

Numerical Modeling of High Embankment Built on Soft Soil

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ABSTRACT

Construction of high embankments in coastal areas containing soft soils is challenging. Such soils have high natural water content and are very problematic due to their low shear strength. The use of lightweight fill materials is a possible approach to build on soft soils as they impose lower loads resulting in lower settlements and reducing the possibilities of shear failure. Tire Derived Aggregates (TDA) is a cost-effective lightweight fill material that can be used in road construction. In this study, lightweight TDA fill materials is proposed for construction of road embankments on soft soils. The proposed construction is numerically simulated using the finite element software PLAXIS 2D to check its effectiveness. The results of the analysis indicate that the TDA can be very effectively used to reduce the settlement and stresses of the embankment. A full detailed extensive case study will be done to serve as a journal publication.

RÉSUMÉ

Construire une haute digue en milieu des sols meubles des zones maritimes est un défi affrontant les ingénieurs. La problématique de ce type des sols c'est que leur teneur de l'eau naturelle est bien élevée et leur résistance au cisaillement est faible. Pour construire sur les sols meubles, l'utilisation de matériaux de remblayage légers comme les agrégats dérivés de pneus (TDA), peut être une approche possible car ceux-ci imposent des charges plus faibles, ce qui entraîne une diminution des tassements et réduit les risques de rupture par cisaillement. Le TDA est une matière économique pouvant être utilisé dans la construction de routes. Dans cette étude, l'utilisation du TDA légers comme une matière de remplissage pour la construction de remblais routiers sur des sols meubles est proposée. L'efficacité de cette proposition est simulée et vérifiée en analysant les résultats par le logiciel d'éléments finis PLAXIS 2D. Une étude détaillée sera publiée dans une revue.

1 INTRODUCTION

Millions of tires wear out in North America every single year. Not only they are a fire hazard as what happened recently three years ago in Seseña, Spain (CBC 2016) but also release harmful gases and oily residue constituting a real threat to the environment such as what happened in the Winchester fire in Virginia, USA back in 1983. The Winchester fire resulted in flowing oily tar that contaminated sediments and surface water which costed the USEPA around twelve million dollars and over twenty years to treat. In Canada, the Hagersville (Ontario) fire took place back in 1990 and required environmental treatment measures as well (Mawhinney 1990). To put tires to a better usage, they usually get shredded and become Tire Derived Aggregates (TDA). TDA is a cost-effective lightweight fill material (El Naggar et al. 2016; Sparkes et al. 2019) that is capable of consuming large quantities of tires in the construction of road embankments.

Many researchers have been studying TDA as a material and how can it be used in Civil Engineering applications. ASTM D6270-17 "Standard Practice for Use of Scrap Tires in Civil Engineering Applications" (ASTM 2017) provides material properties, testing procedures, design considerations, and construction practices for the use of TDA. TDA is classified into two types, type A and type B, based on maximum dimension and sieve analysis (ASTM 2017). The use of TDA is being researched in various ways some of which are using it as a lightweight fill over tunnels (Rodríguez et al 2018), pipes (Mahgoub and El Naggar 2019; Meguid and Youssef 2018), foundations

and retaining walls (Reddy et al 2018), and embankments (El Naggar et al. 2019; Meles 2014). Other studies involve studying the deformation and strength of TDA-sand mixtures (Youwai and Bergado 2003; Zhang et al 2018). Numerical modeling and verification have also been undertaken for TDA under various projects (Ni et al 2018).

TDA has been in use for embankments in the United States since 1990 in states of Vermont, Maine, Texas, and New York and as early as the year 2000 in Manitoba, New Brunswick, and Alberta in Canada (Mills et al. 2015). It has also been used in Ontario in 2012 (Macklin 2014) and recently in Nova Scotia (El Naggar et al 2019).

In order to better understand how TDA can help in building over soft soils, a 2D numerical finite element model is built using PLAXIS 2D. This paper aims to look at the factor of safety, settlements, and stresses that an embankment will undergo when built with different proportions of TDA and traditional fill. The fixed factor in this study is the weak soft soil beneath the embankment.

