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Culverts with TDA Inclusions on Yielding and Non-Yielding Foundations

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Abstract: In recent years, studies have sought to analyse the physical and mechanical properties of scrap tires for use as a construction material. The results of these studies reveal that tire derived aggregate (TDA) has favourable properties for civil engineering applications. Among these favourable properties are the light weight, low stiffness, high permeability and low thermal conductivity of TDA. The current uses of TDA in civil engineering applications include: lightweight fill in highway embankment construction and bridge abutment backfill and thermal insulation to limit frost penetration beneath roads and drainage layers in landfills.

This study investigates the behaviour of a deeply buried culvert with and without TDA inclusion considering non-yielding and yielding foundation conditions using numerical analyses method. The data presented in this study show significant advantages of using TDA inclusion on top of deeply buried structures. The results indicate that the inclusion of TDA above a buried structure results in significant reductions in the stresses exerted on the structure, especially on a non-yielding foundation.

1 Introduction

Large stresses are exerted on deeply buried structures, which are resisted by the structure and surrounding material. The applied stresses are distributed within the fill material and then transferred to the structure, where they are resisted by the intrinsic strength of the structural elements. The stresses are then transferred to the founding stratum (Spangler and Handy, 1973). If the founding stratum is non-yielding (i.e. bedrock), the vertical stress on the buried structure can exceed the overburden pressure (Sun et al., 2009). Where conduits, such as structural culverts, are needed under high backfills the Ministry of Transportation Ontario (MTO) typically uses rigid structures, especially when non-yielding foundations are present.

For conventional backfill methods, the settlement of the embankment fill immediately above the culvert is less than the settlement of the adjacent fill. This causes a downward shearing force to act on the structure, which increases the stresses it must resist. This mechanism of interaction between the fill and the culvert is well known and referred to as negative arching (Vaslestad et al. 1993). The reverse situation, positive arching, creates the opposite effect, which is the reduction of the stresses on the culvert. This effect can be achieved through a construction method called the induced trench/imperfect ditch method.

The induced trench/imperfect ditch method (Handy and Spangler, 1973), dictates that a buried structure is to be backfilled, and well compacted, to a certain height above the structure. At this height, a trench of backfill, of width equal to that of the structure, is to be removed and refilled with lightweight material.

Traditionally, this lightweight material has been baled hay or leaves. However, the MTO has recently used TDA as a light weight embankment fill, due to the fact that it is an eco-friendly alternative to other light weight fills. TDA is made from shredded tires; since the province of Ontario generates approximately 12 million scrap tires per year, the material is abundantly available. TDA is already used for numerous purposes within civil engineering, where its material properties, light weight, low stiffness, high permeability and low thermal conductivity, are advantageous.

2 Background

2.1 Marston-Spangler

The Canadian Highway Bridge Design Code (CHBDC, 2006) is silent on the induced trench method (ITM). However, there are analytical methods used for the design of induced trench applications. A design procedure for ITM was initially developed by Marston (1922) and improved by Spangler (1950a; 1950b). This design method quantifies the load on conduits installed by ITM as follows:

[1]
$$W = \mathrm{C_n}.\gamma.\mathrm{B_c}^2$$

where C_n is the load coefficient, γ is the unit weight of fill material and B_c is the out-to-out horizontal span of the conduit. Although graphic illustrations are provided for the computation of coefficient, C_n, there are many practical difficulties, as the parameters used to determine the coefficient cannot be evaluated readily. These parameters include the settlement ratio and the height of the plane of equal settlement to be determined by a graphical method as summarized in Kang (2007). In order to use the Marston-Spangler equation, it is essential to determine the value of the settlement ratio, r_{sd}, which is defined as follows:

[2]
$$r_{\mathrm{sd}} = \frac{\mathrm{s_g} - (s_d + s_f + d_c)}{s_d}$$

where s_g is the settlement of the surface of compacted soil, s_d is the compression of fill in the ditch within the height of the place, s_f is the settlement of flow line of pile, d_c is deflection of conduit, (i.e. shortening of its vertical dimension), and (s_d+ s_f + d_c) is settlement of the critical plane. Although the settlement ratio, r_{sd}, is a rational quantity used in the development of the load formula, it is very difficult to determine the actual value that will be developed in a specific case. However, Spangler and Handy (1982) presented some recommended values of the settlement ratio for various culvert types and foundation deformation characteristics based on field observations on actual culverts under embankments. The load coefficient, C_n, values may be determined graphically using the settlement ratio, r_{sd}, in association with the projection ratio, ρ', defined as the depth to width ratio of the ditch.

