# Soil-Structure Interaction of Cut and Cover Tunnel Using Tire-Derived Aggregates Above Crown Level

by

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Dalhousie University is located in Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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**ABSTRACT**

Tire-derived aggregates (TDA) are increasingly considered for reuse globally due to their unique properties, including lightweight composition, strong hydraulic conductivity, superior thermal insulation, and the potential for vibration damping. Notably, TDA exhibit distinctive granular characteristics, with a significant portion of deformation being recoverable. This recoverable deformation is a critical attribute that enhances the material's resilience, particularly in scenarios involving dynamic forces or cyclic loading.

This study focuses on investigating the behavior of Tire-derived aggregate (TDA) when placed above a Cut & Cover railway tunnel. The primary aim is to mitigate the static load at the crown and observe lining relief resulting from the introduction of the TDA layer. To analyze the tunnel, a Plaxis-3D finite element model has been developed, incorporating various assumptions about the constitutive model of the TDA material.

The study reveals that placing a TDA layer above the tunnel has a significant effect on both the bending moment and displacement of the lining. The term "significant effect" denotes observable and impactful changes in the structural behavior of the tunnel. These changes, including a reduction in static load and lining relief, contribute to the overall stability and performance of the tunnel structure, thereby potentially reducing the risk of structural failure.

In terms of the constitutive models used for analysis, a Hardening Soil Model elastoplastic model, with the exception of an elastic model applied to concrete, is employed. The study considers three Plaxis-3D models: one-TDA layer, two-TDA layer, and a tunnel surrounded by the TDA layer. This approach allows for a comprehensive investigation into how the presence and arrangement of TDA layers influence the structural response of the tunnel.

In summary, this study delves into three constitutive models, assessing their effectiveness in optimizing the bending moment, minimizing deformation at the tunnel lining, and mitigating the risk of failure. The findings provide valuable insights for future applications of TDA in similar engineering scenarios, emphasizing the importance of TDA recoverable deformation and its potential to enhance structural resilience.

# LIST OF ABBREVIATIONS AND SYMBOLS USED

## Abbreviations

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ASCE | American Society of Civil Engineering |
| FHWA | Federal Highway Administration |
| ASCE | American Society of Civil Engineers |
| ASTM | American Society for Testing and Materials |
| CHBDC | Canadian Highway Bridge Design Code |
| CSA | Canadian Standards Association |
| FE | Finite Element |
| FEM | Finite Element Model |
| BM | Bending Moment |
| HSM | Hardening Soil Model |
| HSM-Small | Hardening Soil Model with Small Strain |
| LRFD | Load and Resistance Factor Design |
| MC | Mohr Coulomb |
| NBCC | National Building Code of Canada |
| ONT | Ontario |
| SSI | Soil Structure Interaction |
| TDA | Tire Derived Aggregate |

**Symbols**

| | |
|---|---|
| c’ | Effective cohesion |
| Cu | Undrained shear strength |
| D | Diameter |
| $d$ | Depth |
| E | Modulus of elasticity |
| $E_{50}$ | Secant modulus |
| $E_{oed}$ | Tangent stiffness from odometer test |
| $E_s$ | Soil modulus of elasticity |
| EI | Bending stiffness |
| EA | Hoop stiffness |
| Fy | Yield strength |
| Fu | Tensile strength |
| G | Shear Modulus |
| hc | Backfill height above the tunnel crown |
| H | Backfill height |
| $Ko$ | At-rest earth pressure coefficient |
| L | Length |
| M | Bending Moment |
| Pref | Reference pressure |

## STATEMENT

Cut & Cover tunnel construction is a methodical process employed in the creation of subsurface passages, particularly integral in urban and railway infrastructure projects. This methodology initiates with the excavation of an open trench or cut in the ground, meticulously following a predetermined path delineating the intended tunnel. Within this trench, reinforced concrete walls and a base slab are systematically constructed, forming the fundamental structure of the tunnel. The incorporation of steel reinforcement into these concrete elements is crucial, enhancing their strength and overall durability to withstand the anticipated loads during the tunnel's operational lifespan.

Following the construction of the concrete structure, the open trench undergoes a subsequent phase of being covered or backfilled, effectively concealing the tunnel beneath the ground and restoring the surface for regular use. The structural design of a Cut & Cover tunnel is an intricate process, considering various engineering aspects such as soil conditions, groundwater levels, and the projected loads the tunnel will encounter. Waterproofing measures are often integrated into the design to mitigate the risk of water ingress, ensuring the longevity and structural integrity of the tunnel over time.

In the specific context of this study, the conventional Cut & Cover tunnel design is enriched by the strategic integration of Tire-derived aggregate (TDA) above the tunnel structure. TDA, recognized for its lightweight and deformable characteristics, introduces an innovative element to the established construction method. The study endeavors to comprehensively understand how this layer of TDA influences the structural behavior of the tunnel, particularly concerning the reduction of static load and addressing potential risks related to tunnel deformation.

The employment of sophisticated modeling tools, notably the Plaxis-3D finite element model, augmented by the inclusion of the Hardening Soil Model elastoplastic model for materials like TDA, facilitates a detailed simulation of the tunnel's structural response under various conditions. This advanced modeling approach allows for a nuanced exploration of the complex interactions within the tunnel structure, providing insights into how TDA affects structural parameters such as bending moments. The research objectives extend beyond optimization, aiming to identify the most effective constitutive model for TDA within this specific engineering context.

Beyond the immediate scope of the study, the insights gleaned from this research significantly contribute to the broader field of tunnel engineering. The findings hold the potential to shape the trajectory of future designs and constructions of concrete Cut & Cover tunnels. By advancing the understanding of how innovative materials, such as TDA, can be effectively integrated, the research paves the way for enhanced structural efficiency, resilience, and sustainability in tunnel engineering practices. These contributions resonate not only within the academic and research community but also reverberate through practical applications, influencing the evolving landscape of urban and railway infrastructure projects globally.

# ACKNOWLEDGEMENTS

I am profoundly grateful to THE ALMIGHTY for His boundless blessings and guidance, empowering me to tread the path of righteousness. My deepest appreciation goes to Dr. Hany El Naggar for his exceptional mentorship and steadfast encouragement throughout my research journey. Under his guidance, I have grown both academically and personally, and I am truly privileged to have him as my mentor.

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# CHAPTER-1 INTRODUCTION

## 1.1 Research Background

The development of underground tunnels, driven by humanity's desire to overcome geographical barriers and enhance connectivity, is integral to modern urban and transportation infrastructure. Among the methodologies in tunnel engineering, the Cut & Cover technique stands out as versatile and widely adopted **Figure 1-1,** (WSP, 2022). Its impact is evident in the extensive network of subterranean passageways supporting modern societies. This thesis explores the historical roots, contemporary applications, and ongoing advancements of the Cut & Cover technique, aiming to deepen our understanding of this engineering marvel and its profound influence on modern urban landscapes. Through comprehensive examination, we uncover the intricate details of its implementation and its crucial role in shaping urban development.(Hung, 2009)

**Figure 1-1: Excavation of trench and installation of concrete lining for a cut and cover tunnel construction (Zvěrotice Tunnel – Overall View)**

The Cut-Cover technique stands as a testament to human ingenuity in overcoming geographical obstacles. It embodies a distinctive methodological paradigm characterized by the initial excavation of an open trench meticulously aligned with the intended tunnel path (WSP, 2022). Subsequently, reinforced concrete structures are methodically constructed within this trench. The strategic use of steel reinforcement enhances the strength and durability of these concrete elements, enabling them to withstand a myriad of anticipated loads throughout the tunnel's operational lifespan.

The efficacy of the Cut-Cover technique is underscored by its remarkable adaptability to various contexts and its pivotal role in shaping intricate underground networks. This versatile method has been instrumental in the creation of subways, roadways, and utility tunnels. It offers a reliable solution for navigating urban landscapes where space constraints or specific geographical conditions necessitate innovative engineering approaches.

From its early applications in the construction of simple pedestrian walkways during the Roman Empire (Diamond & Kassel, 2018) the method has undergone significant advancements. Today, it finds sophisticated use in complex transportation networks, seamlessly integrating with existing urban environments (Sakurai & Matsuda, 1998). This characteristic makes cut & cover an invaluable tool for city planners and engineers seeking efficient solutions for expanding transportation networks.

Furthermore, the Cut-Cover technique has proven vital in addressing challenges associated with soil conditions, groundwater levels, and the need for waterproofing. The careful consideration of these factors during the structural design phase ensures not only the longevity of the tunnel but also its resilience in the face of varying environmental conditions (EWickham & Tiedemann, 1976)

## 1.2 Cut & Cover Tunnel Construction

The intricacies of Cut & Cover tunnel construction unfold as a systematic process that initiates with the precise excavation of a trench meticulously aligned with the intended trajectory of the tunnel (WSP, 2022). This deliberate alignment ensures that the tunnel seamlessly integrates into the urban or transportation landscape it is meant to serve. Within this excavated trench, the core components of the tunnel structure take shape – reinforced concrete walls and a base slab. The meticulous construction of these elements is a testament to the precision required in the early stages of the process, forming the bedrock of the tunnel's overall structural integrity(Mouratidis, 2008.)

The integration of steel reinforcement into the concrete elements is not a mere detail but a critical engineering consideration(Bertolini, 2008). This infusion of steel confers a level of strength and durability necessary for the tunnel to endure the myriad loads it is expected to face throughout its operational lifespan. Whether it's the weight of vehicles traversing a roadway tunnel, or the forces exerted by the surrounding soil, the robustness imparted by steel reinforcement ensures that the tunnel structure remains steadfast and reliable in the face of dynamic and potentially challenging conditions.

Upon the meticulous completion of the concrete structure, the next phase of the process involves concealing the open trench. This is achieved through backfilling or covering, an operation executed with precision to seamlessly restore the surface for regular use. The significance of this step extends beyond aesthetic considerations – it is a pivotal moment in the transformation of the subterranean space into a functional component of the urban or transportation infrastructure. The careful concealment of the trench marks the culmination of the construction effort, rendering the tunnel invisible to the surface yet serving as a crucial conduit beneath (Tiedemann & Associates, 2016.).

The structural design of Cut & Cover tunnels is a multidimensional endeavor, requiring a comprehensive consideration of various factors. Soil conditions, a variable often unique to each construction site, demand careful analysis to understand the potential impacts on the tunnel's stability. Similarly, groundwater levels introduce a layer of complexity, necessitating strategies to prevent water ingress and ensure the tunnel remains dry and resilient. Anticipated loads, stemming from the volume and nature of traffic or other usage, are intricately woven into the design considerations. It is this holistic approach that distinguishes Cut & Cover tunnel construction – a method that goes beyond the mere act of building a passageway to becoming a harmonization of engineering, geotechnical, and environmental considerations (Plumey et al., 2006).

The incorporation of waterproofing measures (Alkorgeo & Portugal Ltda, 2011.) further underscores the commitment to the long-term structural integrity of the tunnel. Water, with its potential to compromise the stability of the tunnel structure, is a formidable adversary that demands pre-emptive engineering solutions. Waterproofing, therefore, becomes a safeguarding mechanism, reinforcing the durability of the tunnel against the erosive effects of water over time.

In summary, Cut & Cover tunnel construction is not merely a process of excavation and concrete placement; it is an orchestrated symphony of engineering precision, material science, and environmental consciousness. The alignment of the trench, the construction of reinforced concrete elements, the integration of steel reinforcement, and the meticulous considerations for soil, water, and loads collectively contribute to the creation of a subterranean conduit that seamlessly integrates into the fabric of urban and transportation landscapes while standing resilient against the tests of time and usage.

### 1.3 Innovation in Cut & Cover Tunnel Construction

In recent years, the field of tunnel engineering has undergone a significant paradigm shift, with a growing emphasis on exploring avant-garde materials and methodologies to enhance the efficiency and sustainability of underground structures(Wilton, 1996). A notable frontier in this wave of innovation involves the deliberate integration of Tire-derived Aggregate (TDA) into the Cut & Cover tunnel construction process. TDA, renowned for its lightweight composition and deformable characteristics, introduces a groundbreaking element to traditional construction methodologies, prompting exploration into its potential to address inherent challenges in tunnel construction(Rodríguez et al., 2018).

The strategic incorporation of TDA above the tunnel structure represents a departure from conventional practices, motivated by the aspiration to leverage its distinctive attributes, including lightweight properties, deformability, and vibration damping capabilities. This research endeavors to unravel the multifaceted implications of integrating TDA into the construction process, with a specific focus on its influence on static loads, its potential to mitigate risks associated with tunnel deformation, and its overall contribution to the structural resilience of the tunnel.

This innovative approach marks a pivotal moment in the evolution of Cut & Cover tunnel construction, signifying a departure from established norms and embracing a forward-thinking methodology that seeks to optimize structural performance and enhance the sustainability of underground infrastructure. The investigation into the effects of TDA promises to yield valuable insights, potentially paving the way for a new era of tunnel engineering that seamlessly integrates innovative materials to address the dynamic challenges of urbanization and transportation infrastructure.

### 1.4 Advanced Modeling Techniques

This study investigates the influence of Tire-Derived Aggregate (TDA) on the structural performance of cut-and-cover tunnels. Finite element modeling (FEM) techniques are employed to analyze the complex interactions between soil and TDA within the tunnel environment. Plaxis-3D software, recognized for its ability to simulate geotechnical and structural behaviors, serves as the primary tool for this exploration. The Hardening Soil model, integrated within Plaxis-3D (Brinkgreve, 2000.), allows for a nuanced consideration of the non-linear material properties of both soil and TDA. This advanced modeling approach facilitates a thorough examination of TDA's impact on critical factors such as deformation, load distribution, and overall structural integrity of the tunnel. By leveraging these techniques, the research seeks to glean valuable insights into the performance and resilience of tunnels incorporating TDA. Ultimately, this knowledge can contribute to the optimization of design and construction practices for cut-and-cover tunnels, fostering the development of more sustainable infrastructure solutions.

## 1.5 Research Objective

1. Investigate the Influence of Tire-Derived Aggregates (TDA) on Structural Behavior:

    - This involves studying how the presence of TDA affects the overall behavior and performance of the Cut & Cover railway tunnel.

    - Key aspects to be considered include load distribution, stress distribution, and deformation characteristics within the tunnel structure.

2. Mitigate Static Loads at the Crown and Observe Lining Relief:

    - Focus on understanding how the introduction of TDA layers above the tunnel mitigates static loads, especially at the crown.

    - Observing lining relief entails assessing how the structural elements of the tunnel respond to the introduction of TDA layers, particularly in terms of reduced stress concentrations and deformations.

3. Develop a Plaxis-3D Finite Element Model:

    - Utilize the Plaxis-3D finite element modeling software to create a detailed numerical model of the tunnel.

    - The model should accurately represent the geometry, material properties, boundary conditions, and loading conditions of the tunnel system.

4. Optimize Bending Moments and Minimize Deformation at the Tunnel Lining:

   - Analyze the structural response of the tunnel to determine how TDA layers influence bending moments along the lining.

   - Aim to minimize deformation at the tunnel lining by optimizing the arrangement and properties of TDA layers.

5. Assess Effectiveness of Different TDA Layer Configurations:

   - Explore various configurations of TDA layers (e.g., one-TDA layer, two-TDA layer, tunnel surrounded by TDA layer) to understand their impact on structural performance.

   - Evaluate the effectiveness of each configuration in terms of load distribution, stress reduction, and deformation control.

6. Provide Valuable Insights for Future Applications of TDA:

   - Draw conclusions from the study's findings to provide insights and recommendations for future applications of TDA in similar engineering scenarios.

   - Identify best practices, design guidelines, and considerations for incorporating TDA in tunnel construction projects.

By elaborating on each point of the research objective, the study aims to provide a comprehensive understanding of how the integration of TDA layers influences the structural behavior and performance of cut & cover railway tunnels, ultimately contributing to advancements in tunnel engineering practices and sustainable infrastructure development.

## 1.6 Scope of Research

The field of study is wide-ranging since it takes an in-depth look at how tire-derived aggregates (TDA) behave and their effects on the structural behavior of a cut & cover tunnel. It also entails analysing the mechanical characteristics of TDA such as density, compressive strength, and elastic modulus under static loading conditions. Additionally, the study aims to explore the structural behavior of the tunnel, considering factors such as load distribution, stress distribution, and deformation characteristics within the tunnel structure in the presence of TDA.

Furthermore, the scope extends to the development of a detailed numerical model of the tunnel using Plaxis-3D finite element modeling software. This model will incorporate various constitutive models for TDA material to accurately capture its mechanical behavior. Through this modeling approach, the study seeks to analyze the structural response of the tunnel, optimize bending moments along the tunnel lining, and minimize deformation by optimizing the arrangement and properties of TDA layers.

Moreover, the study will evaluate different configurations of TDA layers (such as one-TDA layer, two-TDA layer, surrounding TDA layer) to understand their impact on structural performance. This evaluation will include analyzing load distribution, stress reduction, and deformation control for each TDA layer configuration. The findings of the study will provide valuable insights and recommendations for future TDA applications in similar engineering scenarios, aiming to identify best practices, design guidelines, and considerations for incorporating TDA in tunnel construction projects.

Ultimately, the study aims to contribute empirical data and analytical insights to advance tunnel engineering practices. By comprehensively investigating the influence of TDA on the structural behavior of a cut & cover tunnel, the study seeks to contribute to the advancement of sustainable infrastructure development using innovative materials like TDA in tunnel construction.

## 1.7 Overview of the Thesis

**Chapter 1:** Introduction Provides a contextual background on the application of Tire-Derived Aggregate (TDA) in tunnel construction, outlines research objectives, scope, and limitations.

**Chapter 2:** Literature Review Offers an overview of conventional tunnel construction methods and introduces the properties of TDA, previous research findings, and relevant case studies.