2 DEVELOPMENT OF FINITE ELEMENT MODEL

Numerical modeling was conducted on an embankment built on soft soil with typical soil parameters. The developed model was analyzed for settlements, stresses, and factor of safety after reaching the topmost level of the embankment. The analysis was done on four different cases by altering the number of TDA layers that are placed by 0.5 m. This model forms a basis for the extended study that will serve as a journal publication. This model is sought

to prove how TDA can help building on soft soils without collapse under immediate settlement and provide a suitable alternative for other more expensive options like ground improvement techniques.

2.1 Description of Finite Element Model Geometry

PLAXIS 2D was used to build the finite element model. It comprised of a 15 m undrained soft clay layer extended indefinitely in which a 7.5 m high 18 m wide embankment with a slope of 2:1 was built on it. The 18 m is divided to 2 by 2 lanes each of a width of 3.7 m which satisfies both AASHTO and TAC guides for a highway construction. The remaining 3.2 m can be used for a median/shoulders. Four cases were modeled as shown in Figures 1-4: control case T0 which comprised of 7.5 m high traditional fill, T1 case which has a 1 m TDA layer every 2 m of fill, T1.5 case which has a 1.5 m TDA every 1.5 m of fill, and T2 case which has a 2 m TDA every 1 m of fill except the 1.5 m at very top.

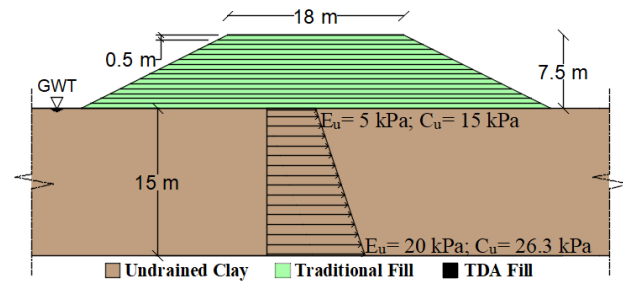


Figure 1 – T0 Case (Control Case)