2.2 Vaslestad Method

The details of this method are outlined in Vaslestad et al. (1993). In this method, the earth loads acting on the buried culverts are calculated by applying an arching factor to the overburden pressure. This arching factor is based on the friction number, S_v. Vaslestad's equation for estimating vertical earth pressures on an induced trench culvert is given as follows;

[3]
$$\sigma_{\mathrm{v}} = N_A.\gamma.\mathrm{H}$$

[4] $$N_A = \frac{1 - e^{-2S_v \frac{H}{B}}}{2.S_v.\frac{H}{B}}$$

where N_A is the arching factor, S_v is Janbu's friction number, B is the width of the culvert, and H is the height of fill above the culvert

3 Methodology

3.1 Analytical Models

This paper comprises the study of soil-structure-interaction for an open-footing rigid culvert with a TDA inclusion on top. The culvert, supported on 1m wide footings, is 3m high, 5m wide. The thickness of the culvert walls are considered to be 0.3m. The height of the backfill is 7m, from the crown of the culvert. Both non-yielding and yielding foundation conditions were considered in the analyses. For both foundation conditions, various arrangements of TDA inclusion were considered within the embankment fill and the results were compared to the base case, where TDA inclusion was not considered. Table 1 summarises the material properties assumed in this parametric study.

Table 1. Material Properties

Material	Unit Weight (kN/m3)	Stiffness (MPa)	Poisson's Ratio	Friction Angle (degrees)
TDA	8	5	0.37	35
Earth Fill	20	80	0.30	35
Concrete	25	14,000	0.20	38
Bedrock	27	20,000	0.30	35
Yielding Soil	20	10 - 200	0.35	20

3.2 Finite Element Analysis

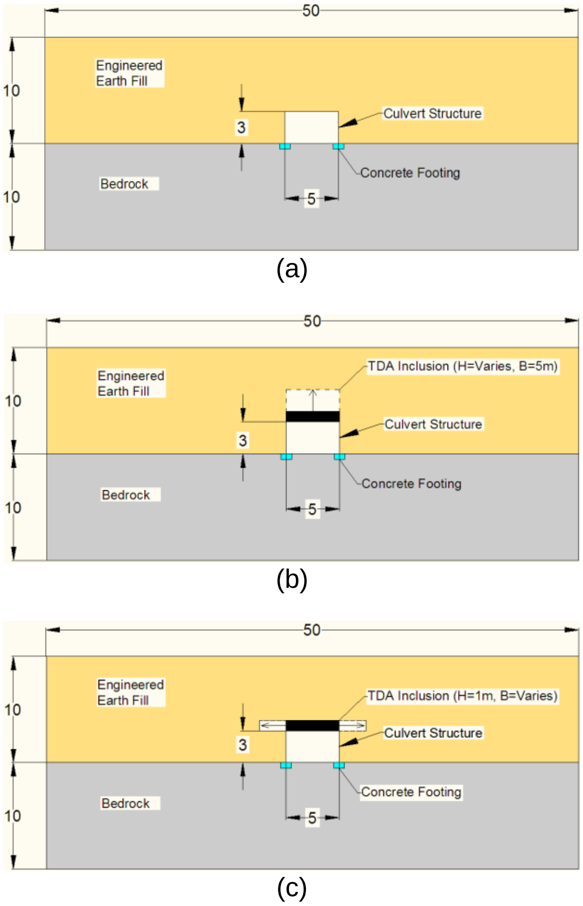
Phase 2 is a two-dimensional finite element analysis program. For this study, two streams of analyses were performed, considering non-yielding and yielding foundation conditions. The first group of models analysed the stresses, due to overburden pressure, acting on a deeply buried open footing concrete box culvert founded on bedrock with an assumed elastic modulus of 20,000 MPa. This property prohibits significant deformation within the foundation stratum. Various configurations of TDA inclusions were studied and results were compared to the analyses cases where no TDA inclusion was considered. For the second group of analyses, yielding foundation soils were considered. It was assumed that the embankment loads result in compression of the foundation stratum. Since the finite element program used in the analyses is not capable of modelling the transient consolidation process, a simplified approach was adopted, where stiffness of the foundation stratum was adjusted such that certain levels of target settlements can be achieved under applied loads. The stiffness of the foundation stratum was incrementally decreased from 200 MPa down to 10 MPa and the response of the culvert-TDA inclusion-embankment fill system was studied.

