Using expanded polystyrene geofoam and tire-derived aggregate in different forms to reduce vertical earth pressure on high-filled cut-and-cover tunnels

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Abstract: Using the high-filled cut-and-cover tunnels (HFCCTs) provides a typical solution for the possibility of using valuable lands with plateau terrain. Because of the high quantities of backfill soil above the HFCCT, at present, the existing estimating methods of the vertical earth pressure (VEP) may not suit the HFCCTs construction. The ability to estimate the load or pressure on the HFCCTs is essential. As a principle, the soil column pressure equation can be used to estimate VEP on the HFCCTs. This study presents a numerical investigation of the effect of using expanded polystyrene (EPS) and tire-derived aggregate (TDA) in different forms on the relative vertical displacements and VEP reduction on the HFCCTs. The results showed a significant VEP reduction on the HFCCTs, especially with the use of TDA in different forms. Also, a comparison is made between the calculated and estimated VEP values on the top of the HFCCT study model with the base conditions using the soil column pressure equation, Li et al. (2019) modified equation, and Abaqus CAE 2019 software. The calculated and estimated VEP values on the top of the HFCCT study model with the base conditions showed that the calculated value using Li et al.'s (2019) modified equation is 27.942% lower than the calculated value using the soil column pressure equation, which is a high percentage of difference. While the estimated value using Abaqus CAE 2019 is 0.156% higher than the calculated value using the soil column pressure equation, which is a low percentage of difference.

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1. Introduction
The high-filled cut-and-cover tunnels (HFCCTs) provide a specific solution for the possibility of using valuable lands with mountainous or hills terrain around the world. The primary property of the various HFCCTs is their high or extra-high backfill soil. However, the huge or very high earth pressure developed or induced on the top or side of the cut-and-cover tunnel (CCT) can cause structural problems and safety concerns. Researches and studies concerning the load reduction effect in the backfill soil above culverts and pipes have been conducted since the early years of the 20th century; but, a limited number of researches focused on and studied HFCCTs-related issues, especially what is related to load and load reduction on the HFCCTs.

Marston pioneered or initiated the concept of “induced trench installation” for rigid pipes buried under high embankment fill. Loads on buried rigid pipes and conduits are usually determined based on Marston’s theory (Li, Jianie et al., 2020).

The HFCCTs are common in northwestern China because the HFCCTs construction allows the reclaiming of usable land over the CCT. However, because of the unique land terrains of the Loess Plateau in this region of China, the backfill soil amount required for HFCCTs is enormous, and the backfill must be sufficiently high to maximize the valuable, usable land. Currently, the major challenges of HFCCTs construction are very high earth pressure and safety concerns related to the existing CCT lining structure (Li, Han et al., 2020).

Numerical investigations and physical experiments were conducted to verify the influences of cross-sectional shape (rectangle and arch) of HFCCTs, foundation settlement, and load reduction using expanded polystyrene (EPS) for the vertical earth pressure (VEP) distribution and vertical displacement around an HFCCT. The numerical analysis results agree well with the experimental results. Moreover, comparisons were made to analytical analysis based on Marston-Spangler's (M-S) theory. The comparisons showed that analytical solutions for buried culverts could not be applied directly to the high-filled cut-and-cover tunnels (HFCCTs). To obtain accurate earth pressure, the engineering designers must take into consideration many influential factors (Li, Jianie et al., 2020).

The earth pressure on the HFCCTs calculation method currently adopted usually gives either overestimation or underestimation results. Unlike the vertical earth pressure (VEP), lateral earth pressure (LEEP) can help stabilize the structure of HFCCTs. The current LEEP estimation methods rely mainly on Rankine's theory or empirical formulas. Using traditional methods has led to errors between the actual and estimated values, and such deviation and difference increases with an increase in the backfill height over the HFCCT. Because of the complex soil arching effect, the current LEEP calculation methods used for HFCCTs need to be modified. The modifications need to consider the characteristics of HFCCT, the geometry of the landform, and the mechanical properties of the backfill soil. Based on that, several influential factors were identified through numerical analysis using the finite element method, and four corresponding coefficients of modification were proposed: \( k_0 \), the cross-sectional shape of the CCT; \( k_1 \), the mechanical properties of the backfill; \( k_2 \), the width of the CCT; and \( k_3 \), the coupled effect of the slope angle and ratio of the width of the valley floor to the width of the CCT. Because the current specifications and LEEP estimation methods may overestimate the LEEP for HFCCTs in valleys, a general equation was formulated for modifying the LEEP coefficient. The general modification equation was verified that agrees well with the numerical analysis results for different cases (Ma et al., 2020).
Physical modeling tests were conducted to investigate load reduction methods that use expanded polystyrene (EPS) in the backfill soil; and structural modifications to the CCTs. The results of the experimental agree well with the results of numerical analysis. The numerical analysis was used to determine suitable EPS thicknesses for load reduction on the CCT when subjected to different backfill heights. The internal forces could be changed by modifying the cross-sectional shape of the lining structure of the CCT to make the concrete of the CCT structure support more compressive loads instead of yielding to bending moments. The study results showed that the coupled effects of load reduction using EPS and cross-sectional modifications of the CCT lining structure could significantly reduce the required thickness of the CCT lining structure, increase the allowable backfill height and enhance the safety of the CCT (Li, Han et al., 2020).

A study was conducted to describe three load reduction measures: expanded polystyrene (EPS); a combination of EPS and geogrid; and a combination of EPS, geogrid, and concrete wedges. A computer program based on the discrete element method (DEM) called PFC2D was employed to examine and analyze the load reduction mechanisms evolution. Parametric studies were conducted to check and investigate six significant and influential factors: the thickness, density, width of the EPS, the level or location where the EPS is placed in the structure, the number of layers of the geogrid, and the tensile strength of the geogrid. The analysis results were based on the observed changes in average VEP, relative vertical displacement of the backfill soil, the contact force among backfill soil particles, and relative vertical deformation of the geogrid. The research determined that these influential factors have significant or considerable effects on the soil arching effect and the tensioned member effect in the load reduction mechanisms. For optimizing load reduction of the earth pressure on the top of HFCCTs, the influential factors’ optimum values were derived (Li, Yao et al., 2020).