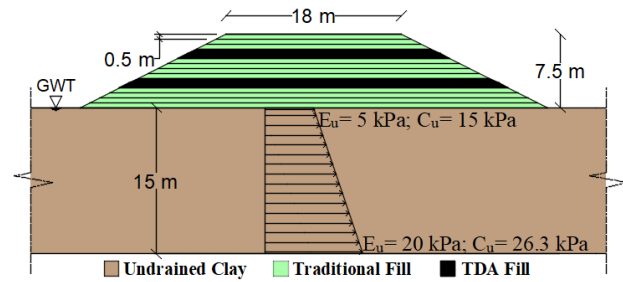


Figure 2 – T1 Case

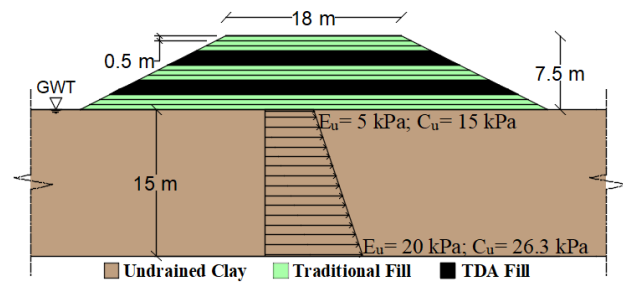


Figure 3 – T1.5 Case

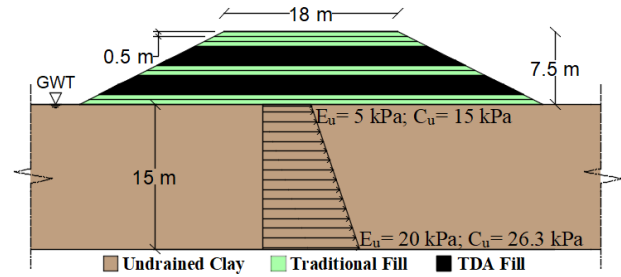


Figure 4 – T2 Case

2.2 Soil Stratigraphy and Material Properties

The soft clay layer was assumed to be horizontal for the model with the ground water table at the ground surface. Analysis was conducted under the undrained conditions. The different parameters of the soil properties were defined according to Look (2014) from his handbook and according to Ghomi (2018) from his thesis on TDA. Material model chosen was Mohr Coulomb, linear elastic perfectly plastic, to be used as first approximations. Since the strata is soft NC clay, the undrained cohesion and modulus of elasticity were set to increase with depth. Tables 1 and 2 below outline the properties used in the model.

Table 1 – Undrained Clay Properties

Soil	γ_{sat} kN/m ³	E_u MPa	ν	c_u kPa	ϕ°	$E_{u,inc}$ MPa/m	$c_{u, inc}$ kPa/m
Clay	15	5	0.5	15	0	1	0.75

Table 2 – Fill and TDA Properties

Soil	γ_d kN/m ³	γ_{sat} kN/m ³	E MPa	ν	c' kPa	ϕ'°
Fill	17	20	35	0.3	5	40
TDA	7	10	4.5	0.5	23.5	25.5

Legend:

- γ_d Dry Unit Weight
- γ_{sat} Saturated Unit Weight
- E/E_u Modulus of Elasticity (Drained/Undrained)
- ν Poisson's Ratio
- c_u/c' Undrained/Effective cohesion
- ϕ/ϕ' Undrained/Effective friction angle
- $E_{u,inc}$ Modulus of Elasticity increasing with depth
- $c_{u, inc}$ Undrained Cohesion increasing with depth

2.3 Construction Sequence

It is required to see the immediate response of soft clay under rapid construction hence placement of layers took place immediately one after the other. Due to that no consolidation was allowed nor analyzed. This is not the way it necessarily happens in real life; however, without

consolidation the worst-case scenario is being assessed as whether the soil can withstand the embankment or not under immediate settlement.

2.4 FE Mesh, Model, and Boundary Conditions

The model constructed was plane strain. It was meshed very fine resulting in 13519 nodes and 1657 soil elements with a minimum mesh quality value of 31% which indicates a good quality mesh. The sides of the clay layer were normally fixed in the lateral direction and free in the vertical direction, whereas the bottom boundary was fully fixed, and the top was set as free. Figure 5 illustrates the mesh.

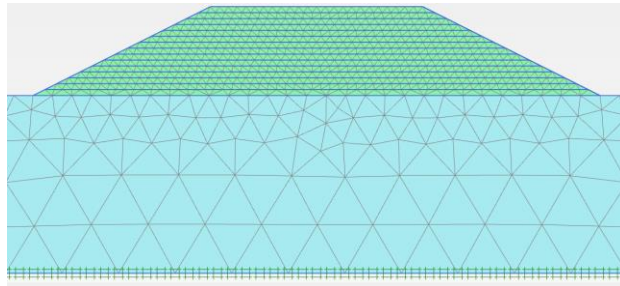


Figure 5 – Mesh of Model

3 RESULTS

The model built was analyzed in terms of factor of safety, settlements, and stresses at specific points among all the four cases. The collapse mechanism that occurred was proven through the factor of safety analysis, excessive settlement that took place, and the slip surface. Furthermore, comparisons concluded that TDA effectively led to lower stresses and settlements overall.