**Chapter 3:** Finite Element Model Development Details the methodology for developing and validating a finite element model to analyze the structural behavior of concrete lining with TDA placed above crown level.

**Chapter 4:** Alternative TDA Configurations Explores various TDA layer arrangements through a parametric study to assess their structural performance and suitability for tunnel construction.

**Chapter 5:** Results and Discussion Presents the results of the finite element analysis and parametric study, followed by a comprehensive discussion on their implications and significance.

**Chapter 6:** Conclusion summarizes the key findings, contributions to the field of geotechnical engineering, and provides recommendations for future research directions.

# CHAPTER-2 LITERATURE REVIEW

## 2.1 Overview of cut and Cover Tunnel Construction Method

Cut and cover tunnel construction represents a fundamental method employed in the creation of underground passages, crucial for urban and transportation infrastructures. This methodological approach begins with the meticulous excavation of an open trench, precisely aligned with the intended trajectory of the tunnel. Within this excavated trench, the essential components of the tunnel structure take shape, including reinforced concrete walls and a base slab (Wilton, 2011.). It is imperative to note that the incorporation of steel reinforcement into these concrete elements is not merely a detail but a critical engineering consideration. This infusion of steel reinforcement enhances the strength and durability of the concrete components, enabling them to withstand a myriad of anticipated loads over the tunnel's operational lifespan(Bertolini, 2008).

Upon the meticulous completion of the concrete structure, the subsequent phase of the process involves concealing the open trench. This is achieved through backfilling or covering, an operation executed with precision to seamlessly restore the surface for regular use. The significance of this step extends beyond aesthetic considerations – it is a pivotal moment in the transformation of the subterranean space into a functional component of the urban or transportation infrastructure. The careful concealment of the trench marks the culmination of the construction effort, rendering the tunnel invisible to the surface yet serving as a crucial conduit beneath(Diamond & Kassel, 2018; EWickham & Tiedemann, 1976).

The structural design of cut and cover tunnels is a multidimensional endeavor, requiring a comprehensive consideration of various factors. Soil conditions, which often vary at each construction site, demand careful analysis to understand their potential impacts on the tunnel's stability. Similarly, groundwater levels introduce a layer of complexity, necessitating strategies to prevent water ingress and ensure the tunnel remains dry and resilient. Anticipated loads, stemming from the volume and nature of traffic or other usage, are intricately woven into the design considerations. It is this holistic approach that distinguishes cut and cover tunnel construction – a method that goes beyond the mere act of building a passageway to become a harmonization of engineering, geotechnical, and environmental considerations.

Moreover, the incorporation of waterproofing measures further underscores the commitment to the long-term structural integrity of the tunnel. Water, with its potential to compromise the stability of the tunnel structure, is a formidable adversary that demands pre-emptive engineering solutions. Waterproofing, therefore, becomes a safeguarding mechanism, reinforcing the durability of the tunnel against the erosive effects of water over time.

## 2.2 Terminology and Standardization

The Federal Highway Administration (FHWA) Technical Manual for Design and Construction of Road Tunnels, (Hung, 2009), offers a comprehensive methodology and specifications for the construction of cut and cover tunnels from bottom to top. This methodology guides various stages of construction, starting with trench excavation and progressing through structural component installation to final backfilling and surface restoration. The manual delineates specific terminology and standards pertaining to key aspects of cut and cover tunnel construction, including haunch, depth, width, backfill, and sidewalls. These specifications ensure structural integrity, safety, and longevity while aligning with industry standards and best practices. By adhering to the manual's guidelines, engineers and contractors can efficiently plan, design, and execute cut and cover tunnel projects with precision and confidence. To enhance understanding, **Figure 2-1** illustrates some widely used terms associated with these structures, providing a visual aid alongside the explained terminology.

1. **Haunch**: The haunch refers to the inclined area between the vertical sidewalls and the base slab of the tunnel. It provides structural support to the tunnel walls and helps distribute loads from the backfill and overlying soil.

2. **Cover Depth**: Cover depth, also known as cover thickness, refers to the vertical distance between the top of the tunnel structure (typically the crown) and the ground surface or overlying pavement. It is an important consideration for ensuring adequate protection of the tunnel structure from external loads and environmental factors.

3. **Width**: The width of a cut and cover tunnel refers to the horizontal distance between the sidewalls of the tunnel. It determines the size of the tunnel cross-section and influences factors such as traffic capacity and internal space.

4. **Span**: Span refers to the horizontal distance between the sidewalls of the tunnel at a specific cross-section. It is typically measured perpendicular to the longitudinal axis of the tunnel and is a critical parameter for structural design and analysis.

5. **Backfill**: Backfill refers to the material used to refill the excavated trench after the construction of the tunnel structure. It provides support to the tunnel walls, helps distribute loads, and stabilizes the surrounding soil.

6. **Spandrel**: The spandrel is the portion of the tunnel sidewall located between the base slab and the springing line of the arch or roof slab. It contributes to the overall structural stability and load-bearing capacity of the tunnel.

7. **Arch Crown**: The arch crown is the highest point of the tunnel's arch-shaped roof slab or crown. It is a critical structural element that supports the overlying soil or pavement and helps distribute loads effectively.

8. **Bedding**: Bedding refers to the layer of material (often concrete or granular material) placed beneath the base slab of the tunnel to provide a stable foundation and distribute loads evenly. It enhances the structural integrity and performance of the tunnel.

9. **Sidewalls**: Sidewalls are the vertical structures that form the sides of the cut and cover tunnel. They provide lateral support to the tunnel structure, resist soil pressures, and contribute to overall stability.

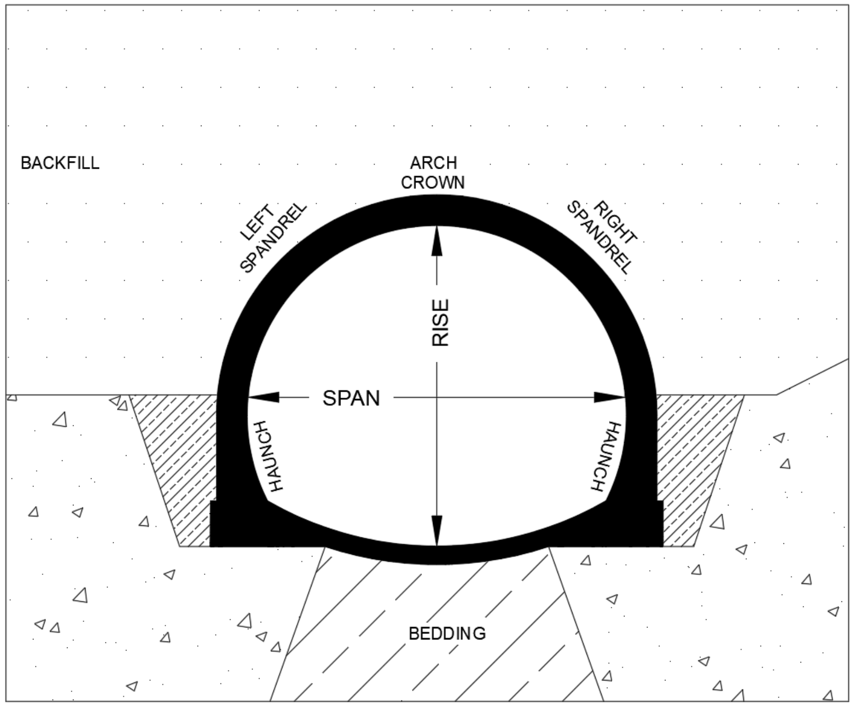



**Figure 2-1: Visualization of the terminology related to cut and cover tunnel**

## 2.3 Significance of Geotechnical Investigation

Before starting the construction of a cut and cover tunnel or even dumping the first load of backfill, it's crucial to conduct thorough geotechnical investigations. Think of these investigations as laying the groundwork for the entire project's success. They involve digging deep into the ground to understand what's beneath the surface – things like soil properties, how much weight the soil can bear, and any potential problems the site might have. These investigations become even more important when we don't have much information about what's underground. They serve as the bedrock upon which decisions about site suitability and risk mitigation are made.

The engineered backfill plays a crucial role in cut and cover tunnels. Composed primarily of well-graded granular soils, this backfill provides the necessary support and stability for the tunnel structure. The selection of the right soil for this purpose is a decision that reverberates throughout the tunnel's lifespan. Engineered backfill suitability is classified according to (ASTM D2487-2006), as presented in **Table-2-1**. This classification system categorizes soils based on their properties and compaction characteristics. Engineers rely on these guidelines to ensure that the selected soils meet the stringent criteria for stability and compaction, laying the foundation for a robust structure.

The secant modulus of soil stiffness, represented as $Es$, is a key parameter that varies depending on soil type and compaction level. This value provides insights into how a soil's stiffness evolves under different compaction conditions, a vital aspect of cut and cover tunnel design. Canadian Highway Bridge Design Code CHBDC, (Ministry of Transportation,2006.) outlines specific $Es$ values for different soil groups and various Standard Proctor densities defined by (ASTM D698-12 (2021), These values serve as a compass for geotechnical engineers, guiding their decisions during design and construction.

**Table-2-1: Soil Classification on** (ASTM D2487-06)

| **Soil Group** | **Grain Size** | **Soil type** |
|---|---|---|
| I | Coarse | Well graded gravel<br>Well sandy gravel<br>Poorly graded gravel<br>Poorly sandy gravel<br>Well graded sand<br>Well gravelly sand<br>Poorly graded sand<br>Poorly gravelly sand |

| Soil Group | Grain Size | Soil type |
|---|---|---|
| II | Medium | Clayey gravel<br>clayey-sandy gravel<br>Clayey sand<br>clayey gravelly sand<br>Silty sand<br>silty gravelly sand |

**Table-2-2: Secant Modulus of soil values for various soil groups and different standard proctor densities in accordance with (ASTM D698-12 (2021)**

| Soil Group | Standard Proctor Density % | Secant Modulus of Soil Es Mpa |
|---|---|---|
| I | 85 | 6 |
| | 90 | 12 |
| | 95 | 24 |
| | 100 | 30 |
| II | 85 | 3 |
| | 90 | 6 |
| | 95 | 12 |
| | 100 | 15 |

The importance of $Es$ values cannot be overstated, yet it's imperative to acknowledge their dynamic nature. These values undergo changes depending on factors such as soil group and compaction density. To harness the power of these values, they are often graphically represented against Standard Proctor densities, Geotechnical analysis using $Es$ values aids in understanding how the soil will behave under different loading conditions. This knowledge is pivotal for predicting settlement, evaluating bearing capacity, and assessing lateral earth pressure. Armed with this information, engineers can make informed decisions, ensuring the structural integrity of the cut and cover tunnels.

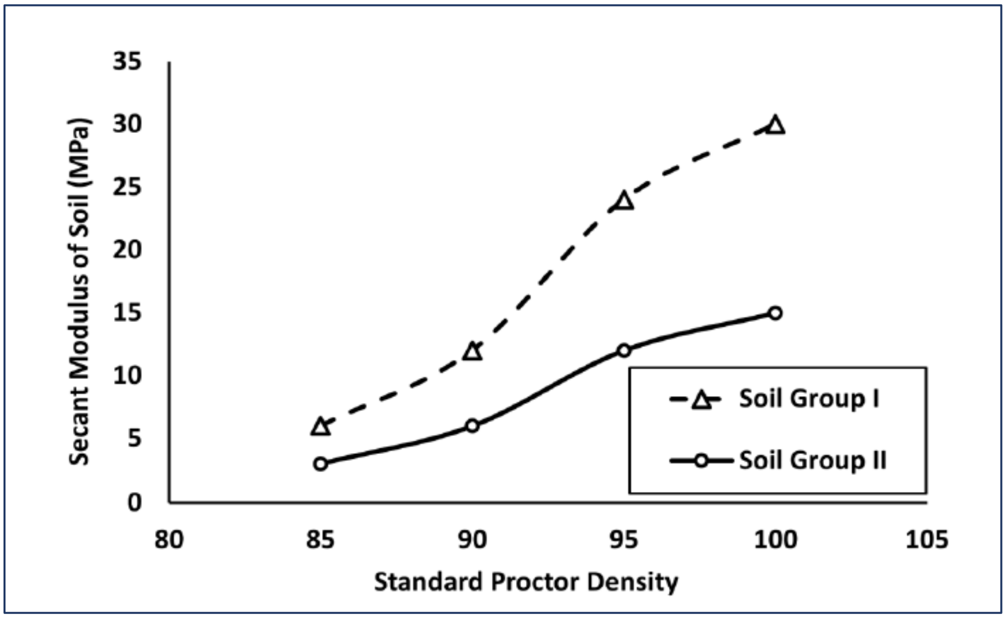



**Figure 2-2: Variation of $Es$ with Standard Proctor Density for Different Soil Groups (Metwally, 2023)**

## 2.4 Introduction to TDA

Tire-derived aggregates (TDA) offer a sustainable solution to the environmental challenges posed by scrap tire disposal. These recycled materials possess a multitude of advantageous properties, making them suitable for various civil engineering applications. The production process involves shredding scrap tires into various sizes, typically ranging from 12 mm to 300 mm according to (ASTM D6270, 2008). While the standard defines this upper limit, there might be a possibility of a small percentage (around 10%) exceeding this size during the shredding process, depending on the specific equipment and practices employed by some manufacturers (Dickson et al., 2001; Mills & McGinn, 2010; Pincus et al., 1994; Upton & Machan, 2015).

**Production and Classification of TDA:** TDA production involves mechanically shredding scrap tires into various fragments. These range in size, offering a versatile material for construction applications. Standards like (ASTM D6270, 2008) categorize TDA into two main types based on particle size distribution:

- **Type A TDA:** Falling between 12 mm and 70 mm (Meles, 2014).
- **Type B TDA:** Ranging from 70 mm to 300 mm (Meles, 2014).

**Table 2-3: Classification based on the size of the shredded tire pieces (ASTM D6270, 2008)**

| Size (mm) | Classification |
|---|---|
| <0.425 | Powdered Rubber |
| 0.425-2 | Ground Rubber |
| .0425-12 | Granulated Rubber |
| 12-50 | Tire Chips |
| 50-305 | Tire Shreds |
| 12-305 | Tire Derived Aggregates |

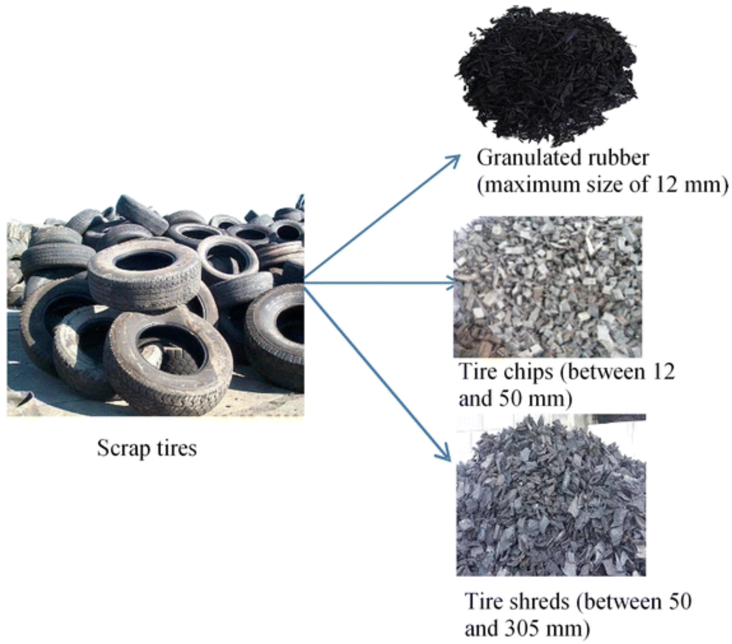



**Figure 2-3: Sustainable utilization of scrap tires for geotechnical applications: Scrap tires being processed into TDA through cutting into various sizes**

**Table 2-4: Gradation of TDA Material (Rodríguez et al., 2018)**

| Maximum Size (mm) | Percentage Passing (%) |
|---|---|
| 450 | 100 |
| 300 | 90 |
| 200 | 75 |
| 75 | 50 |
| 38 | 25 |
| 4.75 | 1 |

The utilization of TDA in civil engineering applications offers a sustainable solution to the environmental challenges associated with scrap tire disposal. In North America alone, millions of tires are discarded annually, contributing to tire stockpiles and environmental hazards(El Naggar, 2018). By repurposing scrap tires into TDA, these materials are diverted from landfills and stockpiles, reducing environmental pollution, and conserving non-renewable aggregates for future generations. TDA has been successfully used in several jurisdictions in North America and around the world since the early 1990 (Dickson et al., n.d.; Humphrey et al., n.d.; Meles, 2014.).

(Azevedo et al., 2012) estimated that each seven people alive produces one scrap tire per year on average. This average is not evenly scattered; advanced countries have a higher rate of scrap tires per capita compared to developing countries. In North America, approximately 250 million tires are discarded each year in the United States and 30 million in Canada (El Naggar, 2018). Disposal issues along with a continuing increase in tire production have increased tire stockpiles. Finding sustainable ways to dispose of these tires continues to be a severe problem throughout the world not only in North America. Consequently, shredding tires to TDA and using it in civil engineering applications provides a sustainable solution for these environmental problems. The economic and ecological benefits of using TDA as an engineered fill material are evident as large volumes of scrap tires are diverted from landfills and stockpiles and, at the same time, equal volumes of non-renewable aggregates are saved.

TDA has outstanding geotechnical properties, preserves its structural integrity, and weighs approximately 60% less than conventional geomaterials. The lightweight characteristic of TDA coupled with its structural integrity makes it a suitable material to be used as an engineered backfill over cut and cover concrete existing tunnel. In this research, an innovative solution is introduced in which a layer of TDA is placed over a cut and cover tunnel.

