular concrete pipe, the total vertical earth load on a buried pipe ranges from 1.35 to 1.45 times the weight of the column of earth applied over the outside diameter of pipe; the total horizontal earth load on a buried pipe ranges from 0.3 to 0.45 times the weight of the column of earth over the outside diameter of pipe in standard installations with various bedding thickness and soils; and the earth pressure distribution on the pipe can be calculated based on the force diagram provided in CSA S6-06 (2006) for four standard installations.

Since the installation method for the existing sewers is not clear, it is not applicable to use the Marston-Spangler theory or the force diagram provided in CSA S6-06 (2006) to review the load condition of the existing sewers under the new embankment. Use of FEM analysis to simulate the time-history of construction is the best way to determine the loading conditions on the existing sewers under the new embankment as well as for the modelling of protection systems to mitigate impacts on the existing sewers.

4 Finite Element Analysis

A soil-structure interaction analysis using a two-dimensional FEM computer program (RS2, Version 9) was performed to evaluate the loads on the existing circular sewer and the horseshoe-shaped sewer.

4.1 Circular Sewer

The soil profiles selected for the analyses were based on the boreholes drilled near the sewer. The boundary elevations for each soil layer used in the analysis are provided in Table 1. The surface of bedrock was taken at El. 10.7 m. Bedrock is modelled as an incompressible material and thus is considered as the fixed boundary. The marl was assumed to be replaced by new fill during embankment construction. Note that the unit weight of new fill is much higher than that of marl. This assumption will give a higher loading on the sewer, which is a conservative approach. The soil surrounding the sewer is assumed to be backfill comprised of existing fill and the thickness of the existing fill is taken as 0.5 m. The new pavement on the top of the embankment consists of 290 mm asphalt concrete, 200 mm granular base of MG20, and 590 mm granular subbase of MG112. The groundwater level was taken at El. 15.8 m in the analysis.

Table 1. Unfactored soil, EPS Geofoam and concrete parameters

Material type (Elevation)	Unit weight γ (kN/m^3)	Friction angle (degree)	Young's modulus (MPa)	Poisson's ratio
New fill	18.2	32	50	0.3
New light weight sand fill	16.8	32	30	0.3
Granular fill (MG-20)	22.9	35	100	0.3
Granular fill (MG-112)	18.9	32	50	0.3
MSE fill	22.0	36	50	0.3
Existing fill	18.2	32	50	0.3
Marl (>El. 17.0 m)	12.1	–	6.9	0.3
Silt to silty sand (till) (El. 17.0 to 10.7 m)	20.9	36	100	0.3
EPS Geofoam	0.21	–	5	0.12
Concrete/Asphalt	24	–	29700	0.2
Water	9.81	–	<0.2	0.49

Since the existing circular, reinforced concrete sewer installed in 1990 was found to be in good condition on the basis of visual inspection and intrusive testing, consideration was given to reduce the weight of the new embankment using relatively light weight sand fill above the existing sewer with the secondary intention of inducing the arching effect. The objective, of course is to limit the load on the sewer so as not exceed its structural capacity for axial force, bending moment and shear force. Consideration is also given to use compressible material (i.e. EPS geofoam) to achieve this same effect. Since the EPS geofoam will compresses more than the surrounding fill, the load on the sewer will be less than the calculated overburden pressure due to the side friction, resulting in a positive arching above the sewer. This is called the induced trench method (also called an imperfect ditch). Field measurements conducted by Vaslestad et al. (2011) confirmed the positive arching effect on buried rigid culverts using the EPS geofoam.

The unfactored soil parameters and elevations of the soil layers used in the analysis are listed Table 1, including unit weight (γ), Young's modulus (E), Poisson's ratio (μ), and angle of internal friction (ϕ). Young's modulus for cohesionless soils was estimated from the available pressuremeter data. The coefficient of earth pressure at rest, K_o is taken as 0.5. The cohesion (undrained shear strength) of the marl is taken as 40 kPa. The apparent cohesion of the EPS geofoam is taken as 68 kPa. The cohesion for other soils is taken as 0.1 kPa. The assumed E for the EPS geofoam is taken as recommended for EPS100 by the Transportation Research Board (2004) and the Poisson's ratio for the EPS geofoam is as recommended by the EPS Industry Alliance (2012). It is noted that the analysis result is not significantly affected by Young's modulus of EPS geofoam. The assumed Young's modulus for the soils is based on CSA S6.1-14 (2014).