3.1 Factor of Safety Analysis

The aim of the factor of safety analysis is to see how TDA helped the embankment not to fail as construction progressed. This is due to the fact that TDA is lightweight which in turn reduced the total pressure and hence total load on the soft clay layer underneath. The factor of safety was monitored for the last four layers at elevations of 6 m, 6.5 m, 7 m, and 7.5 m as seen in Figure 6. The results came as expected with a drop of the factor of safety as construction progressed for the same case; however, it is important to know that case T0 is classified as collapse beyond 6.5 m as factor of safety drops below 1. This is also clearly proven in the next result section of excessive settlement. It is also seen very clearly that the addition of TDA raised the factor of safety for all elevations among all the cases. As more TDA layers were added, the increase in the factor of safety showed that it is non-linear and favorable. In other words, 1 m TDA raised the factor of safety by 30%; however, adding 2 m of TDA might result in an increase of factor of safety by 80%. Figure 6 illustrates the results obtained for the factor of safety analysis.

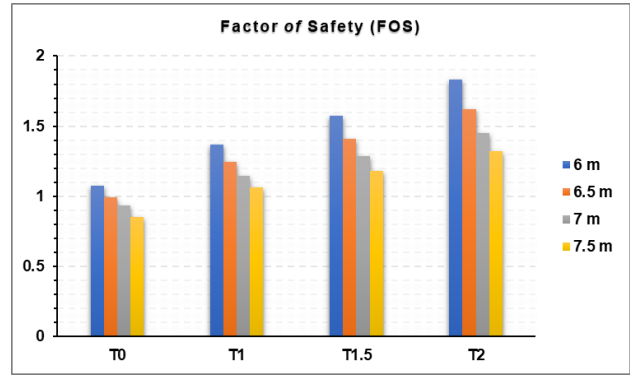


Figure 6 – Factor of Safety Analysis

3.2 Excessive Settlement Analysis

As seen in Figure 6 above, the control case factor of safety drops below 1 after 6.5 m elevation. This was interesting so it was looked at in terms of settlement at the highest point of embankment starting at 6 m and beyond as layers are added. Results for the settlement as shown in Figure 7 below showed an almost two-fold increase in the amount of settlement that took place beyond 6.5 m. The stress path and failing points were also looked at in how the collapse failure was progressing. At 7 m, a complete slip surface can be seen clearly. These analyses confirm that the embankment failed beyond 6.5 m for the T0 case which comprised of traditional fill only. Hence, the use of TDA not only increased the factor of safety but prevented collapse and excessive settlements to occur. A detailed section on settlements for cases T1, T1.5, and T2 at the targeted height of 7.5 m which utilizes TDA can be found under Section 3.3.

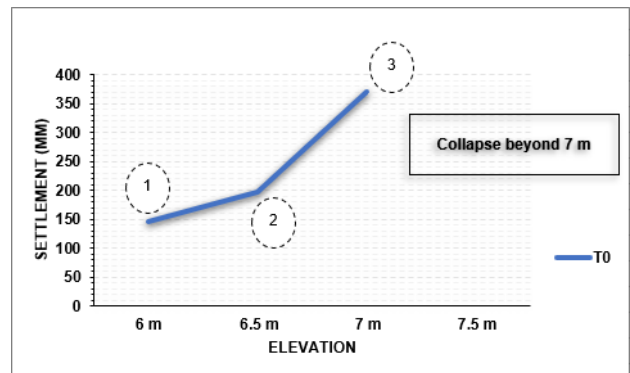


Figure 7 – Excessive Settlement Analysis (points 1-3 reference construction stages shown in Figure 8)

Points 1-3 in Figure 7 refer to Figure 8 found below at their respective elevation for the control case (T0) which are 6 m, 6.5 m, and 7 m. Figure 8 shows the failure points and how at 7 m a complete slip surface was formed, and collapse occurred.