Tire-derived aggregates (TDA) are pieces of shredded tires and mostly consist of synthetic rubber combined with steel belts. They are classified as type A with a maximum dimension of 200 mm in any direction and type B with a maximum dimension of 450 mm in any direction or 300 mm for at least 90 % of the sample by weight(ASTM D6270-2020). The TDA sample used in this study were type A and were shredded and processed by Halifax C&D recycling Ltd located in Enfield, Nova Scotia(El Naggar, 2018; Mahgoub & El Naggar, 2019). Since the shear box's width was limited to 305 mm, particles larger than 75 mm were removed from the sample. Therefore, the maximum particle size was limited to one-fourth of the shear box length to eliminate boundary and size effects (Humphrey et al., 1993). Due to TDA particle sizes were measured using a ruler, due to their flat and elongated shapes. According to (El Naggar, 2018), particle size characterization of TDA makes them unsuitable for sieve analysis.

## 2.5 Exploring Prior Studies of Cut & Cover tunnel and TDA Application in Construction

### *2.5.1 Considerations on the Design of Cut-and-Cover Tunnels*

In the study conducted by (Plumey et al., 2006), an alternative method for considering soil-structure interaction in cut-and-cover tunnels is presented. The research highlights the effects of soil pressure-induced deformations on the surrounding soil and the subsequent stress redistributions, which can lead to a more favorable situation for the structure. The behavior of the soil and the structure is evaluated independently using a finite-element model, considering factors such as soil-structure geometry, mechanical properties, and the capacity of the reinforced concrete structure to accept displacements required to develop soil strength.

The study proposes a separate evaluation of soil and structure behaviors based on the convergence-confinement method. This method involves analyzing the characteristic curves of the soil and structure, which describe the relationship between generalized pressure (H) and characteristic displacement (w). The soil is modeled as elastic perfectly plastic with a Mohr-Coulomb yield criterion, while the structure's response to soil action is represented by its characteristic curve.

Several failure mechanisms are analyzed, including frame and arch-shaped tunnels **Figure 2-4** considering different soil-structure interactions. The research illustrates the development of unloading arches in the soil and their influence on the structure's response. It discusses the differences in stress distributions and contact stresses compared to traditional assumptions, emphasizing the significance of unloading arches in redistributing stresses and supporting the structure.

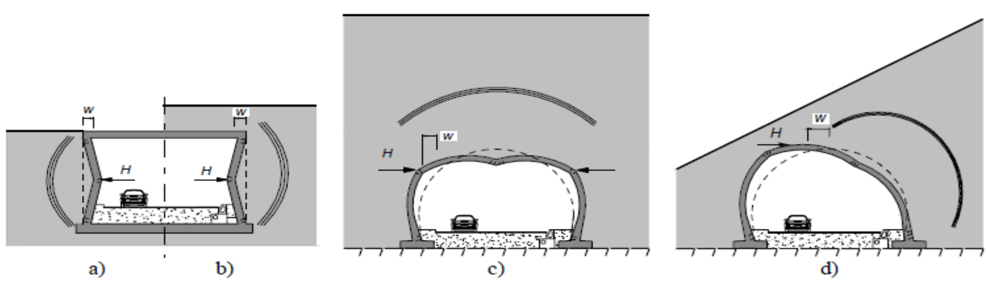



**Figure 2-4: Visual representations of failure mechanisms in frame and arch-shaped cut-and-cover tunnels with unloading arches, showcasing characteristic displacement patterns (w) and generalized pressure distributions (H) (Plumey et al., 2006)**

The study evaluates the equilibrium of the complete system based on kinematical compatibility criteria, considering different failure modes and soil-structure interactions. It presents characteristic curves for soil and structure under various conditions, highlighting the importance of system equilibrium and the role of soil-structure interaction in determining the ultimate limit state behavior and ductility of cut-and-cover tunnels.

Furthermore, the research addresses specific scenarios such as asymmetrical loading and the influence of soil and structure properties on system behavior. It emphasizes the need for a detailed nonlinear analysis to account for soil-structure interaction effects, especially in cases where the soil reaches its complete plastic state with relatively small displacements of the structure.

The study yields invaluable insights into the design aspects of cut-and-cover tunnels, highlighting the critical importance of grasping soil-structure interaction. It underscores the need to consider various factors like geometry, mechanical characteristics, and failure mechanisms to uphold structural integrity and flexibility.

### *2.5.2 Considerations of Uses of TDA Application*

- Researchers (Mahgoub & El Naggar, 2019) have conducted on "**Using TDA as an Engineered Stress-Reduction Fill over Preexisting Buried Pipes**" extensive investigations into the utilization of Tire-Derived Aggregate (TDA) as a viable backfill material to enhance the stress arching mechanism and alleviate stresses transferred to buried pipes. Notably, the study by (Mahgoub & El Naggar, 2022) stands out as a comprehensive examination of TDA's performance through full-scale tests and numerical modeling. Their findings underscored the remarkable stress reduction capabilities of TDA, with the material acting as a resilient stress cushion that mitigated stress concentrations on preexisting pipes by up to 50%

when compared to conventional backfill materials. Furthermore, (Mahgoub, 2019) observed that the TDA layer facilitated the transfer of up to 28% of the applied stresses to the surrounding soil, thereby alleviating the load borne by the buried pipes and contributing to enhanced structural stability.

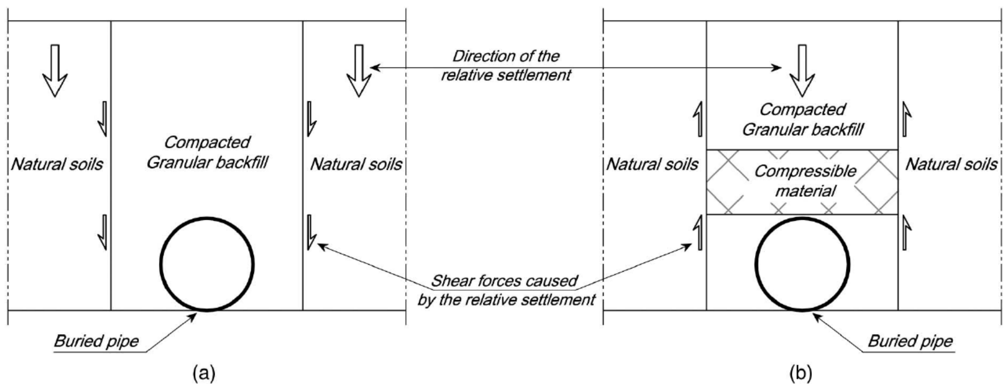



**Figure 2-5: (a) one without compressible material above the buried pipe and the other (b) with compressible material.** (Mahgoub & El Naggar, 2019)

Furthermore, the exploration of different configurations of the TDA layer has yielded valuable insights into optimizing its effectiveness in reducing pipe stresses and minimizing footing settlement. (Mahgoub & El Naggar, 2022) delved into the impact of varying TDA layer thicknesses on pipe stresses and footing settlement, reporting compelling findings that underscored the direct relationship between TDA thickness and stress reduction. Their study revealed a linear reduction trend in pipe stresses as the thickness of the TDA layer increased, with reductions ranging from 20% to 40% for TDA thicknesses ranging from 0.25B to 1B, where B represents the footing's width. These findings highlight the potential for tailored design considerations to optimize the use of TDA and achieve desired stress reduction outcomes in buried infrastructure projects.

Moreover, advancements in numerical modeling techniques have facilitated in-depth analyses of complex soil-structure interactions, providing valuable insights into the behavior of alternative construction materials such as TDA. (Mahgoub, 2019; Mahgoub & El Naggar, 2019, 2020, 2022) leveraged 3D finite element models to simulate the interaction between buried pipes, footings, and TDA backfill materials, offering a comprehensive evaluation of TDA's performance. Their simulations exhibited excellent agreement with field test results, confirming the efficacy of TDA in reducing pipe stresses and enhancing overall structural stability. (Mahgoub & El Naggar, 2019) reported maximum stresses at the pipe's interface of 80 kPa for Setup 1 and 52 kPa for Setup 2 showed in **Figure 2-6**, underscoring the substantial stress reduction achieved with TDA backfill materials and reinforcing its potential as a sustainable alternative in buried infrastructure projects.

In summary, research on Tire-Derived Aggregate (TDA) has demonstrated its significant potential in reducing stress concentrations on buried pipes by up to 50% compared to conventional backfill materials. Studies have shown that increasing TDA thickness leads to linear reductions in pipe stresses, offering tailored design options. Numerical modeling has further confirmed TDA's effectiveness in reducing stresses and enhancing structural stability in buried infrastructure. Overall, TDA presents a sustainable solution for improving the resilience of buried infrastructure systems, with ongoing research expected to optimize its application in civil engineering projects.

- (Naggar et al., 2016) conducted a comprehensive study on **"Innovative Application of Tire-Derived Aggregate around Corrugated Steel Plate**

**Culverts"** to investigates the potential of Tire-Derived Aggregate (TDA) as a backfill material for Corrugated Steel Plate (CSP) culverts. Author mentioned that, compacted soil has been the primary choice for culvert backfill, but it poses limitations such as exerting significant pressure on the culvert, leading to increased stresses and potential deformation, especially for larger culverts or those under heavy loads. Moreover, uneven settlement of the backfill material can cause misalignment and damage to the culvert over time. The procurement of large quantities of soil for backfilling also raises environmental concerns such as soil erosion and habitat disruption.

The compressibility of TDA helps distribute loads more evenly, potentially reducing earth pressures on the culvert compared to compacted soil. Mahgoub and (Naggar et al., 2016) experiments using various TDA configurations around the culvert resulted in significantly reduced culvert deformation during backfilling compared to conventional sand backfill. Additionally, the void spaces within TDA may create a positive arching effect, transferring some of the load to the surrounding soil and further reducing pressure on the culvert. This positive arching effect was observed when the backfill height exceeded three times the culvert height.

(Naggar et al., 2016) employed a two-pronged approach, consisting of experimental testing and 3D finite element modeling, to assess the effectiveness of TDA backfill and optimize its use. Experimental testing involved four full-scale tests using steel tanks filled with sand and TDA in different configurations **Figure 2-6** around a CSP culvert: Setup 1, Setup 2, Setup 3, and Setup 4. The models considered various properties such as soil, TDA, culvert, and loading plate, following the construction sequence from the experiments. This comprehensive approach allowed researchers to analyze the behavior of the culverts under various loading conditions beyond the limitations of physical testing.

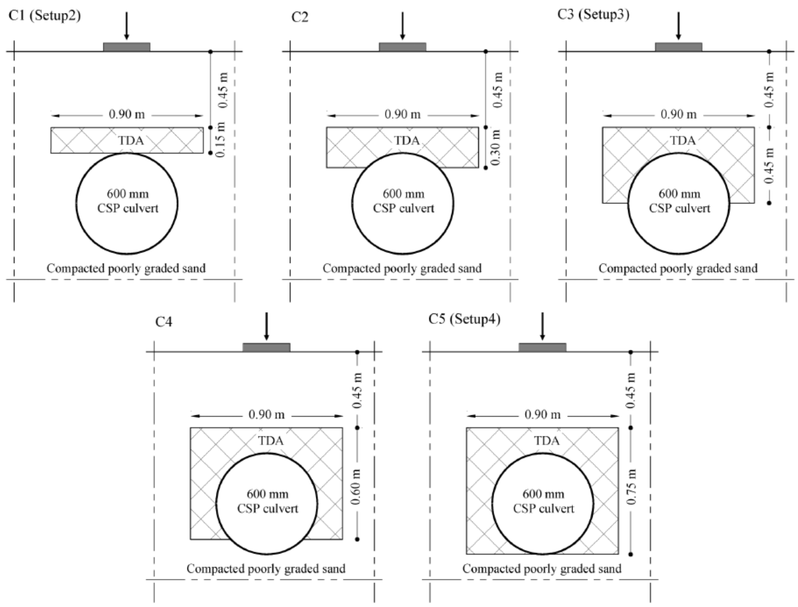



**Figure 2-6: Exploring different TDA Configurations: Strategies to Reduce Culvert Stress (Ahmed Mahgoub et. al, 2020)**

The combined research findings revealed several key considerations for the optimal use of TDA backfill for CSP culverts. The placement of TDA within the culvert envelope was found to influence culvert stresses under surface loads, with different setups resulting in varying stress and deformation levels. Moreover, the stiffness of the material used in the top layer above the TDA was identified as crucial, enhancing the punching shear capacity of the system, and improving the arching mechanism. Additionally, the burial depth of the culvert played a significant role, with higher cover heights leading to decreased pressure on the culvert crown in all setups.

- The next research conducted by same authors (Mahgoub & El Naggar, 2020) on **“Using TDA underneath shallow foundations: simplified design procedure”** to investigate the influence of Tire-Derived Aggregate (TDA) backfill on the performance of shallow foundations. Researchers study aimed to assess the effectiveness of TDA in mitigating stress transfer and reducing settlement in shallow foundation systems compared to conventional backfill materials. Through field tests and numerical modeling, they sought to develop a semi-empirical design method to estimate the bearing capacity of shallow foundations supported by TDA layers.

  The field tests conducted by (Mahgoub & El Naggar, 2020) provided valuable insights into the behavior of shallow foundations with TDA backfill. They observed significant improvements in stress transfer and reduction in settlement when utilizing TDA compared to conventional backfill materials. For instance, stress transfer through the backfill reached up to 32% and 28% for different setups, indicating the effectiveness of TDA in mitigating stress transfer. Additionally, TDA resulted in nonlinear footing settlement and transferred pressure responses, highlighting its impact on foundation behavior.

  The experiments involved various setups with different TDA layer thicknesses and footing dimensions, providing valuable insights into the behavior of shallow foundations on TDA backfill. Rectangular footings of varying dimensions were tested, including a footing with dimensions of 1.0 m width and 2.0 m length, placed over a TDA layer 0.5 m thick, subjected to a maximum load of 340 kN. Another example featured a rectangular footing with a width of 0.75 m and a length of

3.5 m, supported by a TDA layer 0.4 m thick, under a maximum load of 260 kN. Lastly, a strip footing with a width of 1.0 m and a length of 10.0 m was examined, resting on a TDA layer 0.5 m thick, bearing a maximum load of 340 kN showed in **Figure 2-7** .

Moreover, the experiments involved monitoring settlement values over time, providing insights into the time-dependent behavior of shallow foundations on TDA backfill. The settlement-time curves exhibited distinctive patterns, indicating the influence of TDA on consolidation and settlement characteristics.

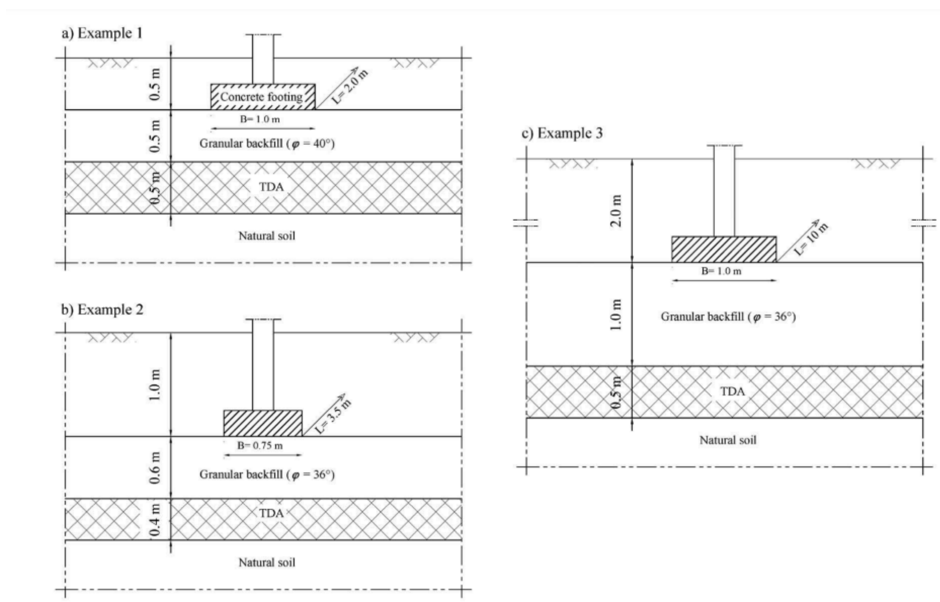



**Figure 2-7: Three shallow foundation designs over layers of tire-derived aggregate (TDA) with different thicknesses, each accompanied by specific dimensions. (Mahgoub & El Naggar, 2020)**

In conclusion, (Mahgoub & El Naggar, 2020)study provides valuable insights into the behavior of shallow foundations on TDA backfill. The findings underscore the effectiveness of TDA in mitigating stress transfer and reducing settlement, contributing to improved foundation performance. The study's comprehensive analysis of field test data, numerical modeling results, and design method development enhances understanding and facilitates the application of TDA in geotechnical engineering practice.

- Subsequent investigation conducted by (Farooq et al., 2021) titled **"Three-dimensional finite element analyses of tyre derived aggregates in ballasted and ballastless tracks"** represents a significant advancement in understanding the effectiveness of Tire-Derived Aggregate (TDA) in improving the performance of railway tracks subjected to dynamic loading conditions. Through sophisticated numerical simulations, the research comprehensively investigated the impact of TDA incorporation showed in **Figure 2-8** on various aspects of track behavior, including settlement, peak acceleration, and vertical stress distribution.