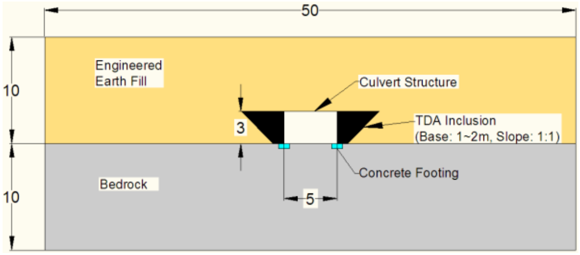
The matrix soil and bedrock were modeled using quadratic solid elements with 3 degrees of freedom per node. The vertical boundaries were extended 25m from the centre of the culvert in each direction, and the lateral boundaries were 10m above and below the level of culvert footings. All degrees of freedoms were restrained at the bottom of the model. The lateral translational degree of freedom of the model boundaries were restrained; while the vertical translational and rotational degrees of freedom were set free.

Verification of the results obtained from numerical analyses of the base model, where no TDA inclusion were considered, was performed in accordance with the simplified design methodology outlined in the CHBDC (2006).

3.3 Analysis Cases

A number of cases were studied in order to determine the arrangement of TDA inclusion that reduced the stresses on the culvert most effectively. These are summarised in Table 2 and depicted in Figure 1. The base case includes the culvert backfilled with conventional fill only (i.e. no TDA inclusion). For Case 1, various arrangements of TDA inclusion were studied in order to determine the effect of increasing the depth of TDA inclusion on top of the structure. This was achieved through increasing the TDA inclusion depth while maintaining a constant TDA width, equal to the culvert's width. In Case 2, the effect of TDA inclusion width was studied by increasing the TDA width on top of the structure, while maintaining a constant TDA inclusion depth of 1m. For both cases, no TDA side fill was considered. For Case 3, the effect of TDA inclusion as side fill was studied by increasing the TDA side fill width while maintaining a constant TDA inclusion depth and width on top of the structure as 1 m and 1x culvert width, respectively. The TDA side fill was measured in metres, horizontally from the base of the culvert. For the 1m side fill arrangement the TDA increases in width, from 1m at the base, at a 45° angle, to the top of the 3m high culvert where it is 4m wide. For the TDA on top of the culvert, the width is expressed as its ratio to the culvert width. The TDA depth is the height of this TDA layer above the culvert.





(d)

Figure 1: Schematics of Problem Geometry (a) Base case, (b) Case 1, (c) Case 2, (d) Case 3.

Table 2: Analysis Cases

Case #	**TDA Side Fill Width at the Base (m)**	**TDA Inclusion Width (X Culvert Width)**	**TDA Inclusion Depth (m)**
Base	N/A	N/A	N/A
Case 1: Increasing TDA Depth			
1A	N/A	1x	1m
1B	N/A	1x	2m
1C	N/A	1x	3m
Case 2: Increasing TDA Width			
2A	N/A	1x	1m
2B	N/A	1.25x	1m
2C	N/A	1.5x	1m
Case 3: Increasing TDA Side Fill Width			
3A	N/A	1x	1m
3B	1m	1x	1m
3C	2m	1x	1m

A reduction ratio is referenced several times within this study. The reduction ratio is the ratio of the maximum section forces or moments at the culvert calculated for the base case to those calculated for various TDA inclusion cases. The higher the reduction ratio is, the more effective the stress reduction by the TDA inclusion is. The reduction ratios were calculated for axial force, shear force and bending moment. The maximum axial force, shear force and bending moment values were the maximum values observed anywhere on the culvert. Thus, the maximum values of axial force, shear force and moment might be at different points along the culvert. The first 10 stages of the analyses assumed a high stiffness, non-yielding foundation conditions and simulated the construction sequence of the culvert and backfilling. After stage 10, the stiffness of the foundation material was lowered in small increments, which allowed the foundation soil to deform under applied embankment loads. This approach was not a physically correct representation of the actual consolidation mechanism. However, since the focus was to study the impact of foundation deformations on the reduction ratios gained by the use of TDA inclusion, this approach was considered to be acceptable. Five additional steps were utilised to simulate various levels of foundation deformation, which approximated a yielding foundation case.