HFCCTs can assist in satisfying the enormous demand for valuable, usable lands. However, this reclamation tunneling construction method involves massive backfill over a CCT, which produces high pressure on the tunnel. A better understanding of load reduction mechanisms that can reduce this load could also help to improve safety and reduce design costs. The load on top of CCTs can be reduced using relatively low compacted (RLC) soil; however, using the RLC soil layer in the load reduction on the top of CCTs makes the load transfer mechanisms more complex. Previous studies have either focused mainly on the micromechanical properties of soils or ignored their distinct properties. Thus, if the soil’s micromechanical properties can be appropriately considered, then the mechanisms of load transfer can be understood in a better way. Backfill the CCTs with different relative compaction (R) percentages should be considered: e.g., R= 90% for major backfill soil and R= 80% for the RLC layer placed over the HFCCT (Li, Ho et al., 2019).

The VEP estimating methods either underestimate or overestimate the VEP on the top of HFCCT. To more accurately estimate the VEP distribution, the VEP based on the soil column pressure, \( y_h \) (where \( h \): the height of backfill soil above the CCT and \( y \): the unit weight of backfill material above the CCT), needs to be modified properly. Considering different influential and essential factors, four corresponding coefficients were proposed: \( k_0 \): the effect of the cross-sectional shape of CCT, \( k_1 \): the effect of backfill stiffness, \( k_2 \): the effect of CCT width, and \( k_3 \): slope angle, \( \theta \), and B/D ratio coupling effect. It is determined that \( k_0 \) has little or small influence; the \( k_1 \) and \( k_3 \) reduce, and \( k_2 \) amplifies the \( y_h \). The corresponding general forms for the mentioned coefficients were determined based on the results of finite element analysis. A general equation for VEP estimation for the HFCCT, including the four coefficients, was proposed. Meanwhile, the general form was verified by the numerical analysis and experimental results for different cases. Therefore, the proposed or suggested equation is applicable to estimate the VEP for newly designed or existing HFCCT. Furthermore, this proposed method of VEP estimation can significantly reduce the engineering analysis computational works (Li, Ma et al., 2019).

Finite element analysis was used to study the impacts of cross-sectional shape, tunnel width, slope angle, modulus of elasticity, and the ratio of trench width to tunnel width on the VEP on top
of CCTs. The study results showed that the coefficient of the tunnel width effect nonlinearly increases with an increase in the backfill height. The effect of modulus of elasticity coefficient and the coupled effect of slope angle and the trench width to CCT width ratio decrease nonlinearly. Also, two calculation cases for high-filled railway CCTs were analyzed, and the calculated results were compared with those obtained by numerical simulation (Li, Yao et al., 2019).

A case was reported in which tire-derived aggregate (TDA) was successfully applied to reduce the backfill weight on a cut-and-cover railway tunnel. 3D numerical analyses are used to determine the effect of different assumptions about the TDA constitutive model. Other formations of TDA around the CCT section are also examined. Up to 60% reductions inlining bending moment can be achieved. For the case analyzed, the elastic property of the TDA has little influence on CCT lining loads although it is essential for backfill settlement estimates (Rodríguez et al., 2018).

HFCCT has a 30–50 m backfilling height. However, such a high soil column produces a high pressure on the structure of the CCT, and the structure is prone to crack, causing damages in the structure and difficulty in regular use of the CCT. To provide a structural safety assessment reference of HFCCT, a similarity model test was conducted to study the displacement, variation law of the development of crack, and internal force of HFCCT with λ coefficient (the ratio of the backfill height to the height of the CCT). In the test, a CCT model with a 1:20 similar scale, groove width ratio 1, and slope angle 70° was built using data from the HFCCT on the Lanyu Line. The backfilling process of the CCT on-site was simulated in the testing model simulation box (360 cm long, 120 cm wide and 209 cm high). Also, a numerical model was built using PFC2D to check and verify the accuracy of the model test and further explain the mechanism of crack formation of the HFCCT from a microscopic perspective. The results showed that with the increase of λ coefficient, the bearing stage of the CCT can be divided into three phases: steady growth stage, rapid growth stage, and accelerated growth stage. Furthermore, the development of cracks in the CCT structure is closely related to the internal force and displacement of the CCT. The larger the displacement of the CCT, the larger the ratio of the bending moment to the internal force and the greater the instability of the structure, which will cause the crack to develop more quickly (Zhuo et al., 2020).

This study presents a numerical investigation of the effect of using EPS geofoam and TDA as compressible materials in three different forms on VEP reduction on HFCCTs. The research includes using EPS geofoam and TDA in horizontal, arched, and combined horizontal and arched forms above the HFCCT structure with six thicknesses; 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m and three distances between the bottom of the EPS geofoam and TDA and top of the HFCCT; 0.25 m, 0.5 m, and 1.0 m. The research includes using EPS geofoam and TDA in arched and combined horizontal and arch forms as methods of VEP reduction on HFCCTs which is the first time these methods to be used as methods of any type of loads reduction on HFCCTs. Several influential factors, including the form of the EPS and the TDA, the thickness of the EPS and TDA, and the distance between the top of the HFCCT and the bottom of the EPS and the TDA, will be studied. The analysis results will focus on changes in average VEP and relative vertical displacement of the HFCCT backfill soil prisms.

2. The study model and suggested load reduction methods
HFCCT has a 30–50 m backfilling height. However, such a high soil column produces a high pressure on the structure of the CCT, and the structure is prone to crack, causing damages to the structure and difficulty in regular use of the CCT (Zhuo et al., 2020). Figure 1 shows the cross-section of the HFCCT study model, where a 4-lanes road CCT is located at the base of a valley with 50 m vertical depth, 23.4 m base width, and approximately 70° angles of sides slopes. The backfill height of the CCT is 42.3 m, and the height and width of the CCT were designed to be 7.7 m and 15.4 m, respectively. The study model is quite challenging in terms of the ultrahigh earth pressure on the HFCCT produces from the backfill soil. The parameters of the HFCCT study model were selected to reflect the difficult natural conditions of plateaus terrain.
The research includes using EPS geofoam and TDA in horizontal, arched and combined horizontal and arched forms above the HFCCT structure with six thicknesses; 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m and three distances between the bottom of the EPS geofoam and TDA and top of the HFCCT; 0.25 m, 0.5 m, and 1.0 m. The research includes using EPS geofoam and TDA in arched and combined horizontal and arch forms as methods of VEP reduction on HFCCTs which is the first time these methods to be used as a methods of any type of loads reduction on HFCCTs.