The vertical earth pressure (VEP) is calculated from the unit weight of soils, γ and the lateral earth pressure (LEP) is calculated from K_o. Thus the load factor is related to γ and K_o in the finite element analysis. At the serviceability limit states (SLS), the load factor for γ is taken as 1.0 for γ and K_o. At the ultimate limit states (ULS), the load factor for γ is taken as 1.0 or 1.375 and the load factor for the LEP is taken as 0.8 or 1.0 for different cases based on CSA S6-06 (2006). As the LEP is calculated from the VEL and K_o, the value of K_o is taken as 0.29 or 0.5 as summarized in Table 2.

Table 2 Ranges of load factor and coefficient of earth pressure at rest

Load combination (LC)	α_D	α_E	α_L	α_W	α_{LE}	K_o
LC1 for SLS	1.0	1.0	0.9	1.0	1.0	0.5
LC1 for ULS	1.1	1.375	1.87	1.1	0.8	0.29
LC2 for ULS	1.0	1.0	1.0	1.0	1.0	0.5

The analysed circular sewer at this section is a reinforced concrete pipe with inside diameter of 3.6 m and wall thickness of 349 mm. The sewer was modelled as beam elements. The dead load (DL) of the sewer is calculated from γ, taken as 24 kN/m^3 and its Young's modulus is taken as 29730 MPa. The moment of inertia for the sewer is taken as 0.00354 m^4 at the SLS and as 0.0025 m^4 in the ULS. The load factor for concrete γ is taken as 1.0 or 1.1 based on CSA S6-06 (2006).

The sewer was assumed as being full of fluid with the properties of water. The unit weight of water is taken as 9.81 kN/m^3 and its Young's modulus is taken as a value of less than 200 kPa to make the vertical and horizontal water pressure (WP) on the sewer wall equivalent to the hydrostatic pressure.

The traffic live load (LL) is taken as 17.6 kPa. The load factor for the LL is taken as 0.9 at the SLS and 1.87 at the ULS.

The soils were modeled as Mohr-Coulomb elastoplastic materials and the concrete and steel were modeled as elastic materials.

The load combination (LC) used in the analysis is as follows

$$LC = \alpha_D DL + \alpha_E VEP + \alpha_L LL + \alpha_W WP + \alpha_{LE} LEP \tag{1}$$

where α_D is the load factor for the dead load of sewer; α_E is the load factor for vertical earth pressure; α_L is the load factor for traffic live load; α_W is the load factor for water pressure within the sewer; and α_{LE} is the load factor for lateral earth pressure. The values of the load factor are listed in Table 2. Two load combinations at the ULS and one load combination at the SLS have be analyzed. The other load combinations do not govern and thus were not checked.

The construction sequence was simulated in the FEM static analysis as follows:

Stage 1 Initial ground condition with the sewer and existing retaining wall;
Stage 2 Installation of the EPS geofoam or placement of the light weight fill;
Stage 3 Construction of embankment; and
Stage 4 Adding LL surcharge.

Figure 2 shows the partial FEM mesh after construction of the embankment with a 4.7 m wide and 1 m high zone of the EPS geofoam above the existing sewer for the SLS load case at a section of up to 9 m high embankment. The finite element mesh was 92 m long and 16.3 m high. The bottom boundary was restrained from both vertical and horizontal movements. The left-hand and right-hand boundaries were free to move in the vertical direction.