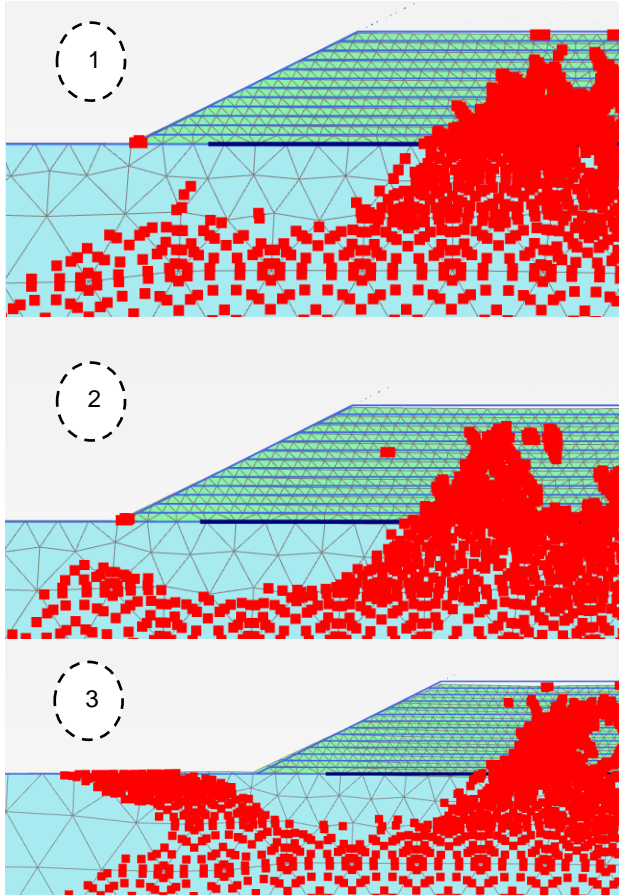


Figure 8 – Failure Points at Elevations 6, 6.5, and 7 m

A closer look at the deformed shapes at 6.5 m and 7 m can be found below in Figure 9. Not only collapse took place but also bulging of the nearby clay increased significantly. Scale provided in photo is in metres.

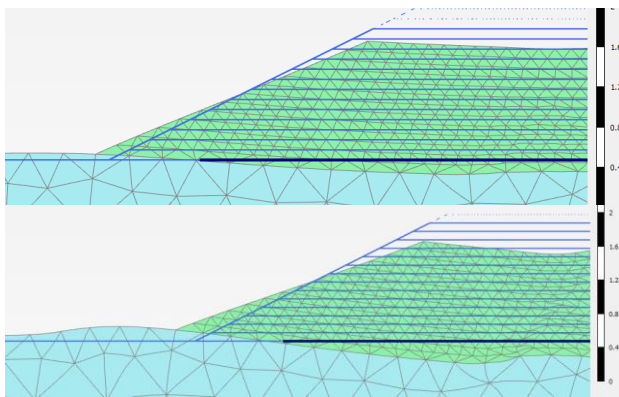


Figure 9 – Deformed Mesh at 6.5 and 7 m Embankment Height respectively

3.3 Settlement Analysis

For the settlement analysis, three points on the embankments were chosen to be monitored which were the toe, crest, and top center as per Figure 10. To do comparisons before and after the collapse, two levels were chosen one at 6.5 m and the other at 7.5 m. Results shown in Figure 11 at 6.5 m proved that TDA does in fact reduce the immediate settlement; however, it is clearly seen that a large change occurs between T0 case and T1.5 case (192 vs 109, 55 vs 29) hence 1 m TDA is highly effective.

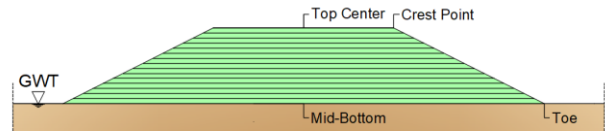


Figure 10 – Location of Points Chosen

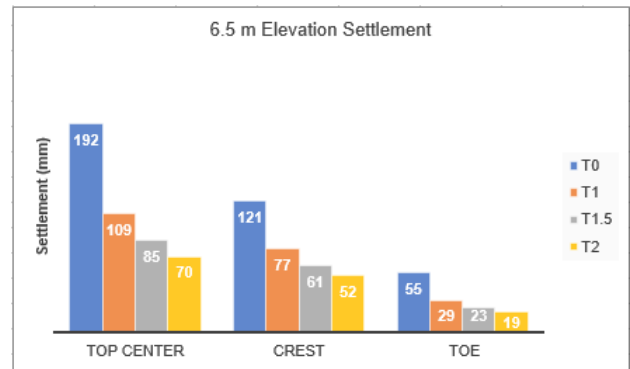


Figure 11 – Settlement at 6.5 m Embankment Height

From Figure 12, as you increase TDA layers settlement will still decrease. The remarkable point would be the large increase in settlement due to the addition of the final 1 m of fill when compared to the 6.5 m values where the center exhibits the largest increases (189 vs 109 for center), and which is expected as it deforms more/less like a beam.