3. Materials parameters

3.1. Backfill soil parameters

The physical and mechanical properties of the backfill soil were determined by conducting the relevant laboratory tests. The cohesion, c, the internal friction angle, φ, and Young's modulus value were determined by performing triaxial compression tests. Standard test following ASTM D4253-00 was used to obtain other properties, such as optimal moisture content and maximum dry density. The soil samples were taken from an area with plateaus terrain and the soil tests were conducted in the soil lab of Civil Engineering Department—College of Engineering—University of Baghdad. The backfill soil tests results are shown in Table 1.

3.2. Expanded polystyrene (EPS) geofoam parameters

Expanded polystyrene (EPS) geofoam is a rigid cellular plastic foam that has been widely used in geotechnical applications, including slope stabilization (Jutkofsky et al., 2000), rapid embankment construction over compressible soils (Farnsworth et al., 2008), static and dynamic lateral loads reduction on bridge abutments and retaining walls (Bathurst et al., 2007; Hatami & Witthoeft, 2008; Horvath, 1998, 2004; Zarnani & Bathurst, 2007, 2008), as a barrier to dynamic loading (Ossa & Romo, 2011) and as a sub-base fill material (Dugkov, 1998; Dugkov & Scarpas, 1998; Huang & Negussey, 2011; Stark et al., 2004). EPS geofoam composite soil with its engineering and physical properties has been studied with numerical solution (Gao et al., 2012, 2011). Due to its unique properties such as low density, low permeability, and different mechanical behavior, the EPS is widely used in geotechnical applications. A number of studies have shown that the EPS geofoam compressive strength is mainly depending on material density, strain rate, and confining stress (Chun et al., 2004; Hazarika, 2006; Leo et al., 2008; Ossa & Romo, 2009; Wong & Leo, 2006).
For the last four decades, Expanded Polystyrene (EPS) has been successfully used as construction material in the field of geotechnical engineering due to its wide variety of applications such as lightweight fill material in embankments and compressible inclusion in retaining walls (Padade & Mandal, 2012).

For the study purposes, four different densities of expanded polystyrene (EPS) geofoam are selected and procured from a local supplier of EPS geofoam packing materials in Mumbai, India. Figure 2a shows the line sketch, and Figure 2b shows the photograph of the triaxial test specimen of EPS geofoam used in the experimental study. Some of the EPS geofoam mechanical properties are given in Table 2 (Padade & Mandal, 2012).

The experiments were conducted using a standard triaxial loading frame with a triaxial cell to accommodate specimen of diameter 75 mm and height 150 mm (see, Figure Figure 3). As per IS 2720 (Part 11):1993, the Unconsolidated Un-drained (UU) triaxial tests were performed with a constant strain rate of 1.2 mm/min. A Linear Variable Differential Transducer (LVDT) and load cell were used to measure the vertical displacement and deviator load, respectively. With up to a maximum axial strain of 15%, all the tests were conducted (Padade & Mandal, 2012).

| Table 1. Engineering properties of backfill soil |
|-----------------------------------------------|
| Cohesion (c) (KPa) | Internal friction angle (φ) (°) | Young’s modulus (E) (MPa) | Poisson’s ratio (ν) | Optimum moisture content (W_{opt}) (%) | Maximum dry density (p_d) (Kg/m³) | Saturated density (p) (Kg/m³) |
|-------------------|---------------------------------|--------------------------|--------------------|---------------------------------------|-------------------------------|-----------------------------|
| 7.2               | 36                              | 11.250                   | 0.3                | 25.1                                  | 1690                          | 1870                        |

*Figure 2. Triaxial test specimen of EPS geofoam (a) line sketch and (b) photograph (Padade & Mandal, 2012).*
| Density of EPS geofoam (Kg/m³) | Unit weight of EPS geofoam (kN/m³) | Compressive Strength (kPa) | Initial Modulus (kPa) | Tensile Strength (kPa) | Flexural Strength (kPa) | Shear Strength (kPa) |
|-------------------------------|-----------------------------------|---------------------------|-----------------------|-----------------------|------------------------|---------------------|
| 15                            | 0.15                              | 61.95                     | 2480.76               | 154.59                | 149.9                  | 83.65               |
| 20                            | 0.20                              | 91.39                     | 4070.55               | 216.40                | 211.3                  | 94.37               |
| 22                            | 0.22                              | 110.53                    | 5508.16               | 244.54                | 240.6                  | 121.57              |
| 30                            | 0.30                              | 146.80                    | 7550.28               | 407.78                | 277.0                  | 139.27              |
When the EPS geofoam specimens were tested under triaxial loading conditions, no specific failure surface was observed. With the increase in the deviator load, the specimens were getting compressed and marginal or small sidewise bulging was observed. A similar pattern was observed in all the EPS geofoam densities and confining pressures. The deformation of the EPS geofoam test specimen with different densities is shown in Figure 4 (Padade & Mandal, 2012).

Deviator load was noted or recognized for each increase of axial deformation of EPS geofoam specimen. Deviator stress-strain relationships of EPS geofoam with different unit weights under different confining pressures are shown in Figure 5. For all the tested unit weights of EPS geofoam, the stress-strain relationship was linear up to the axial strain value of around 2%; later, it was observed that there was no significant change in the deviator stress value with respect to the increase in axial strain value. As the unit weight of the EPS geofoam is increased, the deviator load
is increased for all the confining pressures. For all the unit weights and confining pressures, the principal stress difference was almost equal (Padade & Mandal, 2012).

The strength parameters of different unit weights of EPS geofoam were calculated by constructing Mohr’s circles. The constructions of Mohr’s circles for different unit weights of EPS geofoam are shown in Figure 6. The cohesion value of EPS geofoam increased with an increase in the unit weight, and there was a marginal or slight increase in the angle of internal friction. The strength parameters of EPS geofoam obtained from the triaxial tests are given in Table 3. It was noticed from the strength parameters, the cohesion value has a significant and considerable effect on the strength of EPS geofoam. Figure 7 shows the correlation of cohesion values with respect to the corresponding unit weight of EPS geofoam. Regression analysis is carried out for different unit weights of EPS geofoam and best fitted to a curve expressed as Equation 1 (Padade & Mandal, 2012).

\[ C = 894.7 \gamma_g^2 - 214.3 \gamma_g + 45.78 \]  

(1)

Where:

\( C \) is the cohesion (kPa).