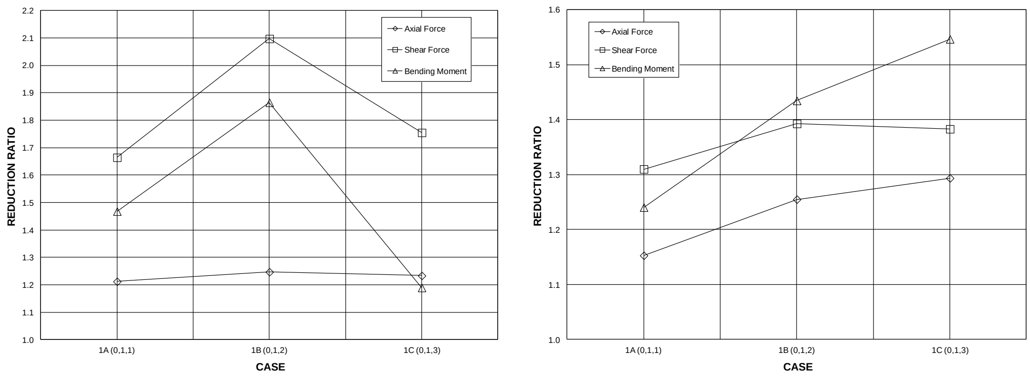
4 Results and Discussions

4.1 Case 1 – Effect of TDA Depth

Case 1 analyses the effect of TDA inclusion depth on the reduction ratio. This was achieved through increasing the TDA inclusion depth, while maintaining a constant TDA inclusion width, equal to the culvert's width. TDA side fill was not used in this case. Figure 2 depicts the variation of reduction ratios calculated for section forces and moments with the depth of TDA inclusion for non-yielding and yielding foundation cases, respectively. The reduction ratios shown in Figure 2a indicate that the reduction of axial forces by the TDA inclusion is minor. The largest reduction ratio for axial forces was calculated as 1.25. The reduction ratio was calculated as 1.85 and 2.1 for bending moments and shear forces, respectively. Case 1B, where the TDA inclusion depth on top the culvert is 2m, is the best case for axial force (25% reduction), shear force (110% reduction) and bending moment (85% reduction).

The reduction ratios shown in Figure 2b indicate that increasing TDA inclusion depth resulted in an increase in the reduction ratios for axial force, shear force and bending moment for the yielding foundation case, at the serviceability limit of 25mm. The maximum reduction ratio obtained for axial force was 1.28 (28% reduction), which was comparable to the reduction ratio calculated for the non-yielding foundation case (25%). However, the reduction ratios for shear force and bending moment were calculated as 1.44 (44% reduction) and 1.39 (39% reduction), respectively, for the TDA inclusion of 2m. The results also show that these ratios increase with thicker TDA inclusions in yielding foundation cases.

The results show that the determination of optimum depth of TDA inclusion depends on the foundation deformations. However, it was seen that larger reduction ratios were obtained for non-yielding foundations at the same depth of TDA inclusion.



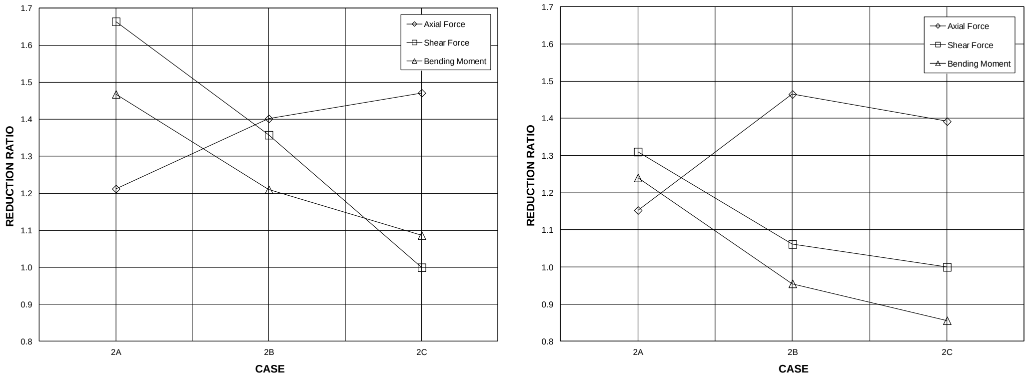
(a) (b)

Figure 2: Reduction Ratio Variation with Increasing TDA Depth a) Non-yielding b) Yielding Foundation

4.2. Case 2 - Effect of TDA Width

The effect of TDA width on the section forces and moments was studied by increasing the width of TDA inclusion, while maintaining a constant TDA depth of 1m. No TDA side fill was considered. Figure 3 depicts the variation of reduction ratios with the width of TDA inclusion for both non-yielding and yielding foundation conditions. The reduction ratios shown in Figure 3a indicate that the reduction ratios for axial forces increased with increasing TDA inclusion width for non-yielding foundations. However, when increasing TDA inclusion width the reduction ratios for shear forces and bending moments were observed to reduce. The results shown in Figure 3b indicate that a similar trend was present for yielding foundation conditions. The results showed that the maximum reduction ratios for shear forces and bending moments were observed in Case 2A, which includes a TDA inclusion with width equal to the width of the culvert.