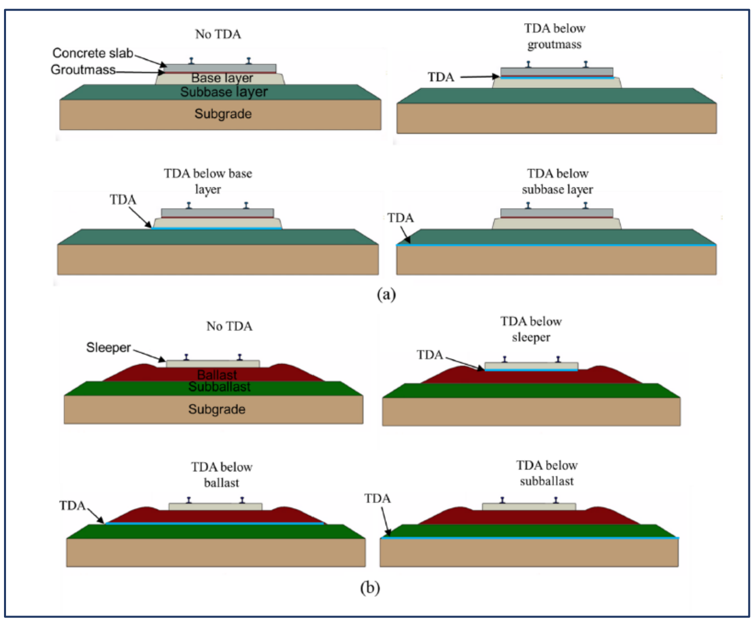



**Figure 2-8: Geometry showing location of TDA below different components of (a) slab track (b) ballasted track used in this study** (Farooq et al., 2021)

One of the key findings of the study was the substantial reduction in peak acceleration achieved using TDA. The incorporation of TDA led to a remarkable 50% reduction in peak acceleration for slab tracks and a 42% reduction for ballasted tracks. These results highlight the pivotal role of TDA in minimizing vibration levels, thereby enhancing passenger comfort, and reducing track wear. For instance, at a train speed of 360 km/h, the settlement in a slab track was approximately 0.88 mm, indicating the stabilizing effect of TDA on track structures.

Moreover, the study underscored the effectiveness of TDA in mitigating settlement issues commonly observed in railway tracks. Settlement values of approximately 0.88 mm and 18.4 mm were reported for slab tracks and ballasted tracks, respectively, at the end of 1 million load cycles. These findings demonstrate the ability of TDA to stabilize track structures and maintain long-term performance under cyclic loading conditions.

The investigation also delved into the influence of train speed and axle load on track behavior. In slab tracks, vertical elastic displacement exhibited **Figure 2-9** a decreasing trend with increasing train speed, while settlement decreased with higher train speeds. Conversely, ballasted tracks displayed a more complex response, with settlement exhibiting a fluctuating trend in response to varying train speeds. This differential behavior emphasizes the importance of considering track type when evaluating the impact of dynamic loading on track performance.

Furthermore, the study highlighted the role of TDA in reducing vertical stress levels in track components. The incorporation of TDA effectively reduced vertical stress in lower components of slab tracks for varying train speeds and axle loads. Similarly, in ballasted tracks, TDA primarily reduced vertical stress levels, with horizontal stress reduction observed at greater depths.

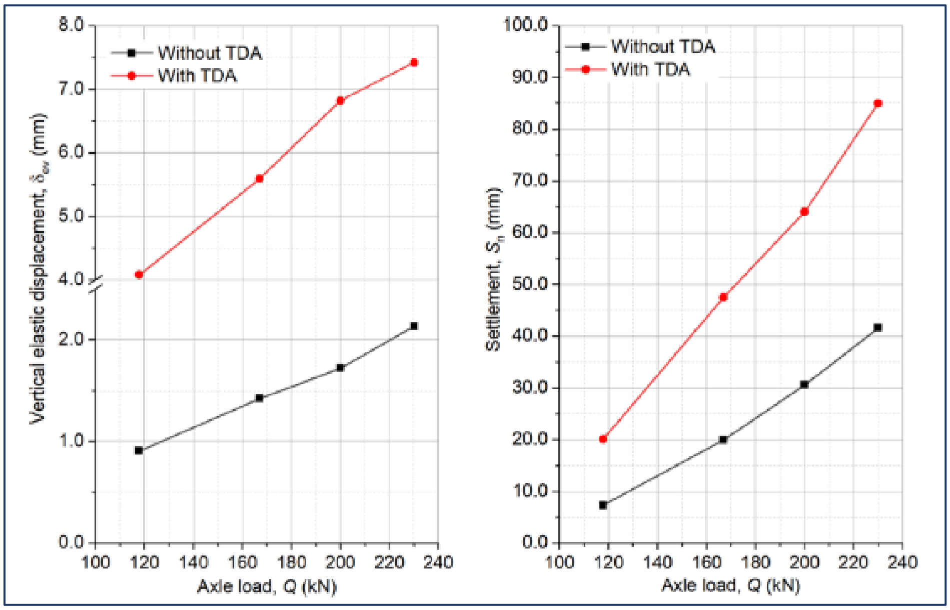



**Figure 2-9: Variation of horizontal elastic displacement with axle load for (a) Slab track (b) ballasted track** (Farooq et al., 2021)

Overall, the findings by Farooq et al. underscore the significant potential of TDA in enhancing the resilience and performance of railway tracks under dynamic loading conditions. The comprehensive numerical simulations provided valuable insights into the behavior of TDA-incorporated tracks, emphasizing the importance of considering factors such as train speed, axle load, and track type in optimizing track performance and longevity.

## 2.6 Behaviour of Concrete Tunnel Lining

The research conducted by (El & Steele, 2012) TAC 2012 investigated the stress distribution around shallow tunnels constructed using the cut-and-cover method showed in

**Figure 2-10**. The study focused on analyzing the effects of backfill compaction quality and the relative stiffness of the tunnel lining on stress redistribution, tunnel deflection, and contact pressure transferred to the ground through tunnel foundations.

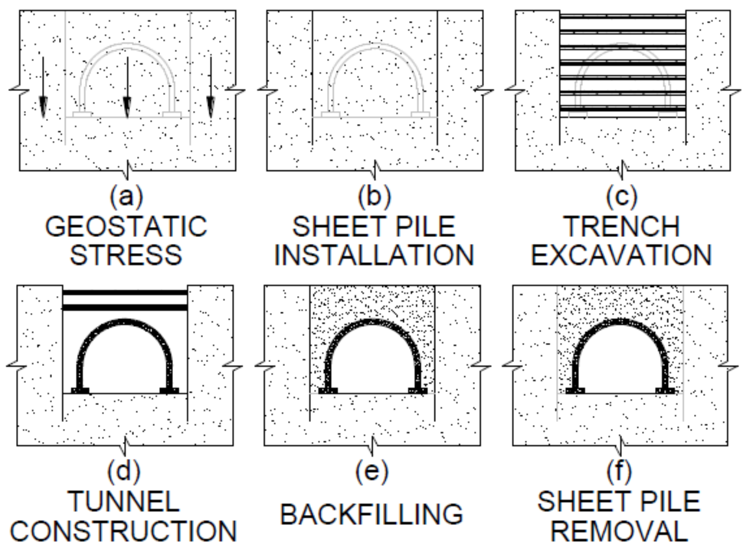



**Figure 2-10: The typical construction sequence of the simulated cut-and-cover tunnel. (El & Steele, 2012)**

Shallow tunnels, typically constructed at depths ranging from 9 m to 12 m, are often cut-and-cover arch-shaped concrete tunnels. These tunnels are supported by strip footings in a dense sand layer. The dimensions of the tunnel considered in the study were 10 m wide by 8 m high, with 4 m of cover over the crown. The tunnel walls were supported by two 2 m wide and 0.6 m thick strip footings.

Finite element analysis using PLAXIS software was employed to model the soil continuum and simulate construction phases. The material constitutive models for the ground and the granular backfill were assumed to obey the Mohr-Coulomb failure criterion. The tunnel lining and its walls and foundations were assumed to obey the linear elasticity model based on Hook's law of isotropic elasticity. The tunnel lining was modeled as concrete with an elastic modulus (E) of 30 GPa and Poisson's ratio (μ) of 0.20.

The study found that the degree of compaction had minimal impact on vertical side wall stresses but significantly influenced shoulder wall stresses. Ground settlement decreased with increasing tunnel lining stiffness and backfilled compaction quality **Figure 2-11**. Tunnel crown deflection **Figure 2-12** decreased with increased tunnel lining stiffness and backfilled compaction. Furthermore, contact pressure between tunnel foundations and the ground increased with tunnel lining thickness but decreased with backfill compaction quality.

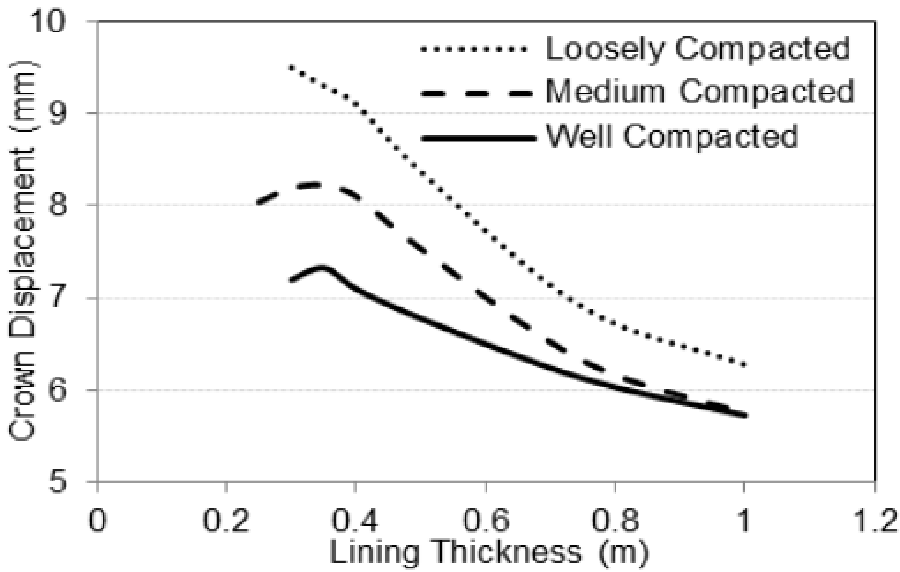



**Figure 2-11: Variation in the crown deflection with lining thickness for three levels of compaction (El & Steele, 2012.)**

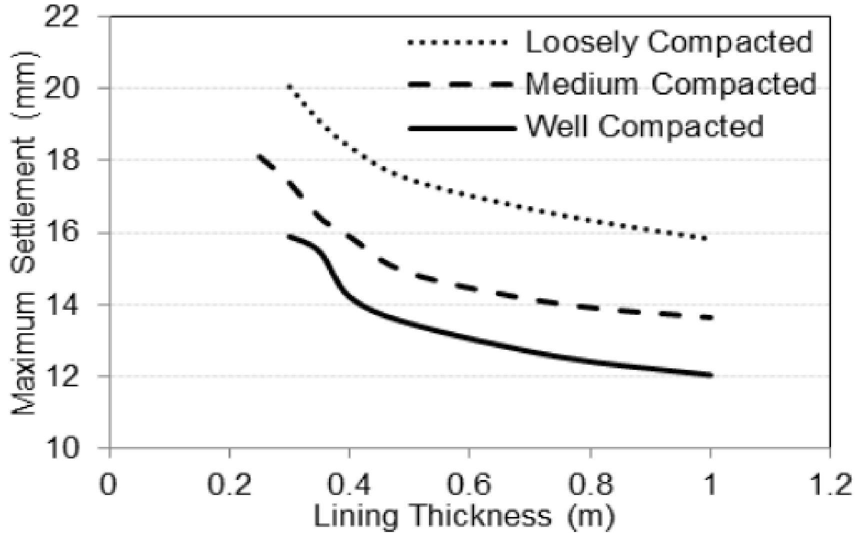



**Figure 2-12: Variation in the maximum settlement with tunnel lining stiffness for three compaction levels (El & Steele)**

The Conclusion of the research by (El & Steele, 2012) provided valuable insights into the stress distribution around shallow tunnels, highlighting the importance of considering backfill compaction quality and tunnel lining stiffness in tunnel design. Understanding these factors is crucial for optimizing tunnel performance and ensuring structural integrity in urban environments.

- In their study, (Sun et al., 2024) conducted research on the **"Geotechnical seismic isolation system to protect cut-and-cover utility tunnels using tire-derived aggregates"** Their study aimed to evaluate the seismic performance of cut-and-cover utility tunnels employing Tire-Derived Aggregates (TDA) as a geotechnical seismic isolation system. The research focused on assessing the effectiveness of TDA backfill in mitigating seismic hazards and enhancing the resilience of critical infrastructure components.

The study investigated four different scenarios **Figure 2-13**, each representing a distinct layout of TDA backfill:

**Case 1:** This case represents the scenario without TDA backfill, serving as the reference or baseline condition for comparison. It involves the utility tunnel being surrounded by conventional soil backfill.

**Case 2:** In this case, the TDA backfill layout is such that it replaces the soil close to the side walls of the structure. This configuration allows for the examination of the influence of TDA backfill on structural response compared to conventional soil backfill.

**Case 3:** Case 3 involves a TDA backfill layout where the TDA is placed above the roof slab of the utility tunnel. This configuration is likely designed to assess the impact of TDA backfill on structural response when placed above the structure.

**Case 4:** In this case, the TDA backfill layout includes a TDA mattress beneath the base slab of the utility tunnel. This configuration aims to investigate the effects of TDA backfill placed underneath the structure.

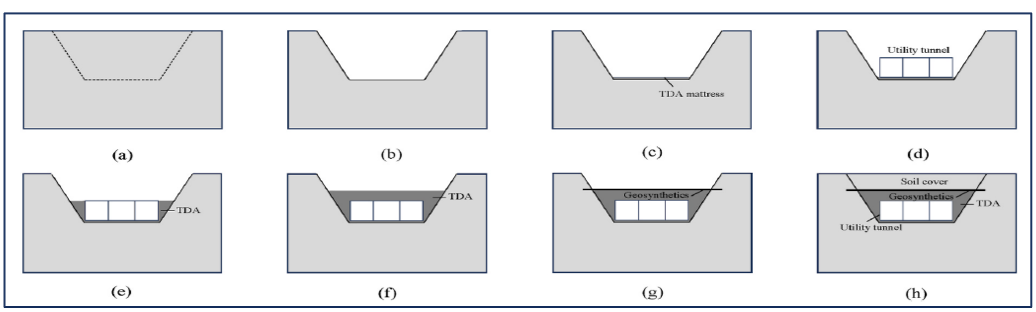



**Figure 2-13: Illustration of the construction procedure for a box cut-and-cover tunnel with Tire-Derived Aggregate (TDA) backfill (Sun et al., 2024)**

Under static conditions, TDA backfill demonstrated the ability to reduce internal forces, with significant reductions observed in bending moments and shear forces along the tunnel structure. For instance, in Case 4, where the foundation soil under the base slab was replaced by a 0.2 m thick TDA mattress, the maximum internal forces were reduced by 20% to 60% compared to the case without TDA backfill (Case 1). Additionally, the presence of TDA backfill led to comparable settlements of surrounding soils, indicating effective control over potential vertical settlement induced by TDA.

Dynamic analyses revealed notable changes in acceleration responses due to the presence of TDA backfill. Accelerations of both isolated and non-isolated utility tunnels increased with motion intensity, with a moderate increase observed in isolated tunnels due to reduced constraints caused by TDA (Cases 2, 3, and 4). The maximum accelerations of the structure generally increased by about 1-1.5 times with TDA backfill, indicating amplified acceleration responses.

Racking deformation, a critical deformation mode of buried structures during seismic events, was analyzed to evaluate the effectiveness of TDA backfill in reducing structural deformations. The efficiency factor ($\alpha$) for racking deformation showed promising results for Cases 3 and 4, with values progressively increasing with motion intensity. For instance, the $\alpha$ value was greater than 20% in Case 3 and reached around 50% in Case 4 for higher motion intensities (PGA = 0.4 g), indicating significant reductions in structural racking deformation.

Rocking rotation, another important deformation response, was compared between isolated and non-isolated structures to assess the influence of TDA backfill showed **Figure 2-14**. The rocking rotation responses were generally comparable between TDA backfilled and non-backfilled tunnels, with slight variations observed under different ground motions and motion intensities.