\( \gamma_g \) is the unit weight of EPS geofoam (kN/m\(^3\)).

The Poisson’s ratio (\(\nu\)) value of EPS geofoam is calculated using Equation 2 given by EDO (1992). The Poisson’s ratio (\(\nu\)) value and other properties of EPS geofoam are illustrated in Table 4.
Figure 6. Mohr’s circle construction for different unit weights of EPS geofoam (a) 0.15 kN/m$^3$, (b) 0.20 kN/m$^3$, (c) 0.22 kN/m$^3$ and (d) 0.30 kN/m$^3$ (Padade & Mandal, 2012).

Table 3. Shear strength parameters of EPS geofoam of different unit weights (Padade & Mandal, 2012)

| Unit weights of EPS geofoam $\gamma_g$ (kN/m$^3$) | Cohesion C (kPa) | Angle of internal friction $\phi$ ($) |
|----------------------------------------------|------------------|-------------------------------------|
| 0.15                                         | 33.75            | 1.5                                 |
| 0.20                                         | 38.75            | 2                                   |
| 0.22                                         | 41.88            | 2                                   |
| 0.30                                         | 62.00            | 2.5                                 |

\[ \nu = 0.0056 \rho + 0.0024 \]  

Where:
For the numerical analysis of this study and to obtain maximum relative settlement between the interior prism and the exterior prisms of the HFCCT backfill soil, the EPS geofoam material with a density of 15 Kg/m³ is selected. The engineering properties of the selected EPS geofoam material are given in Table 4.

3.3. Tire-derived aggregate (TDA) parameters

The American Society for Testing and Materials (ASTM) in ASTM D6270-08, “Standard Practice for Use of Scrap Tires in Civil Engineering Applications”, provided a comprehensive and detailed list of terms and definitions and outlined the standard practice for scrap tires used in civil engineering applications (Geosyntec Consultants, 2008).

TDA has been used as an alternative embankment filling material because of its lightweight. TDA is one-third of the conventional fill material weight and therefore produces less pressure on the underlying material. This can be an advantage and beneficial when designing an embankment fill project in which the underlying foundation soil cannot support the high weight of a conventional soil backfill. In addition to that, TDA has high permeability and, therefore, mainly does not require the placement of sub-drain systems. This will provide additional savings in the cost. TDA as a lightweight fill material has proven to be a cost-effective alternative to other materials such as geofoam and pumice. There are other benefits of TDA in embankment and road fill and applications like reinforcing roadway shoulders, increasing the stability of steep slopes along roadways and providing an insulating layer against frost penetration due to its thermal resistance properties. The ASTM standard divided TDA into two major types used in engineering applications, Type A and Type B, and two fill classes associated with them, Class I and Class II. Type A and Type B are TDA size

![Figure 7. Correlation between cohesion and unit weight of EPS geofoam (Padade & Mandal, 2012).](image)

| Unit weight of EPS geofoam $\gamma_g$ (kN/m³) | Cohesion C (kPa) | Angle of internal friction $\phi$ (°) | Modulus of elasticity E (kPa) | Poisson’s ratio $\nu$ |
|---------------------------------------------|------------------|-------------------------------------|----------------------------|-------------------|
| 0.15                                        | 33.75            | 1.5                                 | 2400                       | 0.10              |
| 0.20                                        | 38.75            | 2                                   | 4000                       | 0.12              |
| 0.22                                        | 41.88            | 2                                   | 5500                       | 0.125             |
| 0.30                                        | 62.00            | 2.5                                 | 7800                       | 0.17              |
classifications used for different engineering applications. Class I and Class II describe the fill lift thicknesses as defined by ASTM D6270-08, Section 6.10.1. Type A material is roughly 75 to 100 mm in size, and Type B material is approximately 152.4 to 304.8 mm. Class I fills are TDA layers that are less than 1 meter in height, and Class II fills describe TDA layers that are between 1 and 3 meters high. Typically Type A material is used in Class I fills, and Type B material is used in applications requiring a Class II fill. Table 5 summarizes Type A and Type B size classifications, and Figure Figure 8 shows photos of typical samples of TDA material. Because TDA is a compressible material, the density of TDA varies depending on whether it is being stockpiled or installed in the project. The stockpile and shipping densities of Type A and B TDA range from 400.461 to 560.646 kg/m$^3$, while compacted in-place density values for Type A and B TDA ranges from approximately 560.646 to 800.923 kg/m$^3$ (see, Table 6; Cheng, 2016).

Modulus of elasticity (E) is the coefficient of proportionality between the applied stress and the measured strain; for example, in a one-dimensional tensile test, the lower values of E are indicative of layer deformation. The elastic modulus (E) for TDA ranges from 1.241 MPa to 5.171 MPa (Geosyntec Consultants, 2008). For comparison purposes, the elastic modulus (E) of dense, drained sands can vary from 41.368 MPa to 82.737 MPa (Kulhawy & Mayne, 1990). The modulus of elasticity (E) for gravel is much larger. Therefore, under the same stress conditions, the TDA will deform much more than soil. Poisson's ratio (ν) is the ratio of transverse strain to longitudinal strain, as measured for example, in a one-dimension tensile test, the Poisson's ratio of TDA is 0.5 (Geosyntec Consultants, 2008), which means that the TDA material would deform at a constant volume. As a comparison, the Poisson’s ratio (ν) for mineral aggregate varies from 0.15 to 0.45 (Kulhawy & Mayne, 1990).

### Table 5. TDA fill classes (ASTM D6270-08 Section 6.10.1–4; Cheng, 2016)

| Characteristics         | TDA Type A | TDA Type B |
|-------------------------|------------|------------|
| Fill Class              | Class I    | Class II   |
| Typical Size            | 75–100 mm  | 150–300 mm |
| Maximum Layer Depth     | Less than 1 m | Less than 3 m |

![Figure 8. Left—Type A tire-derived aggregate (TDA), Right—Type B tire-derived aggregate (TDA; Cheng, 2016).](image)

### Table 6. Densities of type A and type B tire-derived aggregate (TDA; Cheng, 2016)

| Stages             | TDA Type A, Kg/m$^3$ | TDA Type B, Kg/m$^3$ |
|--------------------|----------------------|----------------------|
| Shipping and Stockpiling | 400.461–560.646         | 400.461–560.646         |
| Compacted          | 720.830–848.978       | 720.830–800.923       |
For numerical analysis, the required TDA material engineering properties were selected and summarized in Table 7.