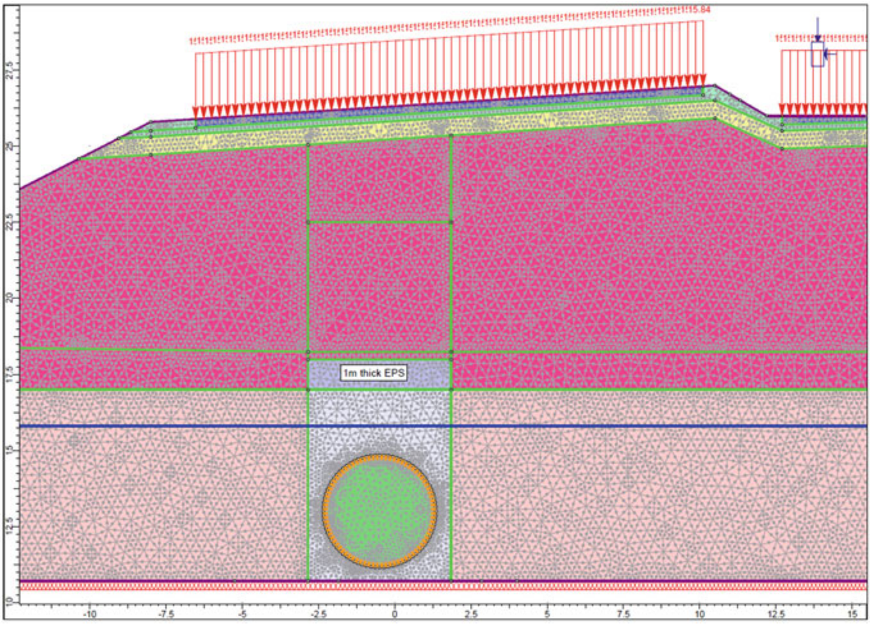

Fig. 2. FEM mesh after embankment construction with EPS geofoam

Typical computer output, such as total vertical stress and bending moment for the existing sewer after the embankment construction with 1 m thick EPS geofoam (Stage 4) for the SLS load case, is shown in Fig. 3. It clearly shows that the total vertical stress on the top of the sewer is significantly reduced to only about 60% of the total vertical overburden pressure due to the positive arching effect. This result is consistent with the field measurements by Vaslestad et al. (2011). This phenomenon could not be modelled by the traditional Marston-Spangler theory.

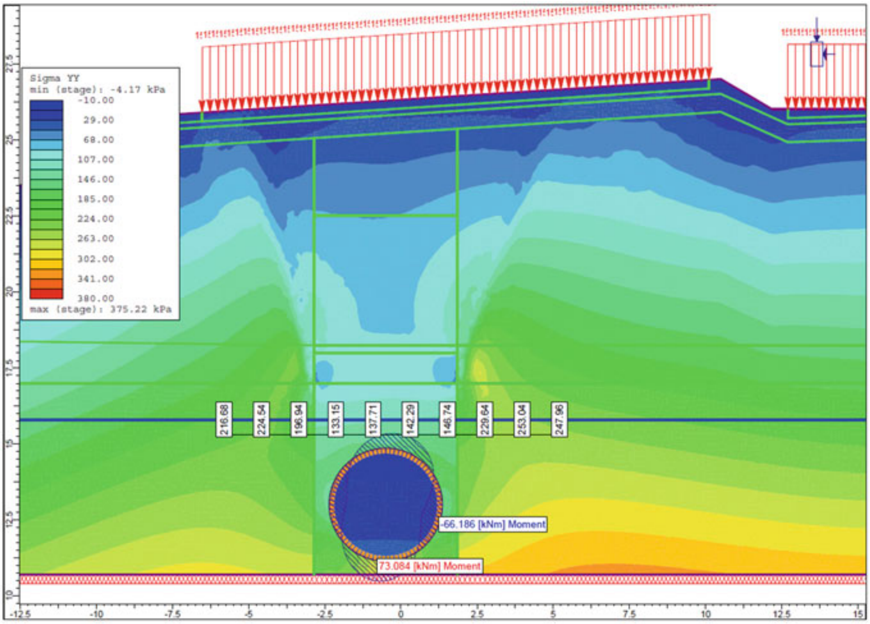

Fig. 3. Vertical stress in soil and bending moment for existing sewer after embankment construction with EPS geofoam

Figures 4, 5 and 6 compare the axial force, bending moment and shear force for the existing sewer after the embankment construction, respectively for three different options: (1) conventional fill; (2) light weight sand fill in a zone of 4.7 m width by 5.5 m height above the sewer; (3) EPS geofoam in a zone of 4.7 m width by 1 m height above the sewer. The axial force, bending moment and shear force for the existing sewer at the existing condition are also shown in these figures. It is found that the axial force, bending moment and shear force for the existing sewer after the embankment construction increase due to the new embankment construction. Comparing to the conventional fill option, both the light weight fill and EPS geofoam options can reduce the additional axial force, bending moment and shear force mainly due to the the positive arching effect. Since the value of Young's Modulus for the EPS geofoam is much smaller than that of the light weight sand fill, the reduction in the axial force, bending moment and shear force using 1 m thick EPS geofoam is more significant than that achieved using the 5.5 m thick light weight sand fill. It is noted that separate stages for the installation of the EPS geofoam (or the light weight sand fill) following embankment construction must be used in the FEM analysis to simulate the positive arching effect. If the EPS geofoam or light weight sand fill following embankment construction are modelled in one single stage, the positive arching effect is insignificant. The variation of soil parameters was also considered in the analysis. It is found that the influence in the variation of the soil parameters to the analysis results is insignificant as the variation in the load factors is bigger than that of the soil parameters themselves.