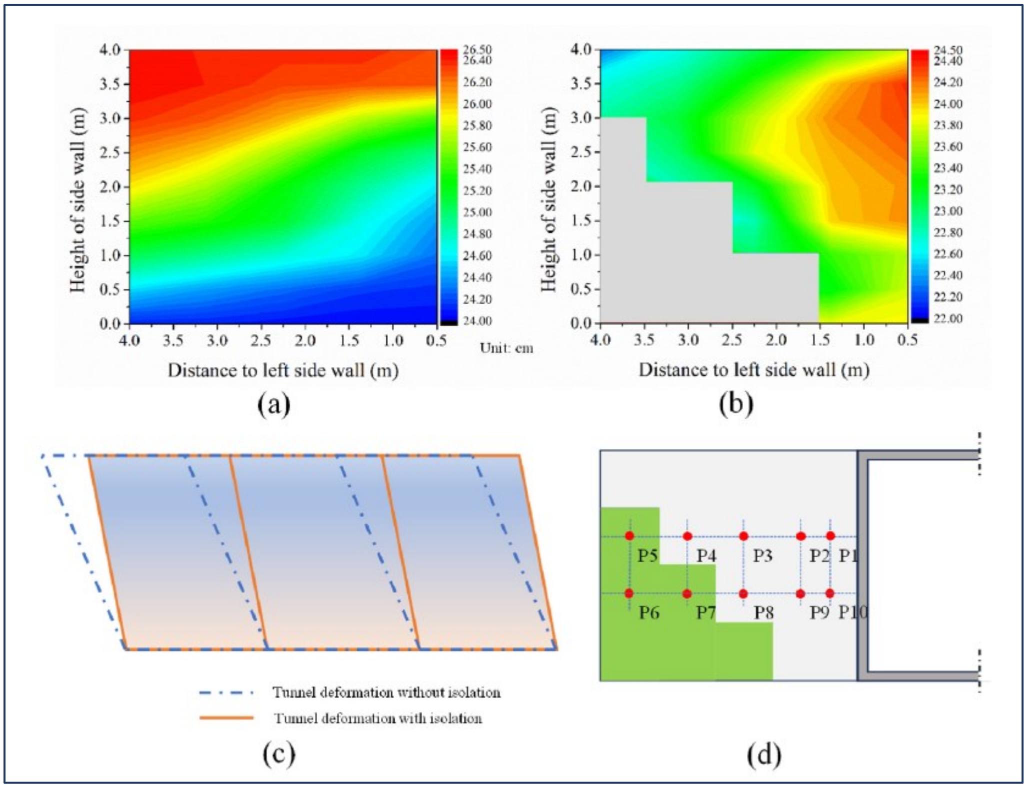



**Figure 2-14: Maximum horizontal displacement of (a) non-isolated tunnel; (b) isolated tunnel; (c) structural deformation; and (d) monitoring points (Sun et al., 2024)**

Analysis of seismic-induced internal forces, including bending moments and shear forces, demonstrated the effectiveness of TDA backfill in reducing internal forces along the tunnel structure. The maximum efficiency factors ranged from around 65% for bending moments to approximately 75% for shear forces in Case 4, indicating substantial reductions in internal forces with TDA backfill.

- In comprehensive study conducted in February 2023, (Alshibany et al., 2023) the "Sustainable Use of Tire-Derived Aggregate in the Protection of Buried Concrete Pipes under Combined Soil and Traffic Loads showed in **Figure 2-15**." The research aimed to assess the efficacy of tire-derived aggregate (TDA) in reducing bending moments induced in the walls of buried concrete pipes subjected to combined soil and traffic loads.

The study employed validated three-dimensional finite element analyses to examine two trench configurations: one involving conventional compacted well-graded backfill material and the other integrating a 150 mm TDA layer on top of the pipe crown.

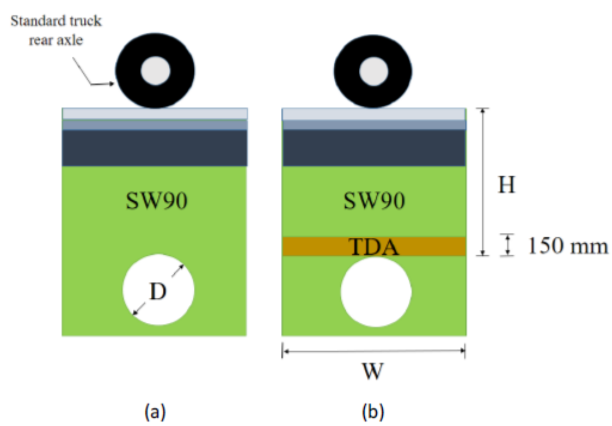



**Figure 2-15: Trench configuration (a) conventional backfill configuration (CB) and (b) TDA configuration (Alshibany et al., 2023)**

The concrete pipe examined had an inner diameter of 0.6 m and a wall thickness of 0.094 m. The study adopted the hardening soil model (HSM) to simulate the behavior of the TDA material and the trench soil (SW90). The TDA used in the research, classified as Type A TDA according to (ASTM D6270-08), consisted of shredded tires and fine aggregate with a particle diameter range of 13 mm to 63 mm. Material properties of the TDA, including unit weight, modulus of elasticity, and Poisson's ratio, were calibrated, and set to specific values. The compacted TDA exhibited a unit weight approximately one-third to one-half of typical compacted soil's unit weight.

The analyses were conducted using PLAXIS 3D software with 10-noded tetrahedron elements modeling the subgrade, surface layer, base, subbase, and backfill material (SW90 and TDA). Boundary conditions were standardized, with the model fixed at the base and the sides of the model free only in the vertical direction and fixed in other horizontal directions. Interface elements with a reduction factor ($R_{int}$) of 0.7 were created around the pipe to simulate soil-structure interaction.

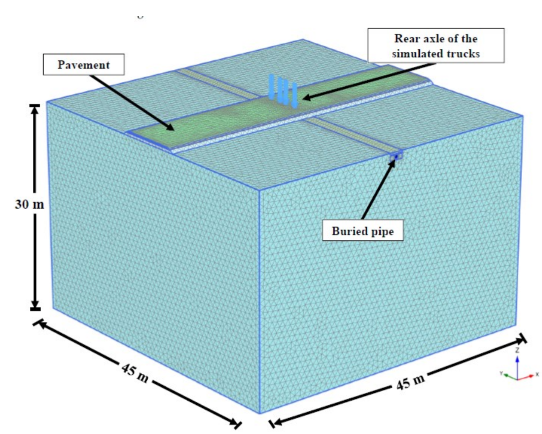



**Figure 2-16: Plaxis 3D model to study soil structure interaction used by (Alshibany et al., 2023)**

To represent traffic loading, the study utilized rear axles of two H25 trucks **Figure 2-16**, accounting for critical loading conditions. Sensitivity analysis guided the selection of very fine mesh density to ensure accuracy. The methodology included six stages: determining at-rest soil stresses, modeling trench excavation, layout of buried pipe, refilling trench, laying road layers, and loading truck's rear axle.

The findings demonstrated that the TDA layer effectively reduced the induced pipe wall bending moment compared to conventional backfill material alone. The highest decrease in bending moment values occurred at a burial depth of 1 m, ranging from 26% to 42% across different road sections. However, the distribution of induced bending moment around the pipe remained unaffected by the presence of TDA.

Moreover, the study observed a decrease in TDA effectiveness in reducing the pipe-bending moment as burial depth increased, attributed to a decline in positive soil arching. The percentage decrease in maximum bending moment stabilized after a certain burial depth **Figure 2-17** indicating a plateau in TDA efficiency across different road types.

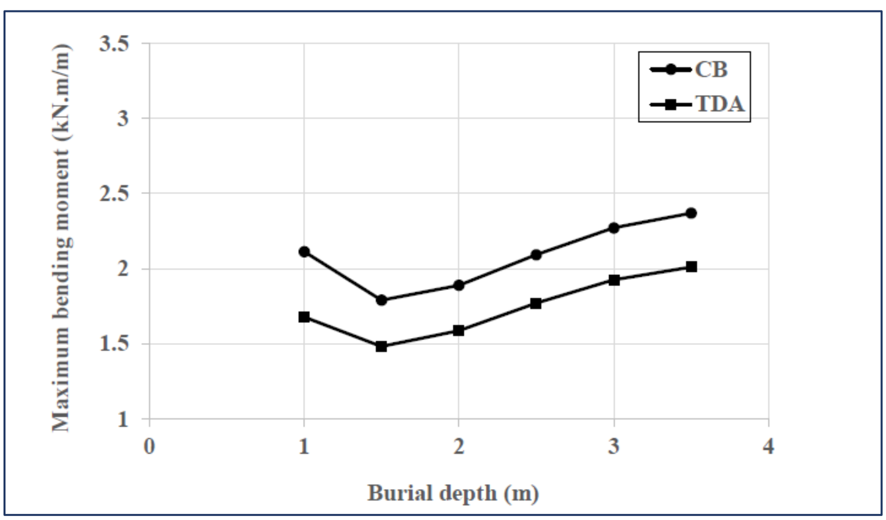



**Figure 2-17: The relationship between the burial depth and the maximum bending moment for CB and TDA configurations for unpaved road section(Alshibany et al., 2023)**

In summary, the study by (Alshibany et al., 2023) offers valuable insights into TDA's role in mitigating bending moments in buried concrete pipes subjected to combined soil and traffic loads. Through advanced finite element analyses and consideration of various burial depths and road conditions, the study enhances understanding of TDA performance and its implications for sustainable backfill materials in underground constructions.

# CHAPTER-3 DEVELOPMENT OF THREE- DIMENSIONAL FINITE ELEMENT MODEL FOR CUT AND COVER TUNNEL USING TIRE DERIVED AGGREGATES ABOVE CROWN LEVEL

## 3.1 General

In this chapter, the soil-structure interaction of cut-and-cover tunnels utilizing tire-derived aggregates (TDA) above the crown level is investigated. Tire-derived aggregates, commonly known as TDA, have emerged as a promising solution for reducing the weight of fill material in various engineering applications. The utilization of TDA offers several advantages, including lightweight properties, high hydraulic conductivity, good thermal insulation, and vibration damping potential (Brunet et al., 2016)

The disposal of large amounts of used tires worldwide raises environmental worries, prompting policy initiatives aimed at promoting the reuse and recycling of end-of-life tires to tackle these concerns (Meles, 2014). TDA presents an ideal recycling outlet due to its ability to utilize waste rubber efficiently with minimal post-processing cost (Ahn et al., 2014)

Despite its benefits, the widespread adoption of TDA in construction projects remains relatively marginal, primarily due to technical challenges and environmental concerns. Previous incidents of self-combustion in TDA fills raised environmental apprehensions, leading to the development of empirical design guidelines to mitigate such risks ((Ad Hoc Civil Engineering, 2002; ASTM D6270, 2008). However, subsequent research has clarified the underlying causes and provided methodologies for analysis and prevention. (Sellasie et al., 2004; Wappett & Zornberg, 2006)

Technical challenges also stem from the unique properties of TDA as a construction material. Unlike traditional soils, TDA exhibits significant grain deformation and elongation, requiring careful consideration of its elastic properties in engineering analyses(Drescher et al., 1999; Lee et al., 1999). Laboratory testing of full-size TDA is challenging due to its large size, necessitating reliance on field demonstration projects for validation and confidence-building (Strenk et al., 2007).

This chapter focuses on a recent field test conducted on a cut-and-cover railway tunnel in Spain (Rodríguez et al., 2018), where TDA was employed above the crown level to reduce lining loads. The tunnel served as a demonstration project to explore the potential benefits of TDA in tunnel construction. The field test involved the placement of TDA layer above 1m at the tunnel crown, followed by comprehensive monitoring and numerical analysis to assess the performance of TDA.

## 3.2 Tunnel Geometry and Construction

The construction of the tunnel involved a meticulous process of excavating through alternating layers of sandstones and siltstones on-site to achieve the desired grade. The tunnel's cross-section, as illustrated in **Figure 3-1**, showcased the height of backfilling materials, the thickness and width of Tire-Derived Aggregate (TDA), and the sidewalls, along with the placement of a tunnel arch at the substrate (sandstone). This carefully engineered design featured a sturdy arch section supported by the natural ground, serving as the backbone of the tunnel, and providing structural integrity while minimizing the need for extensive excavation.

To bolster the stability of the tunnel, especially in areas with good rock quality in the lower third of the section, only what was necessary to cast the arch was excavated. Behind this arch, a narrow-excavated section was filled with lean concrete, optimizing the use of materials while ensuring structural integrity.

Additionally, **Figure 3-2**, which includes longitudinal sections, provides detailed information about the length of TDA and the sections A-A and B-B, where the analysis of bending moment and displacement at the tunnel crown is conducted. These measurements and analyses are crucial for understanding and optimizing the structural performance of the tunnel.

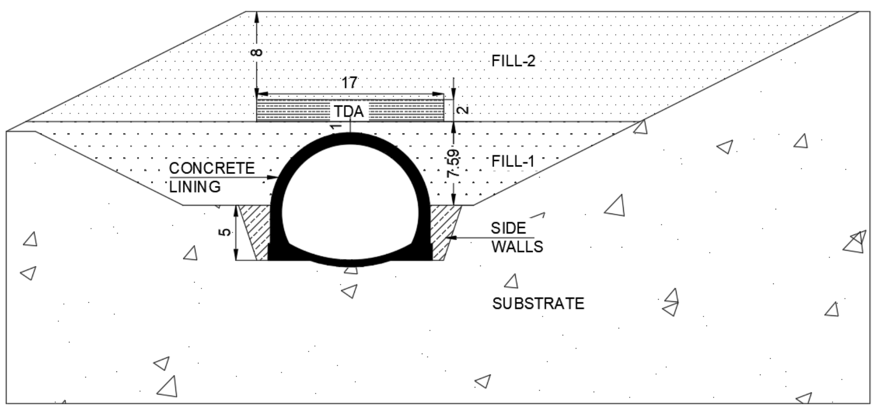



**Figure 3-1: Cross-section view of the cut-and-cover tunnel at 82m, revealing tunnel geometry, TDA, and filling materials with dimensions**

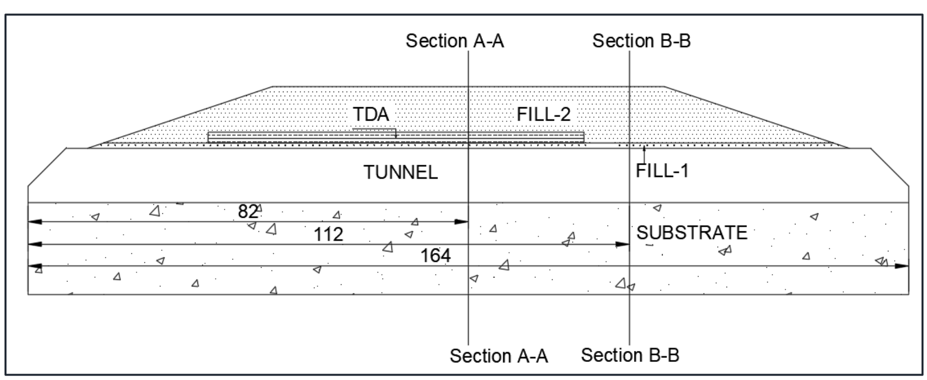



**Figure 3-2: Tunnel Longitudinal Profile and Calculation Section Location**

The fill material used to cover the arch section was divided into three distinct zones to cater to different structural requirements:

1. **Granular Fill 1:** This high-quality granular fill, was meticulously placed around the tunnel, extending up to 1.5 meter above its crown. Its purpose was to provide foundational support and stability to the tunnel structure.

2. **Tire-Derived Aggregate (TDA) Layer:** A critical component of the tunnel's construction, the TDA layer, adhered to Type B specifications outlined in ASTM standard D6270. This layer, symmetrically positioned about the tunnel axis, spanned 70 meters in length, 17 meters in width, and 2 meters in thickness. Placed 1 meter above the tunnel's crown, the TDA layer was enveloped in a geotextile to prevent mingling with the surrounding granular fill.

3. **Granular Fill 2:** This medium-quality granular fill was utilized above 1.5 meters of the tunnel's crown. Except for areas substituted by the TDA layer, this fill material provided additional structural support and stability to the tunnel's covering.

### 3.3 The Considered Field Studies

In the implementation of the cut-and-cover tunnel, a conventional bottom-to-top construction approach was adopted, involving the placement of precast concrete lining within a pre-excavated trench. This widely recognized construction method is commonly employed in various transportation and drainage projects, offering structural stability and ease of implementation.

The field study conducted by (Rodríguez et al., 2018) serves as a significant reference point for validating the numerical model developed for this case study. The precast concrete lining, in this instance, was positioned with its top approximately 6.5 meters above the existing ground surface, providing a uniform surface width of approximately 12.5 meters across the entire span of the concrete lining.

To ensure structural stability, the foundation of the structure was established on class three sandstone rock (substrate) with specific material properties. The elastic modulus (E) of the substrate was determined to be $10^6$ kPa, indicating its ability to resist deformation under applied stress, while the Poisson's ratio (μ), representing the material's lateral contraction when compressed, was measured at 0.25.

The soil material properties, crucial for assessing the stability and behavior of the structure, are summarized in **Table 3-1** These properties include parameters such as density, shear strength, and compressibility, which influence the structural response of the tunnel and surrounding soil during construction and operation.

During the construction process, meticulous attention was given to the compaction of the structural backfill and the gradual buildup of the tunnel over the concrete lining. A soil cover of 9.5 meters was then added atop the tunnel, providing additional stability and protection to the underlying structure.

Furthermore, the dimensions and distribution of tire-derived aggregate (TDA) utilized in the study played a crucial role in enhancing the performance of the tunnel. The TDA, characterized by its lightweight properties and high hydraulic conductivity, was strategically placed within the fill covering to reduce weight and alleviate stress on the tunnel lining.

The length and distribution of the TDA layer, along with other pertinent parameters such as thickness and compaction, were carefully considered to optimize the structural integrity and performance of the tunnel by (Rodríguez et al., 2018). This meticulous planning and implementation ensured that the TDA effectively mitigated static loads on the tunnel lining, resulting in improved stability and reduced bending moments.

**Table 3-1: Employed soil Material properties in (Rodríguez et al., 2018) field test.**

| Material | $\gamma$ (kN/m³) | $E$ (kN/m³) | $v$ | ϕ° | $c$ (kPa) |
|---|---|---|---|---|---|
| Substrate | 26 | $10^6$ | 0.25 | 40° | 800 |
| Fill-1 | 19 | $1x10^4$ | 0.30 | 35° | 0 |
| Fill-2 | 18 | 3470* | 0.30 | 25° | 5 |
| Rockfill | 22 | $2x10^5$ | 0.30 | 45° | 200 |
| Concrete | 24 | $3x10^7$ | 0.20 | - | - |

### 3.4 Finite Element Model Development

**Soil Profile**: The constitutive law of soils in the Hardening Soil model is represented by a set of mathematical equations, extensively documented in the (PLAXIS 3D-Reference Manual, 2020). Parameters required for this model can be determined through conventional triaxial compression tests on the soil. These parameters include the Secant stiffness in standard drained triaxial tests ($E_{ur}^{ref}$), unloading/reloading stiffness ($E_{ur}^{ref}$), tangent stiffness for primary oedometer tests ($E_{oed}^{ref}$), elastic unloading-reloading Poisson's ratio ($vur$), angle of dilation ($\psi$), and Mohr-Coulomb strength parameters (c and $\varphi$).