4. Analytical estimation of vertical earth pressure (VEP)
Based on the analyses, the vertical earth pressure is relevant to several parameters such as the width of the CCT (D), the valley width (B), slope angle (θ), and \(y h\) (the height of backfill above the CCT and \(γ\): the unit weight of backfill material above the CCT). Meanwhile, the relative settlement between different soil columns which are analyzed is related to the stiffness of backfill soils, called Young’s modulus or modulus of elasticity, \(E\) (MPa). In addition, the patterns of soil stress distribution on the top of CCT are different between varying cross-sections shapes (Dancygier et al., 2016).

Therefore, the vertical earth pressure, \(q\) (kPa), on top of the HFCCT can be expressed as a function of the parameters mentioned above, using the following form (Li, Ma et al., 2019):

\[
q = f(S, D, E, θ, B, γh)
\]  
(3)
Where:

\(S\): represents the influence of cross-sectional of the CCT.

For the estimation of vertical earth pressure (VEP) on top of the HFCCT for the base condition of the study model (No load reduction method is used), Li et al. (2019), based on the soil column pressure (\(y h\)) modified equation was used. The equation is considering different influential factors, and four corresponding coefficients were proposed: \(k_0\): the cross-sectional shape of CCT effect, \(k_1\): stiffness of backfill effect, \(k_2\): width of CCT effect, and \(k_3\): coupling effect of slope angle, \(θ\), and the valley width to the width of the CCT ratio (the B/D ratio). It is found that \(k_0\) has little influence; the \(k_1\) and \(k_3\) reduce, and \(k_2\) amplifies the \(y h\). With these four coefficients determined and demonstrated as influential factors, the vertical earth pressure on the top of the HFCCT should be modified as follows:

\[
q = k_0k_1k_2k_3γh
\]  
(4)
Where:

\(q\): is vertical earth pressure.

\(k_0\), \(k_1\), and \(k_2\): are the influence coefficients of cross-section shape, elasticity modulus, and the width of CCT, respectively.

\(k_3\): is the coupling effect of slope angle, \(θ\), and the ratio, \(B/D\).

\(k_1\), \(k_2\) and \(k_3\) coefficients are calculated using the following equations:

\[
k_1 = [-0.015\ln(E) + 0.0133\ln\left(\frac{h}{D}\right)] + 1
\]  
(5)
\[ k_2 = \left( -0.0226D + 1.43 \right) \left( \frac{h}{B} \right)^{0.1} \]  

\[ k_3 = \left[ \left( -0.0004 \frac{B}{D} - 0.0034 \right) \theta + 0.0282 \frac{B}{D} + 0.0251 \right] \ln \left( \frac{h}{B} \right) + \left( 0.0548 \frac{B}{D} - 0.1447 \right) \tan \theta + 1 \]  

The calculation of the vertical earth pressure (VEP) on top of the HFCCT for the base condition of the study model is done as in the following:

\[ k_0 = 1 \]
\[ k_1 = \left[ -0.015 \ln (11.25) + 0.0133 \right] \ln \left( \frac{42.3}{15.4} \right) + 1 \]
\[ = (-0.023 \times 1.0104) + 1 \]
\[ = 0.9767 \]
\[ k_2 = \left[ -0.0226 \times 15.4 + 1.43 \right] \left( \frac{42.3}{15.4} \right)^{0.1} \]
\[ = 1.08196 \times 1.10632 \]
\[ = 1.1969 \]
\[ k_3 = \left[ \left( -0.0004 \frac{32.6}{15.4} - 0.0034 \right) \theta + 0.0282 \frac{32.6}{15.4} + 0.0251 \right] \ln \left( \frac{42.3}{15.4} \right) + \left( 0.0548 \frac{32.6}{15.4} - 0.1447 \right) \tan \theta + 1 \]
\[ = (-0.00400779 \times 70 + 0.04284 + 0.0251) \times 1.0014 - 0.1687 + 1 \]
\[ = 0.6164 \]
\[ q = k_0 k_1 k_2 k_3 y h \]
\[ = 1 \times 0.9767 \times 1.1969 \times 0.6164 \times 18.70 \times 42.3 \]
\[ = 569.985 \text{ kPa} \]

5. Numerical analysis

For all the numerical analysis works in this study, Complete Abaqus Environment 2019 (Abaqus CAE 2019), which is based on the finite element method, is employed.

5.1. Model creation

For the numerical analysis works in this study, a finite element model was created with a 1/50 scale of the actual HFCCT study model (see, Figure 9). In the finite element model, the slopes are assumed to be rigid. Abaqus CAE Standard/Explicit Model, which uses plane strain element type, is selected to model the HFCCT. The boundaries at two sides of the finite element model are only vertical displacement is allowed, and the bottom boundary of the model is entirely fixed. The Mohr-Coulomb elastoplastic criterion was used to model the backfill soil. For the EPS geofoam material, in addition to density, elasticity, cohesion, and angle of internal friction, the crushable foam model must be defined in Abaqus CAE 2019 to fit the stress-strain relationship of the EPS geofoam. For the TDA material, the Mohr-Coulomb elastoplastic criterion was used for modeling the properties of the material. The parameters used in the finite element analysis, such as the mechanical properties for backfill soil, EPS geofoam material, and TDA material, are summarized in Table 8.
5.2. Results of numerical analysis

5.2.1. VEP estimation on the HFCCT for the base conditions of the study model (no-load reduction method is used)

A numerical analysis was conducted to estimate the average vertical earth pressure (VEP) on the finite element HFCCT study model with the base conditions (no-load reduction method used; see, Figure 10). The average VEP on the actual HFCCT study model with the base conditions was estimated based on the average VEP estimation on the finite element HFCCT study model, and its value is 792.25 kPa.

Figure 9. The finite element HFCCT model created with 1/50 scale of the actual HFCCT study model.

Figure 10. Contours of average vertical earth pressure (VEP) for the base conditions (no-load reduction method used).