Based on the results of FEM analysis for various loading cases, it is found that the existing sewer can accommodate the loads induced by the new embankment with a

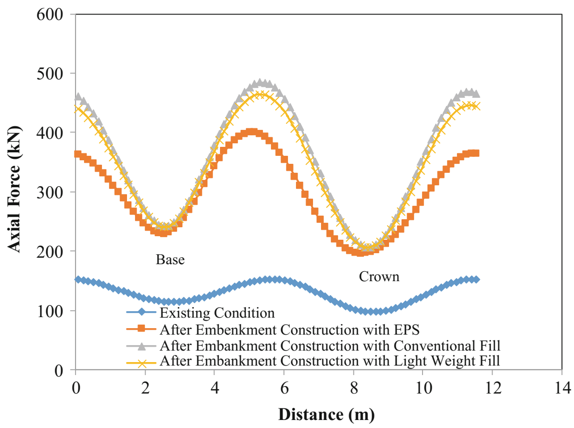

Fig. 4. Comparison of axial force for existing sewer after embankment construction with existing condition for mitigation options

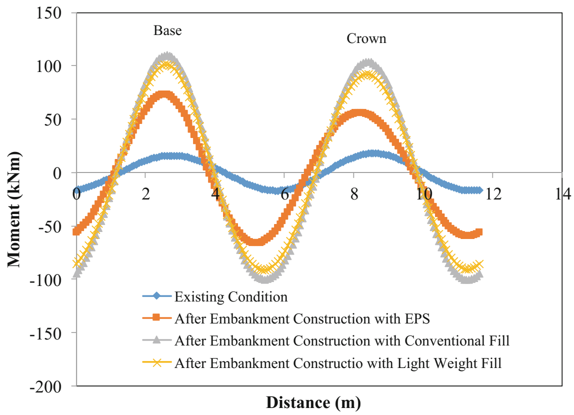

Fig. 5. Comparison of bending moment for existing sewer after embankment construction versus existing condition for different mitigation options

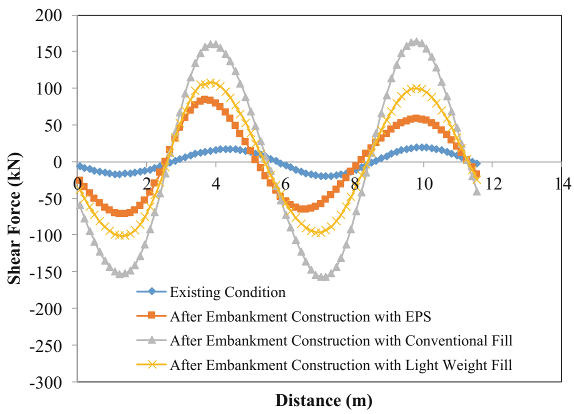

Fig. 6. Comparison of shear force for existing sewer after embankment construction versus existing condition for different mitigation options

zone of light weight sand fill. Thus the light weight sand fill option, which is more economical than the EPS option, is adopted for the new embankment construction over the existing circular sewer.

4.2 Horseshoe-Shape Sewer

The horseshoe-shaped concrete sewer was constructed in 1963. Based on visual condition surveys and core drill findings it was considered that this ageing sewer could not sustain any additional load. Thus two options were proposed: (1) a protection system ("relieving platform") consisting of a concrete slab supported by concrete piles to relieve the additional loading on the existing sewer; and (2) using ultra-light-weight fill (i.e. EPS geofoam) to construct the new embankment.

The soil profiles and parameters used in the analysis are the same as those used for the circular sewer.

The equivalent inside diameter of this sewer is 2.7 m. The thickness of sewer wall varies from 203 mm at the top, 305 mm at the base to 381 mm at the sides. The average thickness and moment of inertia for the sewer were used in the analysis. The moment of inertia at the ULS was taken as 40% of that at the SLS. Young's modulus for the sewer was taken as 20,000 MPa based on the testing of core samples taken from the sewer.

The load cases conducted in the FEM analysis are the same as those for the circular sewer, except that the sewer was assumed to have a dry interior (without water), which is a more critical case.