Additional information from the Plaxis 3D model includes detailed analysis of soil behavior under different loading conditions, such as consolidation, cyclic loading, and stress path changes. The model provides insights into the effect of various factors like soil type, initial stress state, and loading history on soil deformation and strength characteristics. Moreover, Plaxis 3D offers advanced features for simulating complex geotechnical problems, including soil-structure interaction, tunneling, and embankment construction.

During primary loading, the stress-strain behavior exhibits strong nonlinearity, with the primary loading stiffness modulus ($E_{50}$) dependent on confining stress. For small strains, $E_{50}$ is preferred over the initial modulus ($E_0$) due to experimental challenges in determining the tangent modulus. Additionally, the stress-dependent stiffness modulus for unloading and reloading stress paths ($E_{ur}$) and plastic soil stiffness parameters ($E_{50}^{ref}$ and $E_{ur}^{ref}$) can be calculated as follows:

$$E_{50} = E_{50}^{ref} \left( \frac{\acute{c} \cos \varphi - \acute{\sigma}_3 \sin \sin \varphi}{\acute{c} \cos \varphi + p^{ref} \sin \varphi} \right)^m$$

$$E_{ur} = E_{ur}^{ref} \left( \frac{\acute{c} \cos \varphi - \acute{\sigma}_3 \sin \sin \varphi}{\acute{c} \cos \varphi + p^{ref} \sin \varphi} \right)^m$$

Where $E_{50}^{ref}$ represents the reference stiffness corresponding to the reference stress $p_{ref}$, which is typically set at 100 $kN/m^2$ as the default value in the Plaxis 3D model. Similarly, $E_{ur}^{ref}$ denotes the reference modulus for unloading and reloading, also corresponding to the reference stress $pref$ set at 100 $kN/m^2$. It's worth noting that in Plaxis default settings, $E_{ur}^{ref}$ equals 3 times $E_{50}^{ref}$.

To manage the plastic strains resulting from the yield cap, another crucial input parameter utilized in the Plaxis 3D model is the reference oedometer modulus $E_{oed}^{ref}$. Similar to the triaxial moduli, the oedometer modulus $E_{oed}^{ref}$ follows a stress dependency law. This parameter plays a vital role in controlling the number of plastic strains induced by the yield cap mechanism.

In the context of geotechnical analysis using (PLAXIS 3D-Reference Manual, 2020), these parameters are essential for accurately representing the mechanical behavior of soils under various loading conditions. The default values and stress dependency laws associated with these parameters allow engineers to effectively model and analyze soil-structure interactions, slope stability, foundation design, and other geotechnical engineering problems with confidence.

$$E_{oed} = E_{oed}^{ref}\left(\frac{\acute{c}\cos\varphi - \acute{\sigma}_3 \sin\sin\varphi}{\acute{c}\cos\varphi + p^{ref}\sin\varphi}\right)^m$$

Where the power parameter $m$ indicates the degree of stress dependence, documented a range of $m$ values from 0.5 to 1 across various soil types. Specifically, values of 0.9 to 1 were noted for clay soils, aiming to approximate a logarithmic stress dependency. Additionally, in (Rafaa Obrzud Andrzej Truty, 2018) Hardening Soil handbook, correlations from (Vi&b & Atkinson, 1995) are also mentioned.

$$m = 1.13 - \frac{49}{LL+78}$$

(Vi&b & Atkinson, 1995) Correlation:

$$m = 1 - \frac{10.83}{P.I + 18.7}$$

$v_{ur}$ stands for the poisson's ratio of unloading to reloading. The fact that $vur$ is not the standard poisson's ratio (μ) should be noted. It should be left at the default value of 0.2 in the absence of lab data.

### 3.5 Modeling Concrete Tunnel Lining as a Plate in Plaxis-3D

In Plaxis-3D, the process of modeling a concrete tunnel lining as a plate involves meticulous consideration of various factors to ensure accurate representation and analysis. One approach entail creating a plate element to simulate the lining, where the equivalent thickness (d) of the lining is determined based on engineering requirements and design considerations. For example, if the thickness of the concrete tunnel lining is 1000mm, the equivalent thickness (d) in Plaxis-3D would be set as 1 meter.

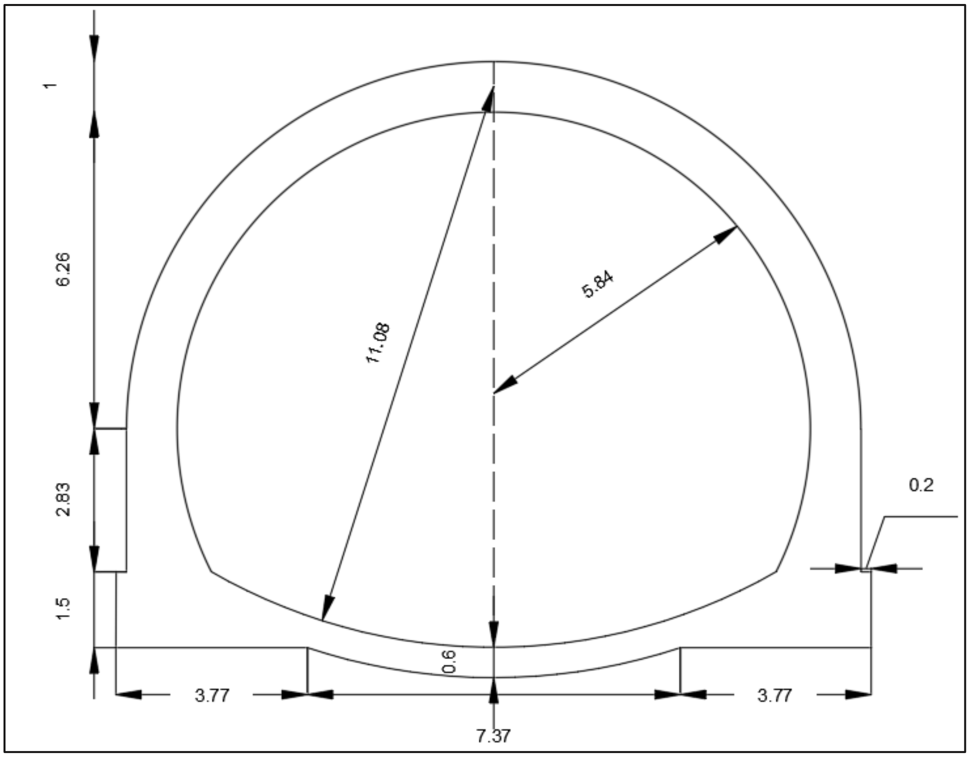



**Figure 3-3: Tunnel Geometry (All Dimension in m)**

This method allows for the direct definition of the relevant parameter (d) within the Plaxis-3D environment. Additionally, it's important to specify the material properties of the concrete lining. If the concrete material is elastic, with mechanical properties such as modulus of elasticity ($E_{concrete}$), Poisson's ratio ($\mu_{concrete}$), and shear modulus ($G_{concrete}$), these properties should be accurately defined in the Plaxis-3D model. These properties determine the stiffness and deformation characteristics of the concrete lining within the analysis.

When employing plate elements to model a concrete tunnel lining in Plaxis-3D, it's essential to address the interaction between the lining and the surrounding soil. The thickness of the plate may partially overlap with the soil, impacting the calculation of the lining's weight (w). In such cases, the actual weight of the plate is the difference between the weight of the plate and the weight of the soil occupying its true volume, considering the unit weight of the concrete ($\gamma_{concrete}$) showed in **Figure 3-4**. By accurately accounting for this interaction and incorporating the elastic properties of the concrete material, engineers can obtain more realistic and reliable results in their analyses.

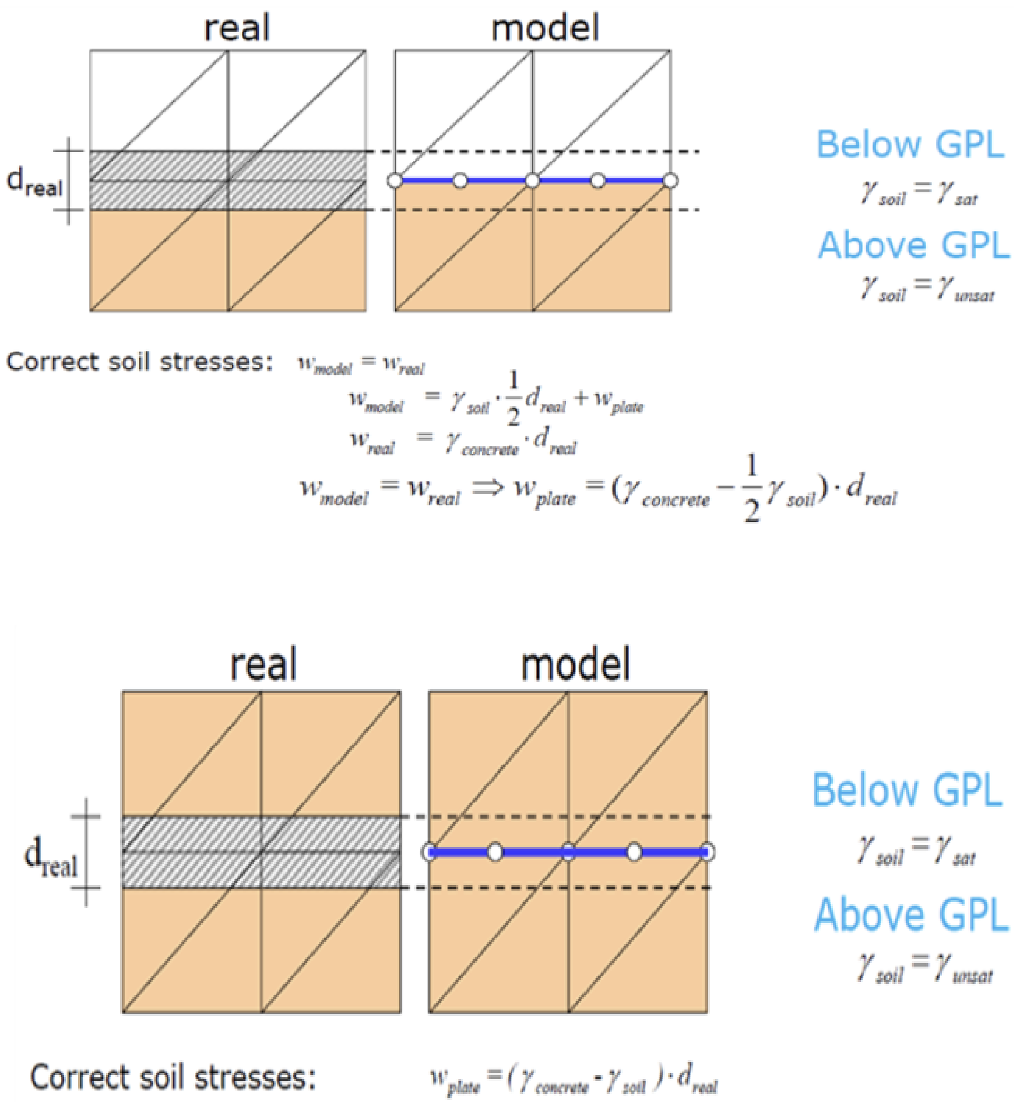



**Figure 3-4: Considerations of modelling a thick slab plate (PLAXIS 3D-Reference Manual, 2020)**

### 3.6 Considerations for Interface Elements

In addition to modeling the concrete tunnel lining as a plate, simulating the interaction between the structure and soil is crucial for comprehensive analysis in Plaxis-3D. This is achieved through the utilization of interface elements, which allow for the representation of relative displacements (such as slipping or gapping) between the structure and soil.

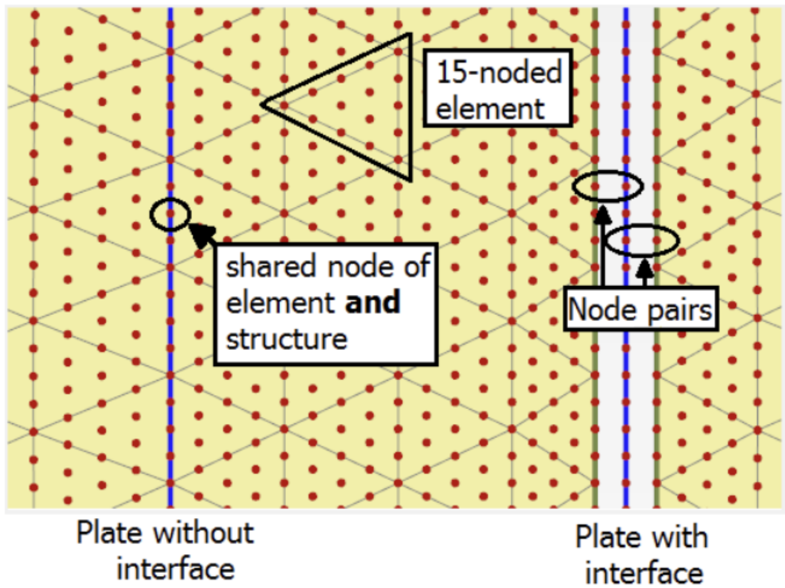



**Figure 3-5: Plate Interface (PLAXIS 3D-Reference Manual, 2020)**

Interface elements in Plaxis-3D create node pairs at the interface of the structure and soil, with each pair comprising one node from the structure and one from the soil. These elements employ elastic-perfectly plastic springs to model gap displacement and slip displacement, enabling engineers to accurately capture the behavior of the soil-structure interface.

Key considerations when using interface elements include the control of slipping behavior through strength properties and the $R_{inter}$ value of the material set. Engineers have the option to directly appoint a specific material set to the interface, providing direct control over interface strength properties without affecting the properties of the surrounding soil clusters.

## 3.7 Integration of Advanced Analysis Techniques

In addition to modeling concrete tunnel linings as plates and using interface elements, Plaxis-3D offers a range of advanced analysis techniques to further enhance the accuracy and reliability of geotechnical analyses. These techniques include advanced material models, such as the Hardening Soil model, which allows for the simulation of complex soil behavior under varying stress conditions.

Furthermore, Plaxis-3D offers advanced capabilities for analyzing soil-structure interaction, including the simulation of structural forces using the Structural forces in volume plates functionality. This allows engineers to accurately assess the structural response of complex systems and optimize design solutions for enhanced performance and safety.

## 3.8 Staged Construction

1. **Initial Phase:** Phase 0 involves obtaining and modeling the in-situ stress state of the ground using PLAXIS 3D. This step provides essential insights into existing stress conditions within the ground, forming the basis for further project analyses and design considerations.

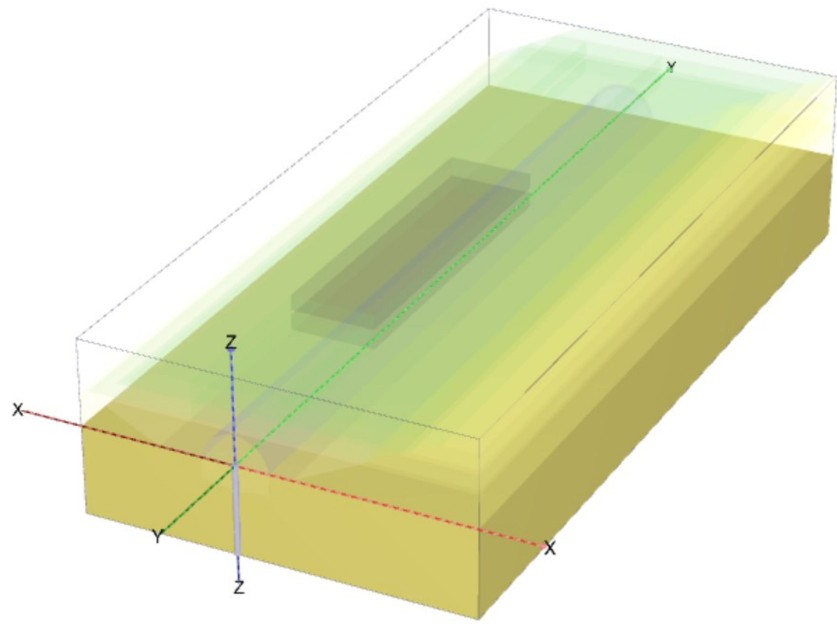


**Figure 3-6: Visualization of Ground Surface Model in Plaxis3D**

2. **Trench Excavation and Grade Preparation:** In Phase 1, trench excavation for the cut-and-cover tunnel was simulated using Plaxis 3D software, reaching a depth of 5 meters and extending to a width of 20 meters showed in **Figure 3-7**.