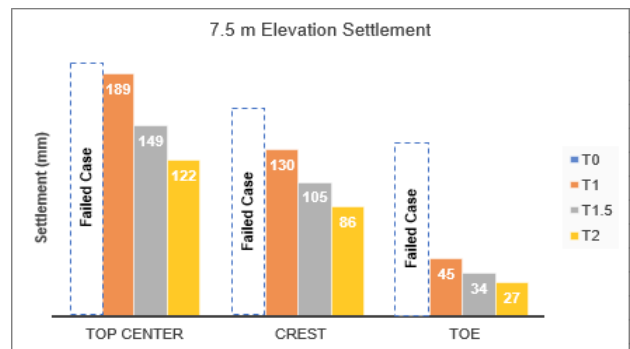


Figure 12 – Settlement at 7.5 m Embankment Height

3.4 Stress Analysis

For the reduction of stress that is expected due to adding TDA layers, it was chosen to do the comparison at the middle bottom of the embankment as illustrated in Figure 10. The stress increased as embankment layers were added which was expected. The stress decreased nonlinearly as more TDA layers were added as seen in Figure 13. For example, stress at 6.5 m were as follows for the cases in order 100, 84, 79, and 72 kPa. Due to the failure case beyond 6.5 m for control case and like the settlement section, the analysis was done for 6.5 m and 7.5 m. Both showed the same trend.

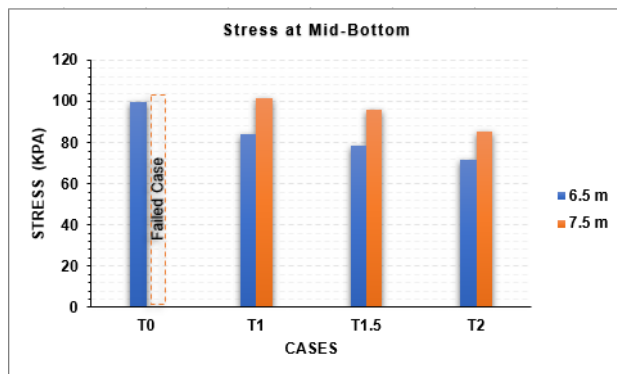


Figure 13 – Stress Analysis

4 CONCLUSIONS

Embankments on soft soils are challenging due to their high-water content and low shear strength. Innovative construction techniques such as the use of Tire-Derived Aggregates (TDA) provide a possible approach to deal with construction on soft soils. In this study, a 2D finite element model was built using PLAXIS 2D in order to better understand how can TDA help when dealing with soft soils. Mohr coulomb, linearly elastic perfectly plastic, was used as the material model.

From the study, it was shown that TDA can be successfully used when the soft soil strata fail under normal fill. TDA will prevent excessive settlements and increase the factor of safety of the embankment greatly. Furthermore, TDA is known to be a lightweight material so it was proven that stress felt by the soft soil will be less. This in turn will also reduce the settlement that an embankment might suffer leading to an extended life of it and the pavement itself which reduces costs in the long run. By using TDA, not only tire fires are being prevented but also tires are being recycled instead of occupying landfill spaces. Nevertheless, certain restrictions need to be followed during construction according to ASTM D6270-17. This study was under immediate and fast construction such that consolidation cannot take place and resembling the worst-case scenario. This is a research in progress and more results on different TDA configurations will be provided later.

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