Figure 7 shows the partial FEM mesh with a relieving platform consisting of a 10.5 m wide by 0.8 m thick concrete slab supported by 406 mm diameter piles at a spacing of 3 m center to center for a new embankment height of 7.5 m for the SLS load case. A gap of 200 mm was placed beneath the concrete slab and the underlying soil to ensure that the embankment load would be taken up by the pile foundation. Even through the width of the relieving platform is about 3 times the sewer width, it could not totally relieve the additional lateral earth pressure on the sewer. With the relieving platform installed 1 m below the existing ground surface, there is a net reduction in the vertical load on the existing sewer and the resulting maximum axial force, bending moment and shear force are not greater than those in the existing condition. Figure 8 shows the typical computer output of total vertical stress and axial force in the existing sewer for the SLS case. It clearly shows that there is no increment in the total vertical stress surrounding the existing sewer.

Figure 9 shows the bending moment for the existing sewer prior to and after a 7.5 m high new embankment construction with the protection system for the SLS load

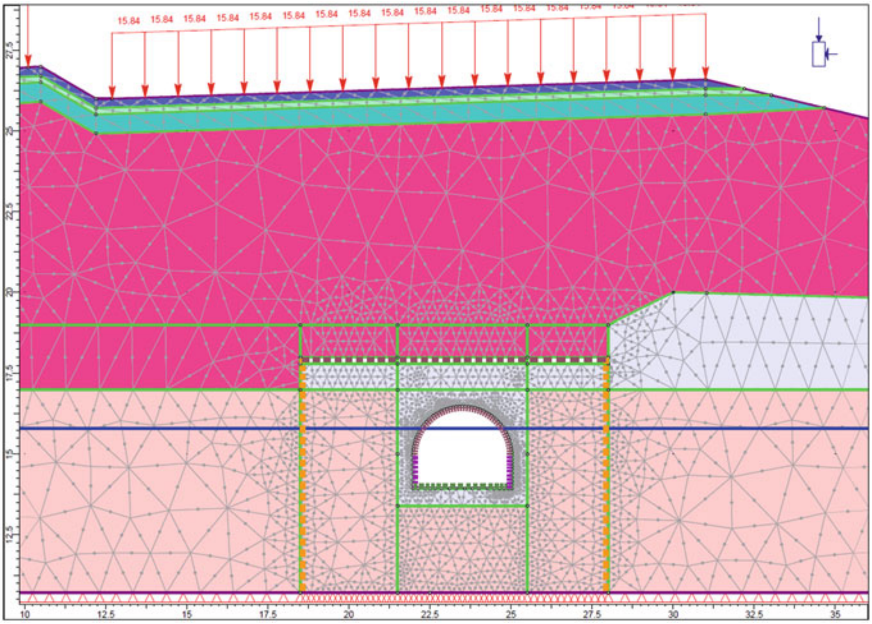

Fig. 7. FEM mesh after embankment construction with a protection system

case. It is found that the maximum bending moment after the embankment construction is not more than that in the existing condition although its distributions are not the same due to slight increase in the horizontal stress and slight decrease in the vertical stress. Similar trends are also found for the axial and shear forces in the existing sewer. The bending moments for the existing sewer after the embankment construction with the EPS option are also shown in Fig. 9 for comparison. Although the EPS geofoam thickness is the same as that of the new embankment and the width of EPS geofoam is 3 times the sewer width, there is an increment of bending moment for the sewer base for a 7.5 m high new embankment as the EPS option could not fully eliminate the increase of the lateral load near the sewer base.

Figure 10 shows the bending moment for the existing sewer prior to and after the embankment construction with the protection system and EPS geofoam for a 3 m high