Table 8. Mechanical properties of materials required for the finite element analysis

| Material                  | Density (p) (Kg/m³) | Unit weight (γ) (kN/m³) | Young’s modulus (E) (MPa) | Poisson’ ratio (ν) | Cohesion C (kPa) | Angle of internal friction (φ) (°) |
|---------------------------|---------------------|-------------------------|---------------------------|-------------------|-----------------|----------------------------------|
| Backfill soil             | 1870                | 18.70                   | 11.25                     | 0.3               | 7.2             | 36                               |
| EPS geofoam               | 15                  | 0.15                    | 2.40                      | 0.10              | 33.75           | 1.5                              |
| TDA                       | 400.461             | 4.00461                 | 0.63                      | 0.2               | 10             | 23                               |

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5.2.2. VEP estimation on the HFCCT with load reduction method using EPS geofoam in a horizontal form

Figures 11 and 12 present the relationships of the average VEP and the percentage of reduction in the VEP on the HFCCT study model with the EPS thickness (in a horizontal form) and the distance between the top of the HFCCT and the bottom of the EPS. In general, as the thickness of the EPS increases, the average vertical earth pressure on the HFCCT is reduced until the EPS thickness reaches 2.5 m, where almost the increase in the EPS thickness above 2.5 m will have no more effect on the vertical earth pressure reduction on the HFCCT. For half of the EPS thicknesses, the best results of vertical earth pressure reduction on the HFCCT were obtained when the distance between the top of the HFCCT and the bottom of the EPS was 0.25 m, and for the EPS thicknesses 2.0 m, 2.5 m, and 3.0 m in relation with the distances between the top of the HFCCT and the bottom of the EPS 1 m, 0.5 m, and 0.25 m, the results of vertical earth pressure reduction are close from each other’s and that indicates the distance between the top of the HFCCT and the bottom of the EPS for the mentioned EPS thicknesses (2.0 m, 2.5 m and 3.0 m) having a small effect on the vertical earth pressure reduction of the HFCCT. The best result of using EPS geofoam in a horizontal form as a method of VEP reduction on the HFCCT is achieved using 3.0 m EPS thickness and 0.25 m distance between the top of the HFCCT and the bottom of EPS, where the average VEP on the HFCCT reduced from 792.25 kPa to 511 kPa (35.5% reduction in the average VEP on the HFCCT; see, Figures 11, 12 and 13).

The EPS geofoam inclusion in a horizontal form leads the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the EPS (see, Figures 14 and 15), the soil prism (interior prism) within the HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism.

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**Figure 11.** The relationship of the average VEP on the HFCCT study model with the EPS thickness (in a horizontal form) and the distance between the top of the HFCCT and the bottom of the EPS.

**Figure 12.** The relationship of the percentage of reduction in the VEP on the HFCCT study model with the EPS thickness (in a horizontal form) and the distance between the top of the HFCCT and the bottom of the EPS.
The results of the load reduction method using EPS geofoam in a horizontal form indicate that the increase in distance between the EPS bottom and the top of the HFCCT does not enhance the soil arching effect but instead increases the average VEP on the HFCCT. Therefore, the optimum distance can be considered the shortest distance between the EPS bottom and the top of the HFCCT.

5.2.3. VEP estimation on the HFCCT with load reduction method using EPS geofoam in an arched form

Figures 16 and 17 present the relationships of the average VEP and the percentage of reduction in the VEP on the HFCCT study model with the EPS thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the EPS. In general, as the thickness of the EPS increases, the average vertical earth pressure on the HFCCT is reduced until the EPS thickness reaches 1.5 m, where the increase in the EPS thickness above 1.5 m have different effects on the vertical earth pressure reduction on the HFCCT with varying distances between the top of the HFCCT and the bottom of the EPS. For most of the EPS thicknesses, the best results of vertical earth pressure reduction on the HFCCT were obtained when the distance between the top of the HFCCT and the bottom of the EPS was 0.25 m. The best result of using EPS geofoam in an arched form as a method of VEP reduction on the HFCCT is achieved using 3.0 m EPS thickness and 0.5 m distance between the top of the
Figure 15. Contours of: (a) Vertical displacement for the base conditions (no-load reduction method used), (b) Vertical displacement for the best result of using EPS geo-foam in a horizontal form as a method of VEP reduction on the HFCCT.

Figure 16. The relationship of the average VEP on the HFCCT study model with the EPS thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the EPS.

Figure 17. The relationship of the percentage of reduction in the VEP on the HFCCT study model with the EPS thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the EPS.
HFCCT and the bottom of EPS, where the average VEP on the HFCCT reduced from 792.25 kPa to 565.25 kPa (28.652% reduction in the average VEP on the HFCCT; see, Figures 16, 17 and 18).

The EPS geofoam inclusion in an arch form leads the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the EPS (see, Figures 19 and 20), the soil prism (interior prism) within the HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism. The idea of using the EPS in an arched form was to reduce more VEP on the HFCCT by dissipating more VEP to the exterior soil prisms then to the side slopes of the valley through increasing the soil arching effect that forms in the backfill of the HFCCT. But unfortunately, the results were not encouraging and not as expected.

Except for the case where the EPS geofoam thickness is 3 m, and the distance between the top of the HFCCT and the bottom of EPS is 0.5 m in which the best result was achieved, the results of the load reduction method using EPS in an arched form indicate that the increase in distance between the EPS bottom and the top of the HFCCT does not enhance the soil arching effect but instead increases the average VEP on the HFCCT. Therefore, the optimum distance can be considered the shortest distance between the EPS bottom and the top of the HFCCT.

Figure 18. Contours of average vertical earth pressure (VEP) for the best result of using EPS geofoam in an arched form as a method of VEP reduction on the HFCCT.

Figure 19. The effect of EPS geofoam inclusion in an arched form on the VEP reduction on the HFCCT study model.
5.2.4. VEP estimation on the HF CCT with load reduction method using EPS geofoam in a combined horizontal and arched form

Figures 21 and 22 present the relationships of the average VEP and the percentage of reduction in the VEP on the HF CCT study model with the EPS thickness (in a combined horizontal and arched form) and the distance between the top of the HF CCT and the bottom of the EPS. In general, as the thickness of the EPS increases, the average vertical earth pressure on the HF CCT is reduced until the EPS thickness reaches 2 m, where the increase in the EPS thickness above 2.0 m have different effects on the vertical earth pressure reduction on the HF CCT with different varying between the top of the HF CCT and the bottom of the EPS. For most of the EPS thicknesses, the best results of vertical earth pressure reduction on the HF CCT were obtained when the distance between the top of the HF CCT and the bottom of the EPS was 0.25 m. The best result of using EPS geofoam in a combined horizontal and arched form as a method of VEP reduction on the HF CCT is achieved using 2.0 m EPS thickness and 0.25 m distance between the top of the HF CCT and the bottom of EPS, where the average VEP on the HF CCT reduced from 792.25 kPa to 538.5 kPa (32.029 % reduction in the average VEP on the HF CCT; see, Figures 21–23).
The EPS geofoam inclusion in a combined horizontal and arched form leads the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the EPS (see, Figures 24 and 25), the soil prism (interior prism) within the HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism. The idea of...
using the EPS in a combined horizontal and arched form was to reduce more VEP on the HFCCT by dissipating more VEP to the exterior soil prisms then to the side slopes of the valley through increasing the soil arching effect that forms in the backfill of the HFCCT. The results were acceptable but not good as expected.