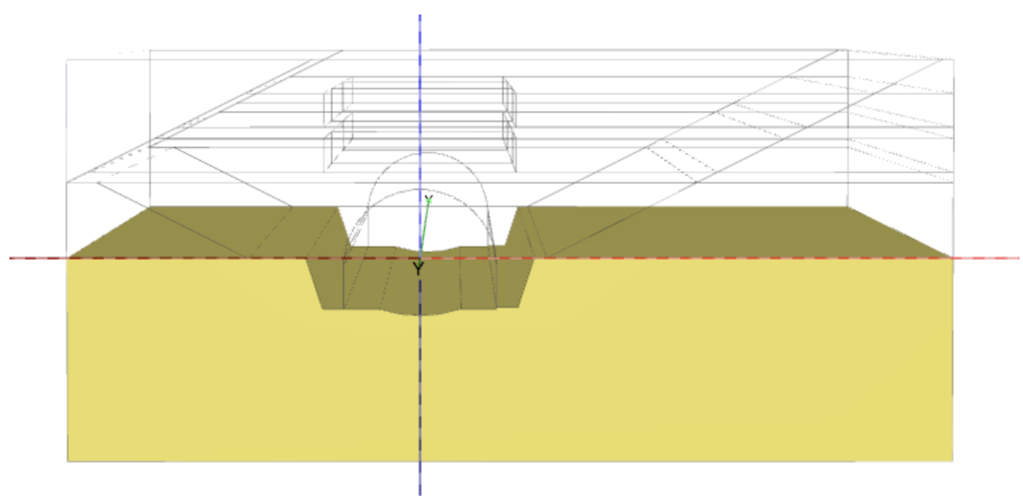


**Figure 3-7: Trench excavation simulation in Plaxis 3D**

### 3.9 Placing Concrete Tunnel Lining

In phase-2 of the tunnel construction process, the activation of the in-situ concrete tunnel lining and lean concrete is simulated using PLAXIS 3D showed in **Figure 3-8** and adopting the Hardening Soil model. This modeling approach allows engineers to meticulously place the concrete lining within the trench excavation area to ensure structural integrity and long-term durability. By inputting specified dimensions and material properties, such as a thickness of 1 meter, width of 12.5 meters, and height of 10.5 meters for the concrete lining, and parameters like a unit weight of 24 $kN/m^3$ and stiffness of $3\times10^7$ for the lean concrete, the virtual construction process is accurately replicated.

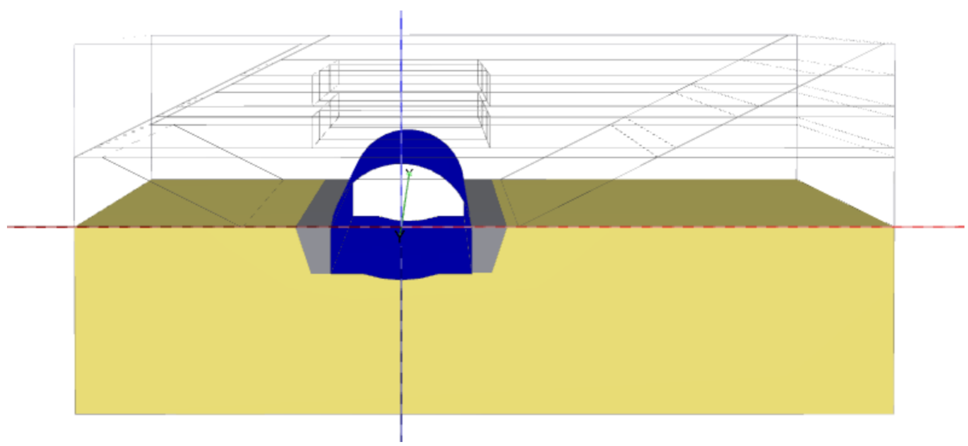


**Figure 3-8: Cast-in-situ tunnel lining positioned in excavated trench with concrete side walls.**

The simulation involves precise alignment, spacing, and joint detailing to prevent water ingress and maintain tunnel integrity. Engineers closely monitor the process to verify compliance with design standards, utilizing non-destructive testing techniques to assess the quality and strength of the concrete lining. This virtual construction effort, facilitated by

PLAXIS 3D and the Hardening Soil model, ensures efficient resource utilization and the successful installation of a robust tunnel lining that safeguards infrastructure.

## 3.10 Filling Granular Fill-1 (Layer-1)

In Phase 3 of the simulation, after activating the concrete tunnel lining and lean concrete, the focus shifts to the placement of Fill-1 in Plaxis 3D showed in **Figure 3-9**. Fill-1 is carefully deposited up to 1.5 meters above the tunnel crown, serving a crucial role in providing support and protection to the tunnel structure. With a unit weight of 19 kN/m³ and a stiffness (E) of 10,000 kPa, granular fill-1 offers robust support while accommodating the dynamic loads and stresses associated with operations. Its cohesive-free (c=0) nature and friction angle (ϕ) of 35 degrees make it an ideal material for providing stable and reliable support around the tunnel structure. This approach, coupled with the careful consideration of the geological composition of the site during tunnel grade preparation, facilitated the seamless integration of granular fill-1 into the overall construction process.

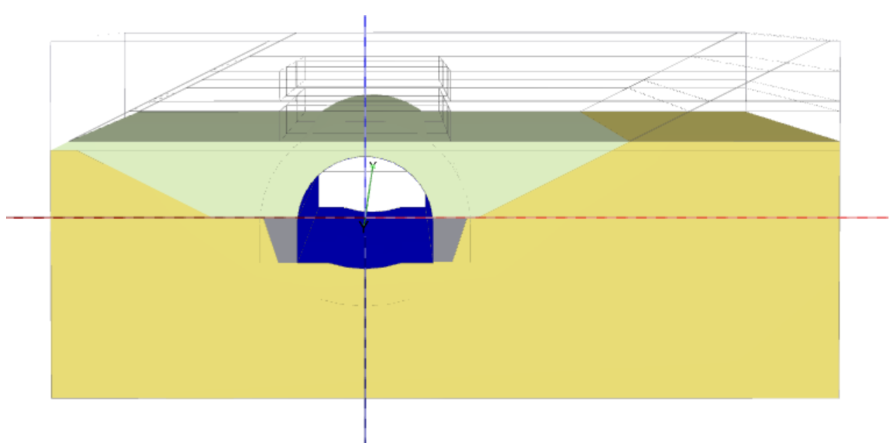


**Figure 3-9: Fill-1 placed above the tunnel crown up to 1.5m height**

Additionally, the utilization of granular fill-1 up to 1.5 meters above the tunnel's crown ensures adequate protection against external elements and potential settlement. The granular fill-1 serves as a protective barrier, safeguarding the tunnel structure from environmental factors such as water ingress and soil erosion. Furthermore, its Poisson's ratio (μ) 0.3 contributes to its ability to withstand deformation under varying environmental conditions, ensuring long-term stability and durability. At the tunnel portals, where additional protection was deemed necessary, rockfill was arranged to further enhance the structural integrity and longevity of the covering fill, ensuring the reliability and safety of the tunnel structure. This comprehensive approach to the placement of granular fill-1 demonstrates a commitment to engineering excellence and ensures the resilience of the tunnel structure in the face of diverse operational and environmental challenges.

### 3.11 Placing TDA Layer

Activation of the TDA layer in Phase 4, following the precise placement of Fill-1 above the tunnel crown showed in **Figure 3-10**, represents a critical step in enhancing the structural integrity and resilience of the tunnel infrastructure within a civil engineering context. Modeling the TDA layer using the Hardening Soil model in PLAXIS 3D ensures its suitability for civil engineering applications, conforming to (ASTM D6270, 2008) specifications as type B TDA, with dimensions of 1 meter thickness, 70 meters in length, and 17 meters in width.

Comprehensive quality control measures are implemented to uphold the integrity of the TDA layer, limiting exposed steel contents and contaminants to enhance its suitability for the intended application. The lightweight yet robust nature of the TDA, with a unit weight

($\gamma$) is 6.4 kN/m³, significantly reduces overall loading on the tunnel structure, thereby alleviating potential stresses on the underlying infrastructure. Furthermore, with a stiffness (E) measured at 630 kPa (Rodríguez et al., 2018) and a cohesive strength (c) of 26 kPa, the TDA layer demonstrates exceptional resistance to deformation and effectively distributes external loads. Additionally, with a friction angle ($\phi$) of 20°, the TDA layer exhibits excellent stability and cohesion. These material properties, coupled with the innovative modeling of the TDA layer using the Hardening Soil model in PLAXIS 3D, contribute to the TDA's ability to withstand applied forces and maintain structural integrity over time within the realm of civil engineering.

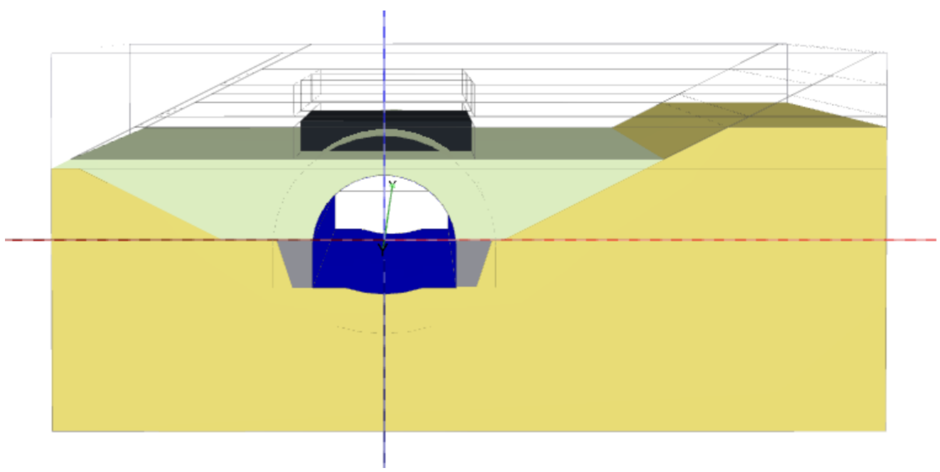


**Figure 3-10: 1-meter-thick Tire-Derived Aggregate (TDA) Layer positioned above Fill-1**

### 3.12 Placing Granular Fill 2

In phase-5, the integration of granular fill-2 into the tunnel infrastructure marks a significant milestone in our engineering strategy aimed at optimizing structural performance and resilience. Granular fill-2, featuring specific material properties such as a unit weight of 18 kN/m³, stiffness (E) of 3470 kPa, Poisson's ratio of 0.3, and a cohesive strength (c) of 5 kPa, is strategically positioned above 1.5 meters of the tunnel crown, except in areas where it is substituted by the Tire-Derived Aggregate (TDA) layer.

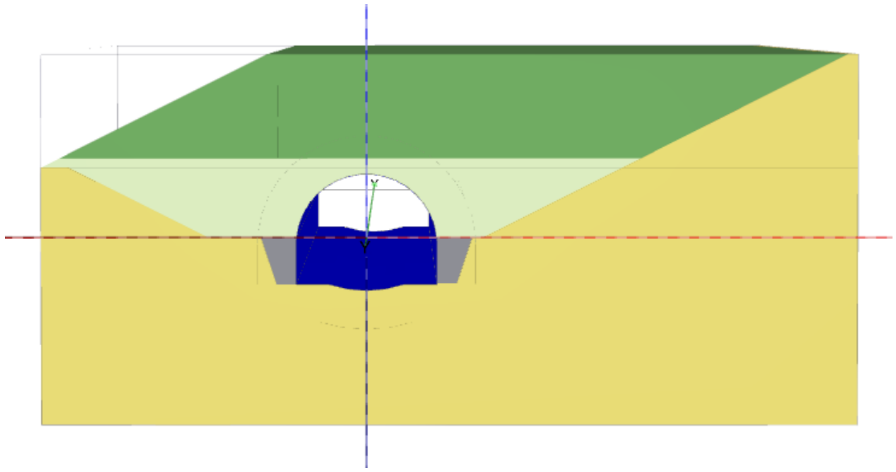


**Figure 3-11: Finalization of ground surface restoration following the placement of Fill-2 above the TDA layer.**

The meticulous placement of granular fill-2, at a height of 8 to 9 meters above the TDA layer, ensures optimal load distribution and support to the tunnel structure. This critical phase in the construction process adheres to established standards, guaranteeing the quality and performance criteria essential for long-term structural resilience. By strategically integrating granular fill-2 into the existing tunnel infrastructure, we leverage its desirable properties to reinforce the structural stability and resilience of the tunnel.

This strategic deployment of granular fill-2 represents a critical step in our ongoing efforts to enhance the reliability and longevity of tunnel infrastructure, demonstrating the effectiveness of innovative engineering solutions in optimizing structural resilience and performance.

## 3.13 Mechanical Properties adopted for Material

Soil and material properties play a pivotal role in the construction of cut-and-cover tunnels, especially when incorporating innovative materials such as tire-derived aggregate (TDA). In this thesis, the construction sequence involved the initial placement of tunnel concrete lining, followed by the pouring of concrete on the sides. Next, Granular Fill-1 was placed around the tunnel, TDA, derived from recycled tires, was strategically placed above the tunnel crown, separated from the surrounding materials by a geotextile layer. Finally, the top layer comprised Granular Fill-2, completing the backfilling process.

The study success relied on a comprehensive understanding of the soil and material properties of each component showed in **Table 3-2**, including TDA, Granular Fill-1, Granular Fill-2, and concrete. Numerical modeling of material properties was conducted to analyze the mechanical behavior of these materials under static loading conditions. The findings informed material model selection for numerical simulations, ultimately optimizing tunnel deformation, and bending moment for the tunnel's structural stability and load-bearing capacity.

This meticulous approach to material selection and placement ensures both the structural integrity of the tunnel and contributes to sustainable and cost-effective construction practices in the field of civil engineering.

**Table 3-2: Adopted Mechanical properties for Modeling**

| Properties | Substrate | Fill-1 | TDA | Fill-2 | Unit |
|---|---|---|---|---|---|
| Soil Model | Hs | Hs | Hs | Hs | - |
| Drainage Type | Drained | Draine d | Drained | Drained | - |
| $\gamma_{unsat}$ | 25 | 19 | 6.4 | 18 | $kN/m^3$ |
| $\gamma_{sat}$ | 25 | 19 | 6.4 | 18 | $kN/m^3$ |
| $E_{oed}^{ref}$ | 205.0e3 | 10.00e3 | 630 | 300.0e3 | $kN/m^2$ |
| $E_{oed}^{ref}$ | 205.0e3 | 10.00e3 | 630 | 300.0e3 | $kN/m^2$ |
| $E_{oed}^{ur}$ | 600.0e3 | 30.00e3 | 1890 | 900.0e3 | $kN/m^2$ |
| $v_{ur}$ | 0.25 | .30 | .20 | .30 | |
| $m$ | .50 | .5 | .5 | .5 | |
| Pre | 20 | 20 | 25 | 20 | |
| $c'_{ref}$ | 800 | 0 | 26 | 5 | $kN/m^2$ |
| $\phi^o$ | 40 | 35 | 20 | 25 | Degree |
| ψ psi | 0 | 0 | 0 | 0 | Degree |
| $R_{inter}$ | 0.67 | .67 | .67 | .67 | - |

### 3.14 Model Validation

In this research study, the accuracy of the finite element model underwent a rigorous validation process by directly comparing it with the outcomes generated by the experimental results. This numerical model was designed to replicate the behavior of the concrete tunnel lining when subjected to identical load conditions as those applied in the physical experiments. The primary focus of this comparative analysis centered on two critical aspects: crown deformation and bending moment.

When scrutinizing the graphical representations of crown deformation **Figure 3-12**, an alignment became evident between the findings of the current study and those of a previous investigation conducted by (Rodríguez et al., 2018). This correspondence between the results from the present research and the prior work by (Rodríguez et al., 2018)serves as a compelling argument in support of the suitability and precision of the numerical model utilized in the current study.

The deformation patterns and displacement magnitudes observed at various locations on the tunnel crown, as compared to (Rodríguez et al., 2018) earlier work, exhibit a depth-dependent trend in bending moment **Figure 3-13.** When comparing the general shape of the displacement profiles, there is a resemblance between the Plaxis3D model and field measurements. The bending moment in my study is 957 kN/m with no TDA layer, which can be attributed to the use of the Hardening Soil model compared to (Rodríguez et al., 2018) Mohr-Coulomb method. Both show a maximum displacement and bending moment at the tunnel crown, indicating a consistent depth-dependent behavior between the two cases. After placing all layers, the bending moment and displacement increase.

Further analysis revealed that the displacement values obtained from the Plaxis 3D model closely resembled the trends observed in the experimental data. For instance, after the excavation and placement of the tunnel lining, a displacement of 1.18 mm was recorded. Subsequently, after the addition of Granular Fill-1 above the 1m crown level of the tunnel, the displacement increased to 6 mm. Further placement of a TDA layer, 2m in height, resulted in a displacement of 7.1 mm. Finally, after adding Granular Fill-2 on top of the TDA layer, approximately 9m above it, the displacement further increased to 18 mm. These results align with the progressive increase in displacement observed in the experimental data from (Rodríguez et al., 2018), despite minor variations in absolute values.

The comparison with the case history and subsequent analyses provided further insights into the behavior of the tunnel system under varying load conditions. The case history demonstrated reductions of up to 50% in lining bending moment with the application of Tire-Derived Aggregate (TDA) as lightweight fill. The subsequent three-dimensional numerical analyses explored the effect of different assumptions about the constitutive model of the TDA material and alternative dispositions of TDA around the tunnel section. Reductions in lining bending moment were achieved, further validating the potential benefits of TDA in reducing static loads on tunnel linings.

These findings not only reaffirm the robustness of the employed numerical model but also provide valuable insights into the potential applications of TDA in optimizing tunnel design and performance under varying load conditions.