However, the reduction ratios for axial forces showed an inverse trend, where they increased with increasing width of TDA inclusion.



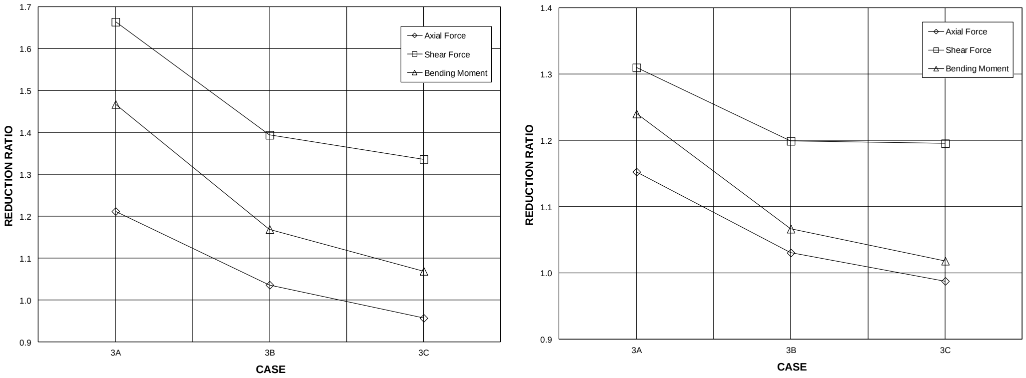
(a) (b)

Figure 3: Reduction Ratio Variation with Increasing TDA Width a) Non-yielding b) Yielding Foundation

4.3. Case 3 - Effect of TDA Fill as Side Fill

The effect of TDA side fill on the section forces and moments was studied by increasing the width of TDA side fill, while maintaining a constant TDA depth of 1m and width of 1x culvert width. Then, various TDA side fill arrangements shown in Figure 1 were studied. Figure 4 depicts the variation of reduction ratios with the various TDA side fill arrangements for both non-yielding and yielding foundation conditions.

Figure 4a (non-yielding foundation) and 4b (yielding foundation) indicate that the reduction ratios for all section forces and moments decreased with the introduction of TDA side fill. The increase in the width of the TDA side fill led to a further decrease on the reduction ratio.