The results of the load reduction method using EPS geofoam in a combined horizontal and arched form indicate that the increase in distance between the EPS bottom and the top of the HFCCT does not enhance the soil arching effect but instead increases the average VEP on the HFCCT. Therefore, the optimum distance can be considered the shortest distance between the EPS bottom and the top of the HFCCT.

5.2.5. VEP estimation on the HFCCT with load reduction method using TDA in a horizontal form

Figures 26 and 27 present the relationships of the average VEP and the percentage of reduction in the VEP on the HFCCT study model with the TDA thickness (in a horizontal form) and the distance between the top of the HFCCT and the bottom of the TDA. In general, as the thickness of the TDA increases, the average vertical earth pressure on the HFCCT is reduced. For half of the TDA thicknesses, the best results of vertical earth pressure reduction on the HFCCT were obtained when the distance between the top of the HFCCT and the bottom of the TDA was 0.5 m. The best result of using TDA in a horizontal form as a method of VEP reduction on the HFCCT is achieved using 3.0 m TDA thickness and 0.5 m distance between the top of the HFCCT and the bottom of TDA, where the average VEP on the HFCCT reduced from 792.25 kPa to 248.15 kPa (68.677% reduction in the average VEP on the HFCCT; see, Figures 26–28).

The TDA inclusion in a horizontal form leads the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the TDA (see, Figures 29 and 30), the soil prism (interior prism) within the
HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism.

The results of the load reduction method using TDA in a horizontal form indicates that the optimum distance between the TDA bottom and the top of the HFCCT enhances the soil arching effect and decreases the average VEP on the HFCCT. In this method of VEP reduction,
the optimum distance between the TDA bottom and the top of the HFCCT can be estimated from the results of the load reduction method using TDA in a horizontal form, and it is not necessarily the shortest distance between the TDA bottom and the top of the HFCCT.

5.2.6. VEP estimation on the HFCCT with load reduction method using TDA in an arched form

Figures 31 and 32 present the relationships of the average VEP and the percentage of reduction in the VEP on the HFCCT study model with the TDA thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the TDA. In general, as the thickness of the TDA increases, the average vertical earth pressure on the HFCCT is reduced. For most TDA thicknesses, the best results of vertical earth pressure reduction on the HFCCT were obtained when the distance between the top of the HFCCT and the bottom of the TDA was 1.0 m. The best result of using TDA in an arched form as a method of VEP reduction on the HFCCT is achieved using 3.0 m TDA thickness and 1.0 m distance between the top of the HFCCT and the bottom of TDA, where the average VEP on the HFCCT reduced from 792.25 kPa to 279.75 kPa (64.689% reduction in the average VEP on the HFCCT; see, Figures 31–33).

Figure 31. The relationship of the average VEP on the HFCCT study model with the TDA thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the TDA.

Figure 32. The relationship of the percentage of reduction in the VEP on the HFCCT study model with the TDA thickness (in an arched form) and the distance between the top of the HFCCT and the bottom of the TDA.

Figure 33. Contours of average vertical earth pressure (VEP) for the best result of using TDA in an arched form as a method of VEP reduction on the HFCCT.
The TDA inclusion in an arched form lead the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the TDA (see, Figures 34 and 35), the soil prism (interior prism) within the HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism. The idea of using the TDA in an arched form was to reduce more VEP on the HFCCT by dissipating more VEP to the exterior soil prisms then to the side slopes of the valley through increasing the soil arching effect that forms in the backfill of the HFCCT. The results were good but not as desired.

The results of the load reduction method using TDA in an arched form indicate that the optimum distance between the TDA bottom and the top of the HFCCT enhances the soil arching effect and decreases the average VEP on the HFCCT. In this method of VEP reduction, the optimum distance between the TDA bottom and the top of the HFCCT can be estimated from the results of the load reduction method using TDA in an arched form. The optimum distance can be the longest or any and not necessarily the shortest distance between the TDA bottom and the top of the HFCCT.
Figure 36. The relationship of the average VEP on the HFCCT study model with the TDA thickness (in a combined horizontal and arched form) and the distance between the top of the HFCCT and the bottom of the TDA.

Figure 37. The relationship of the percentage of reduction in the VEP on the HFCCT study model with the TDA thickness (in a combined horizontal and arched form) and the distance between the top of the HFCCT and the bottom of the TDA.

5.2.7. VEP estimation on the HFCCT with load reduction method using TDA in a combined horizontal and arched form

Figures 36 and 37 present the relationships of the average VEP and the percentage of reduction in the VEP on the HFCCT study model with the TDA thickness (in a combined horizontal and arched form) and the distance between the top of the HFCCT and the bottom of the TDA. In general, as the thickness of the TDA increases, the average vertical earth pressure on the HFCCT is reduced. For most TDA thicknesses, the best results of vertical earth pressure reduction on the HFCCT were obtained when the distance between the top of the HFCCT and the bottom of the TDA was 1.0 m. The best result of using TDA in a combined horizontal and arched form as a method of VEP reduction on the HFCCT is achieved using 2.5 m TDA thickness and 1.0 m distance between the top of the HFCCT and the bottom of TDA, where the average VEP on the HFCCT reduced from 792.25 kPa to 315 kPa (60.239 % reduction in the average VEP on the HFCCT; see, Figures 36–38).