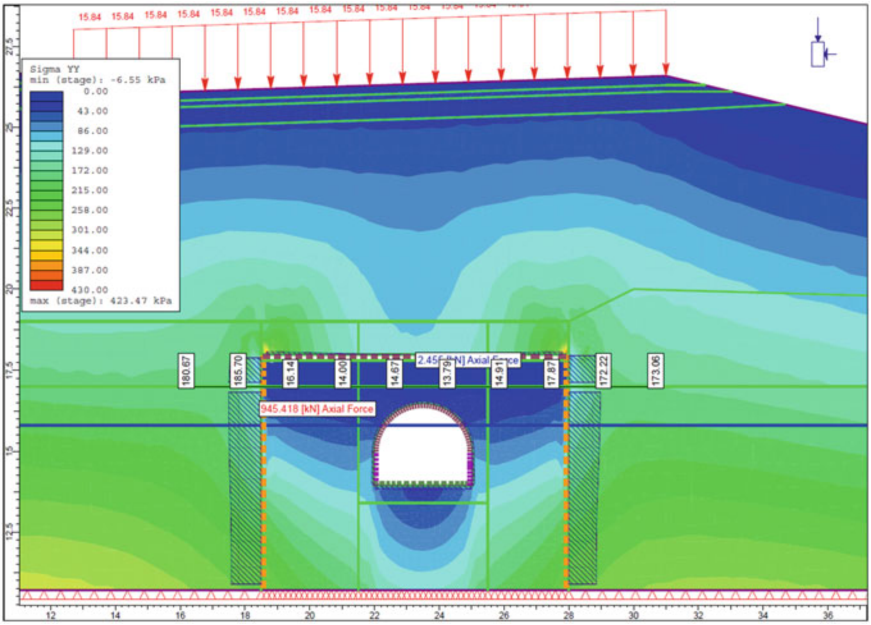

Fig. 8. Vertical stress in soil and axial force in structures after embankment construction with a protection system

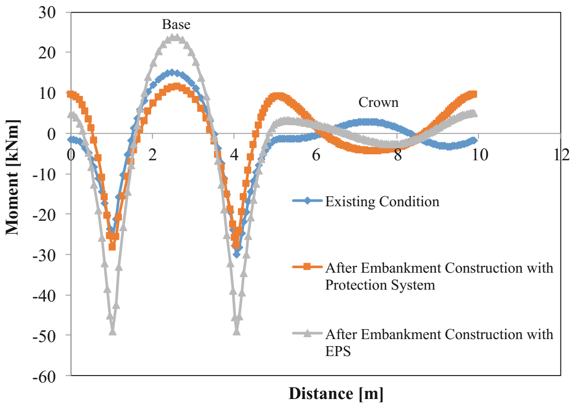

Fig. 9. Comparison of bending moment for existing sewer prior to and after embankment construction with a protection system and EPS geofoam for a 7.5 m high embankment

new embankment for the SLS load case. Similar to the 7.5 m high embankment, the maximum bending moment after the embankment construction with the protection system is not more than that in the existing condition. For the new embankment construction with the EPS geofoam, there is no increment in the bending moment for the sewer base as shown in Fig. 10. The slight decrease in the bending moment for the sewer crown is due to the positive arching effect as the modulus of the EPS geofoam is less than that of soil. There is also no increment in the axial and shear force, indicating that the embankment constructed using the EPS geofoam can successfully eliminate additional loads on the existing sewer for the 3 m high new embankment.

Based on a series of analyses, it is found that for a higher new embankment with a height greater than 3 m, the EPS option could not fully eliminate the additional horizontal load at the sewer base. Thus a more expensive approach using a concrete slab supported by concrete piles is recommended to relief the additional loading on the existing sewer. For a lower new embankment with a height not more than 3 m, the EPS option, which will not increase the bending moment, shear and axial forces for the existing sewer and is more economical than the concrete slab protection system, is recommend.

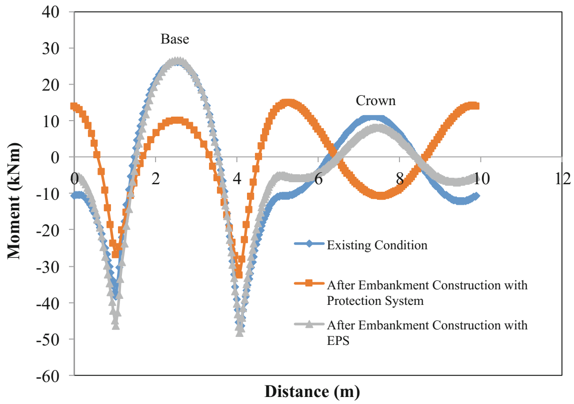

Fig. 10. Comparison of bending moment for existing sewer prior to and after embankment construction with a protection system and EPS geofoam for a 3 m high embankment

5 Conclusions

The additional load on the existing sewers due to new embankment construction can be successfully reduced or eliminated using mitigation methods such as light-weight sand fill, EPS geofoam, or protection systems consisting of a concrete slab supported by concrete piles. Traditional design methods for buried culverts and rigid pipes cannot be used to estimate the loading condition of the existing sewers under the effects of the new embankment due to their lack of ability to account for soil-structure interaction. The widespread use of the finite element method in geotechnical applications makes it possible to directly analyze the interaction of the buried culverts and soil under various mitigation scenarios.

It is found that the light-weight sand fill is most economic material to reduce the additional loads on the sewer, the EPS geofoam is most suitable material to eliminate incremental loads on the sewer for a lower embankment, and the structural protection system is only option to eliminate incremental loads on the sewer for a higher embankment.

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