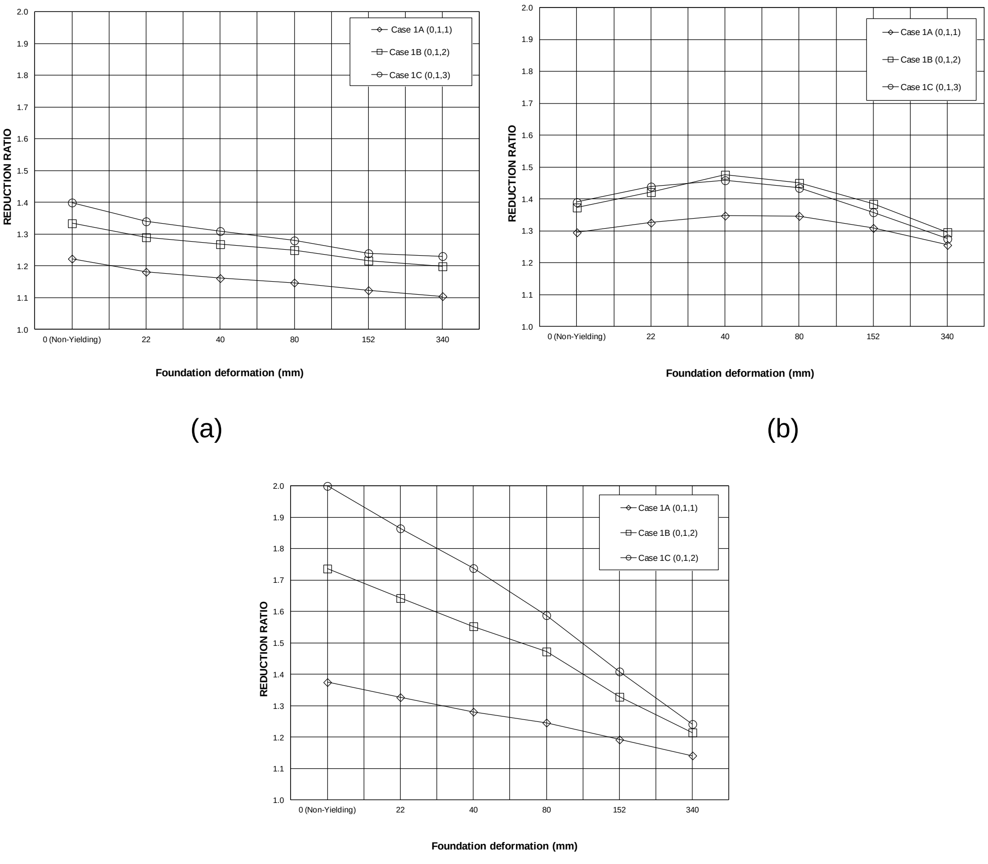


(a) (b)

Figure 4: Reduction Ratio Variation with TDA Side Fill a) Non-yielding b) Yielding Foundation

4.4. The Effect of Ground Deformations on Reduction Ratios

The effect of ground deformations caused by the embankment loads on the stress reduction ratios was evaluated. The three sub-categories of Case 1 (1A, 1B and 1C) were selected for evaluation and the results are depicted in Figure 5. Figure 5a, 5b and 5c depict the variation of reduction ratios for maximum axial force, shear force and bending moment, respectively, considering both non-yielding and yielding foundation cases. Results show that increasing foundation deformations decreases the reduction ratios for all three cases (1A, 1B and 1C) for axial force, shear force and bending moments. For example the reduction ratio for Case 1A decreases from 1.4 to 1.23, when the total deformation is 340mm. The reduction ratio for shear forces decreased from 1.44 to 1.28, for Case 1A, for a ground deformation of 340mm. The largest decrease in reduction ratio was observed in bending moments. For a ground deformation of 340 mm, the reduction ratio decreased from 2 to 1.24.



(a)

(b)

(c)

Figure 5: Reduction Ratio Variation with Ground Deformation a) Axial Force b) Shear Force c) Bending Moment

5 Conclusions

The analysis of the effect of TDA inclusion on the forces and moments in a deeply buried culvert was studied numerically for yielding and non-yielding foundations. The data presented in this study show significant advantages of using TDA inclusion on top of deeply buried structures. The following are the conclusions arising from this study;

- Case 1 analyzed the effect of the depth of TDA inclusion on the section forces and moments. The results showed that the determination of optimum thickness of TDA inclusion depends on the foundation deformations. However, it was seen that larger reduction ratios were obtained for non-yielding foundations for the same depth of TDA inclusion.

- Case 2 analyzed the effect of the width of TDA inclusion on the section forces and moments. The results show that the maximum reduction ratios, for both foundation types, for shear forces and bending moments were observed in Case 2A, which includes a TDA inclusion of width equal to the width of the culvert. However, the reduction ratios for axial forces showed an inverse trend, where they increased with increasing width of TDA inclusion. As in Case 1, it was seen that larger reduction ratios were obtained for non-yielding foundations at the same width of TDA inclusion.

- Case 3 analyzed the effect of TDA side fill on the section forces and moments. The results indicate that the reduction ratios for all section forces and moments were decreased with the introduction of TDA side fill. The increase in the width of the TDA side fill led to a further decrease in reduction ratios.

- The effect of ground deformations caused by the embankment loads on the stress reduction ratios was also evaluated. The results show that increasing foundation deformations lead to decreased reduction ratios for axial force, shear force and bending moments. Thus, the efficiency of TDA inclusion in reduction of stresses should be evaluated in conjunction with estimated long term foundation deformations. Otherwise, time dependant foundation deformations may result in increased stresses during the period of foundation settlements.

It was concluded that with the proper configuration, TDA inclusions can result in a significant reduction in the stresses acting on a culvert. However, a careful interpretation of the foundation deformations is necessary since the magnitude of the reduction is a function of foundation deformations. Thus, the yielding or non-yielding material behaviour of the foundation soil is an important consideration.

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