Figure 38. Contours of average vertical earth pressure (VEP) for the best result of using TDA in a combined horizontal and arched form as a method of VEP reduction on the HFCCT.
The TDA inclusion in a combined horizontal and arched form lead the soil prism (interior prism) within the HFCCT structure width to settle more than the surrounding soil prisms (exterior prisms) due to deformation of the TDA (see, Figures 39 and 40), the soil prism (interior prism) within the HFCCT structure width deform as a reverse arch-shape. Meanwhile, the reduced VEP on the HFCCT structure is equal to the shear force on the soil in the interior prism. The idea of using the TDA in a combined horizontal and arched form was to reduce more VEP on the HFCCT by dissipating more VEP to the exterior soil prisms then to the side slopes of the valley through increasing the soil arching effect that forms in the backfill of the HFCCT. The results were acceptable but not good as expected.

The results of the load reduction method using TDA in a combined horizontal and arched form indicate that the optimum distance between the TDA bottom and the top of the HFCCT enhances the soil arching effect and decreases the average VEP on the HFCCT. In this method of VEP reduction, the optimum distance between the TDA bottom and the top of the HFCCT can be estimated from the results of the load reduction method using TDA in a combined horizontal and arched form. The optimum distance can be the longest or any and not necessarily the shortest distance between the TDA bottom and the top of the HFCCT.
6. Model verification

The calculated and estimated VEP values on the top of the HFCCT study model with the base conditions showed that the calculated value using Li et al.’s (2019) modified equation is 27.942% lower than the calculated value using the soil column pressure equation, which is a high percentage of difference. While the estimated value using Abaqus CAE 2019 is 0.156% higher than the calculated value using the soil column pressure equation, which is a low percentage of difference (see, Table 9).

| Method of VEP calculation | VEP (kPa) | The percentage of the difference with the soil column pressure (%) |
|---------------------------|-----------|-----------------------------------------------------------------|
| The soil column pressure equation (q = γh) | 791.01 | - |
| Li et al.’s (2019) modified equation (q = k0k1k2k3γh) | 569.985 | -27.942 |
| Complete Abaqus Environment 2019 Software (Abaqus CAE 2019) | 792.25 | +0.156 |

Li et al.’s (2019) modified equation is a modification of soil column pressure equation (q = γh) using the ANSYS finite element code to investigate the influences of each of the factors; S, D, E, θ and B which were mentioned previously through four proposed corresponding coefficients, k0, k1, k2 and k3. For the HFCCT study model with the base conditions, by adding the effect of S, D, E, θ and B to the soil column pressure equation through Li et al.’s (2019) modified equation, the VEP on the top of the HFCCT reduced from 791.01 kPa to 569.985 kPa. On the other hand, the estimated VEP value using Abaqus CAE 2019 is almost equal to the calculated value of the VEP using the soil column pressure equation, where the difference between the two values of the VEP is only 0.156% (see, Table 9).

7. Conclusions

This study used Abaqus CAE 2019 software, which is based on the finite element method, to investigate the effect of using EPS geofoam and TDA in different forms on the relative vertical displacements of the HFCCT backfill soil prisms and VEP reduction on the HFCCT due to the relative vertical displacements of the HFCCT backfill soil prisms and soil arching. Several influential factors, including the form of the EPS and the TDA, the thickness of the EPS and TDA, and the distance between the top of the HFCCT and the bottom of the EPS and the TDA, were studied. Also, a comparison is made between the calculated and estimated VEP values on the top of the HFCCT study model with the base conditions using the soil column pressure equation, Li et al. (2019) modified equation, and Abaqus CAE 2019 software. Therefore, several conclusions can be drawn from this study:

1. Concerning VEP reduction on the HFCCT, the presence of EPS and TDA in different forms on top of an HFCCT can transfer the load from the top to the sides of the HFCCT and then to the sides slopes, thereby reducing the VEP on the HFCCT due to soil arching and the relative vertical displacements of the HFCCT backfill soil prisms.

2. The best result of EPS presence on the top of an HFCCT is achieved using the EPS geofoam in a horizontal form as a method of VEP reduction on the HFCCT. This result is achieved by using 3.0 m EPS thickness and 0.25 m distance between the top of the HFCCT and the
bottom of EPS, where the average VEP on the HFCCT reduced from 792.25 kPa to 511 kPa (35.5% reduction in the average VEP on the HFCCT).

(3) The best result of TDA presence on the top of an HFCCT is achieved using the TDA in a horizontal form as a method of VEP reduction on the HFCCT. This result is achieved by using 3.0 m TDA thickness and 0.5 m distance between the top of the HFCCT and the bottom of TDA, where the average VEP on the HFCCT reduced from 792.25 kPa to 248.15 kPa (68.677% reduction in the average VEP on the HFCCT).

(4) Reducing the VEP on the HFCCT will lead the internal forces of the HFCCT lining structure to decrease. Then, the required designing thickness of the HFCCT lining structure can be minimized and improve the safety of the HFCCT when it is subjected to high VEP.

(5) The presence of the TDA material as a compressible material on the top of the HFCCT for load reduction purposes can help clean the environment by using large amounts of the scrap vehicles’ tires in the form of TDA material.

| Nomenclature | Description |
|--------------|-------------|
| HFCCT | high-filled cut-and-cover tunnels |
| VEP | vertical earth pressure |
| EPS | expanded polystyrene |
| TDA | tire-derived aggregate |
| CAE 2019 | Complete Abaqus Environment |
| CCT | cut-and-cover tunnel |
| M-S | Marston-Spangler |
| LEP | lateral earth pressure |
| \( k_0 \) | the cross-sectional shape of the CCT |
| \( k_1 \) | the mechanical properties of the backfill |
| \( k_2 \) | the width of the CCT |
| \( k_3 \) | the coupled effect of the slope angle and ratio of the width of the valley floor to the width of the CCT |
| \( \theta \) | slope angle |
| \( B/D \) | ratio of the width of the valley floor to the width of the CCT |
| DEM | discrete element method |
| PFC2D | Particle Flow Code in 2 Dimensions |
| RLC soil | relatively low compacted soil |
| \( R \) | relative compaction percentage |
| \( h \) | the height of backfill soil above the CCT |
| \( \gamma \) | the unit weight of backfill material above the CCT |
| \( \lambda \) coefficient | the ratio of the backfill height to the height of the CCT |
| \( c \) | Cohesion |
| \( \phi \) | Internal friction angle |
| \( E \) | Young’s modulus |
| \( \nu \) | Poisson’ ratio |
| \( \rho \) | Density |
| \( \gamma_0 \) | Unit weight EPS geofoam |
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