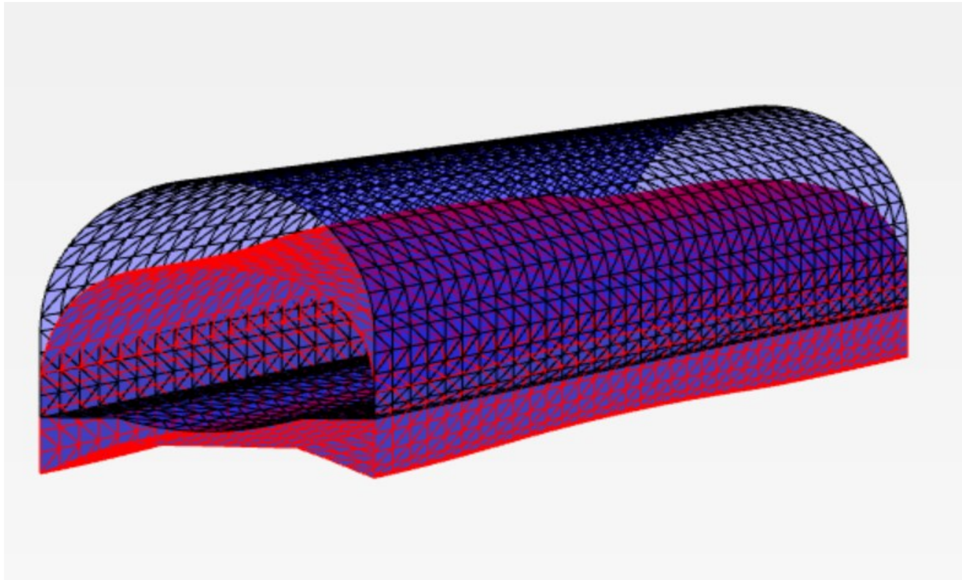


**Figure 3-12: Simulation in Plaxis3D illustrating the deformation of a tunnel lining plate subjected to static loading**

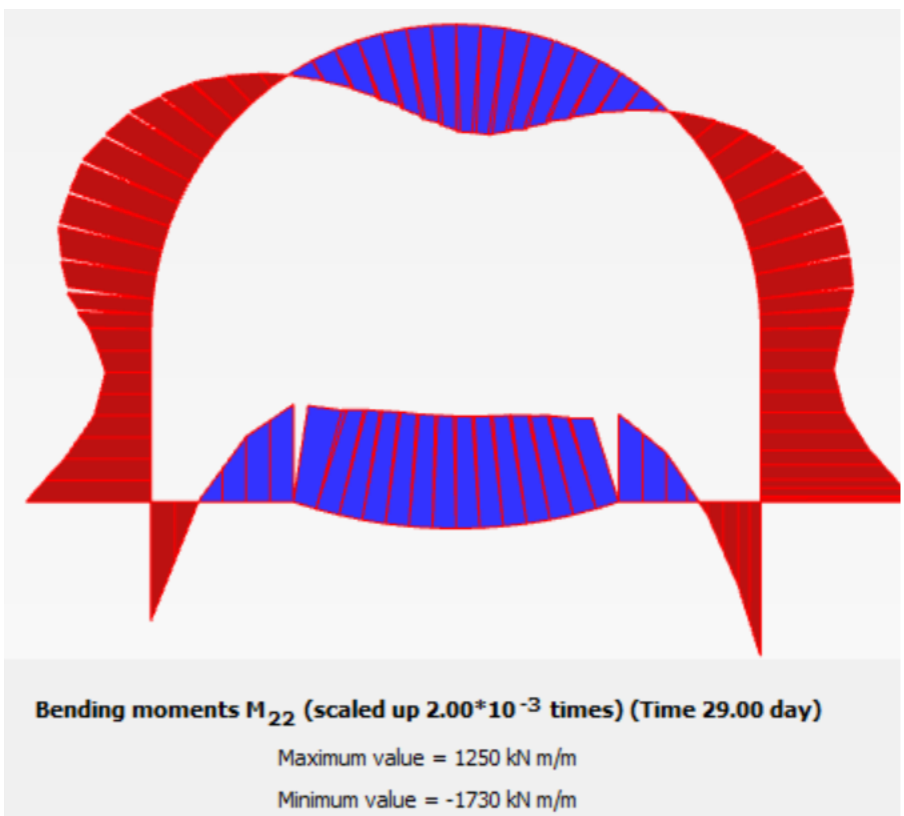



**Figure 3-13: Bending moment analysis at single TDA layer @82m**

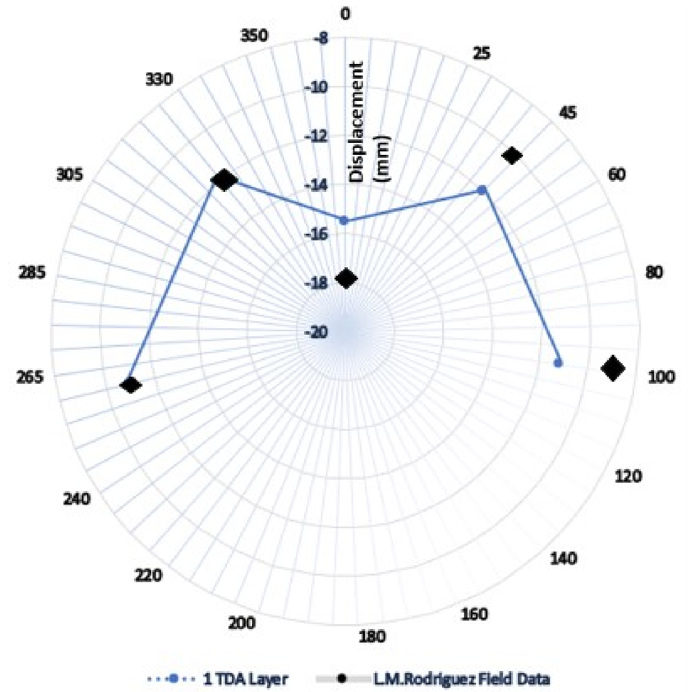



**Figure 3-14: Tunnel Displacement Comparison: 1 TDA Layer vs Experimental Data at Section A-A**

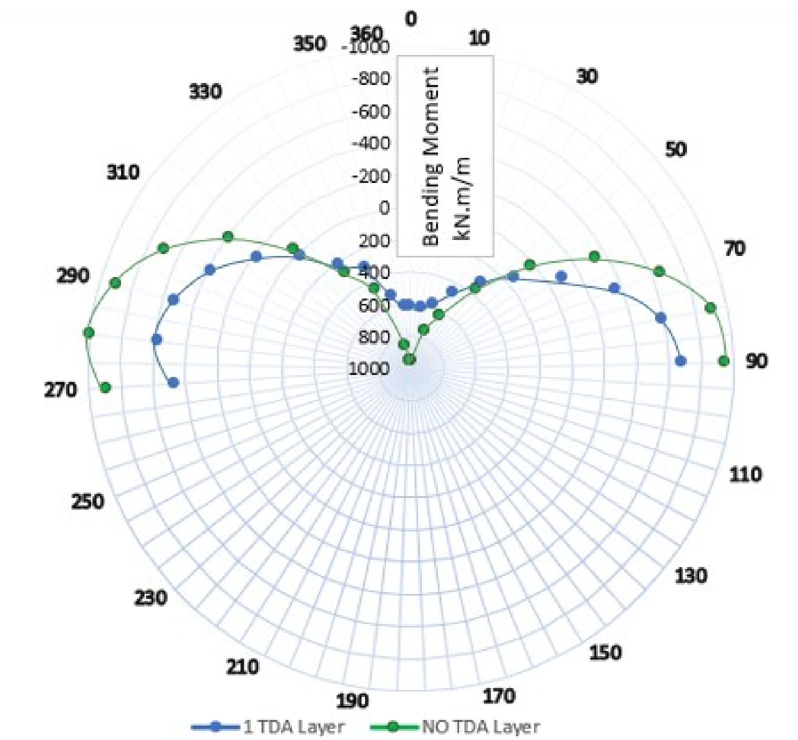



**Figure 3-15: Bending Moment Comparison: 1 TDA Layer vs Experimental Data - Investigating the Influence of TDA on Bending Moments**

## 3.15 Vertical Displacement at Tunnel Crown @82m

The assessment of vertical displacement at the tunnel crown, particularly at Section A-A (Figure 3-2) situated 82 meters from the starting point, is crucial in understanding the settlement behavior during the construction of a cut-and-cover railway tunnel. Drawing comparisons between field data collected during construction and the results obtained from Plaxis-3D analysis provides valuable insights into the accuracy of numerical modeling in predicting tunnel behavior.

In this comparative analysis, the research conducted by (Rodríguez et al., 2018) serves as a foundation, offering detailed accounts of the construction process and methodological considerations that may have influenced settlement readings. Notably, the use of bulldozers to extend the tire-derived aggregate (TDA) material in specific layers and the duration of the final filling phase are highlighted as key factors affecting settlement behavior.

During construction, instrumentation was strategically positioned above the concrete lining before backfilling commenced with Fill-1, the TDA layer, and Fill-2. Notably, significant displacement was observed during the initial month following backfilling, with fluctuations noted in the displacement at the tunnel crown, averaging around -8mm. Subsequent monitoring revealed a maximum displacement of -14mm in the following month. Both the field data and Plaxis-3D analysis exhibited similar trend lines, indicating a degree of correlation between observed displacements and numerical predictions.

(Rodríguez et al., 2018) study further emphasizes the spatial variability in settlement readings along the tunnel, attributed to differences in fill heights at various sections. This spatial variation provides valuable context for interpreting discrepancies between field data and Plaxis-3D analysis results.

While the comparative analysis sheds light on the settlement behavior during tunnel construction, it also underscores the importance of considering construction methodologies and backfilling techniques in interpreting settlement data. The use of bulldozers and the layering process during backfilling are identified as potential influencers on settlement readings, highlighting the need for meticulous monitoring and documentation during tunnel construction.

Given the observed differences between field data and Plaxis-3D analysis results, further investigation is warranted to refine numerical modeling parameters and assumptions. Conducting sensitivity analyses and calibrating the numerical model based on field data could enhance the accuracy of future predictions regarding tunnel behavior and settlement response.

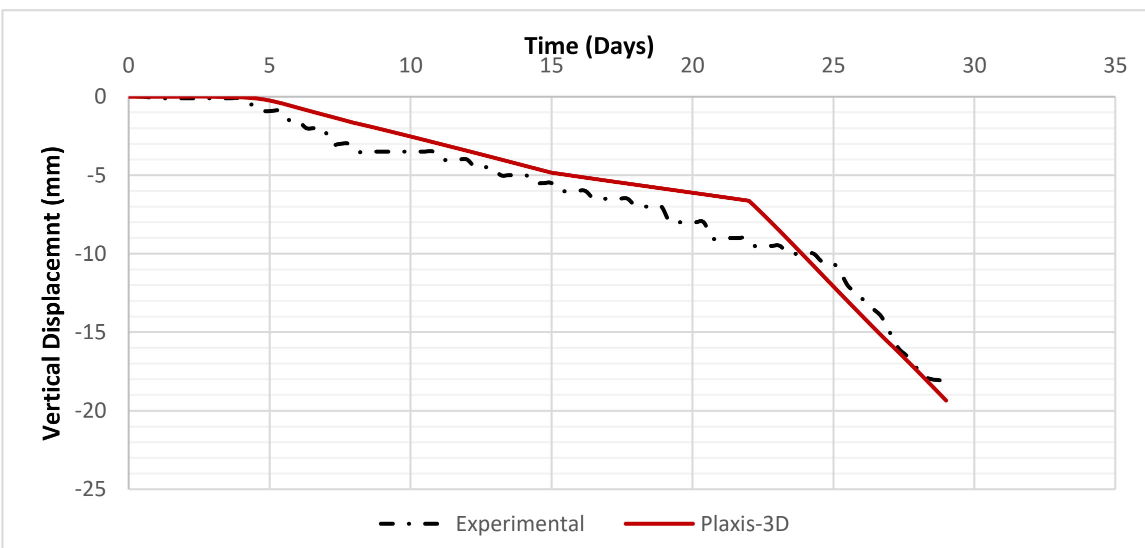



**Figure 3-16: Displacement comparison curves below TDA of L M Rodriguez field result and the developed plaxis3D model at Section A-A**

### 3.16 Vertical Displacement at Tunnel Crown @112m:

Conducting an analysis focusing on the vertical displacement at 112 meters along the tunnel alignment, specifically at Section B-B (Figure 3-2) showed in **Figure 3-17**, we delve into the settlement characteristics within the cut-and-cover construction framework. This evaluation involves a comparison between field measurements and Plaxis-3D simulation results, considering altered construction parameters and a different location along the tunnel alignment. Notably, this assessment excludes the influence of TDA material, with only Fill-1 and Fill-2 present above the concrete tunnel lining.

During the construction phase, the fill was incrementally raised on both sides of the tunnel, maintaining equal heights. Settlement above the fill was not a significant issue, and the TDA material was extended using bulldozers in layers 40 ± 10 cm thick without further compaction. The final filling phase lasted approximately three weeks, after which no significant construction activity occurred. Settlement readings at the crown for the monitoring sections stabilize almost immediately after fill construction stops. Notably, a much-reduced rate of displacement is observed during the first week of July, coinciding with the extension of the TDA layer.

The main effect on settlement readings is due to the variable fill height alongside the tunnel. Sections closer to the tunnel portals with smaller fill heights show smaller settlements. In polar coordinates, plotted co-centric with the section upper arch, it's evident that only sections where the fill is at full height exhibit significant counter flexure. Additionally, piezometric readings consistently indicated a water table located at the original soil substrate.

Despite challenges with some earth pressure cells, the final pressure measured at Section B-B aligns closely with expected values considering fill densities and friction. However, it's essential to note that this assessment excludes sections where cable damage and thermal-induced cell shrinkage affected data reliability.

Switching to Section B-B, with Fill-1 and Fill-2 present but no TDA above the concrete tunnel lining, we observe a vertical displacement of -18.6mm from Plaxis-3D stimulation compared to -18mm from experimental data, indicating close alignment between simulated and observed values at this location.

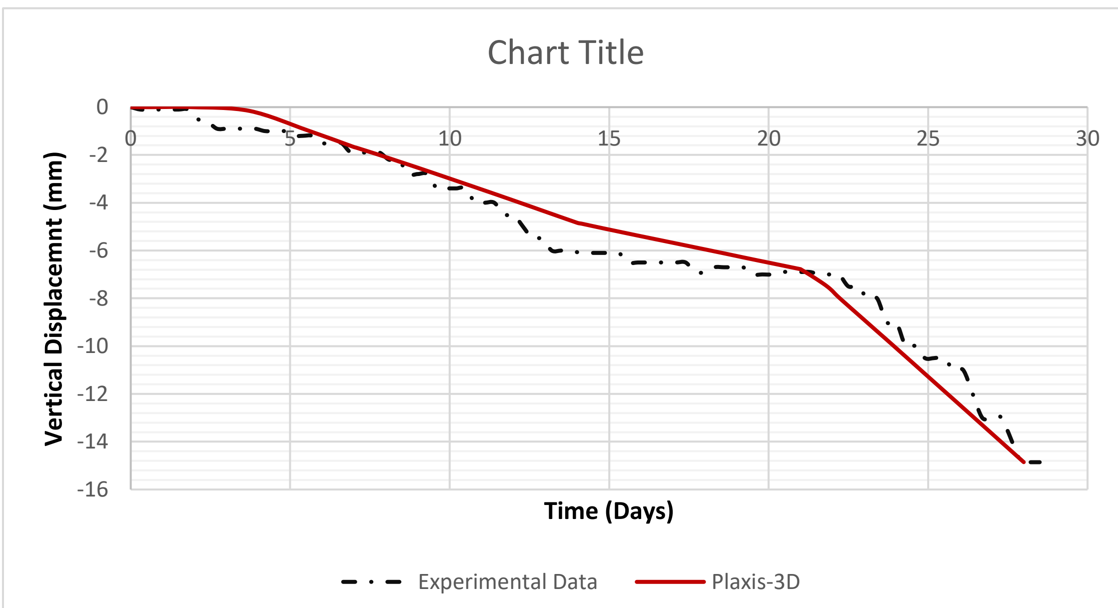



**Figure 3-17: Displacement comparison curves of L M Rodriguez field result and the developed plaxis3D model at Section B-B.**

### 3.17 Final Longitudinal Settlement Profile just above One Layer of TDA and Data from Settlement Platforms

The final longitudinal settlement profile just above one layer of TDA (Tunneling and Underground Construction) reveals a displacement of 384 millimeters. This TDA layer, positioned 1 meters above the tunnel crown and 2 meter thick, falls under category B TDA according to ASTM standard (ASTM D6270-20). This classification denotes a maximum particle size of 450 millimeters and less than 1% content below 4.75 millimeters. Interestingly, this displacement is significantly higher than the typical 198 millimeters observed in the soil at the same depth where TDA is absent, indicating distinct mechanical properties introduced by the TDA layer.

The lightweight composition of TDA, coupled with its advantageous characteristics such as high hydraulic conductivity, effective thermal insulation, and vibration damping capabilities, contributes to its unique settlement behavior. Furthermore, the presence of the TDA layer can lead to an asymmetric distribution of stress around the tunnel lining, thereby influencing the overall settlement pattern. Additionally, the choice of constitutive models for TDA material, ranging from linear isotropic to linear anisotropic and nonlinear isotropic models, impacts settlement predictions, with more sophisticated models often yielding more accurate results.

These factors collectively contribute to the higher displacement observed above the TDA layer compared to the surrounding soil. Understanding the distinct properties and behavior of TDA is essential for accurately assessing its performance in tunnel construction projects. By comprehending these effects, engineers can optimize the design and construction processes, ensuring the efficient and effective utilization of TDA configurations in tunnel projects.

Furthermore, experimental data collected by Luis Medina Rodríguez in 2017 provides valuable insights into the settlement behavior above TDA layers in tunnel structures. At 25 meters distance from the tunnel, the experimental data recorded a displacement of 900 millimeters, while Plaxis 3D simulations indicated a displacement of 98 millimeters. It is important to note that the measuring plate at this distance was broken during construction, which may have influenced the accuracy of the experimental data.

At 82 meters distance (Section A-A), showed in **Figure 3-18,** the experimental data recorded a displacement of -420 millimeters, slightly higher than the Plaxis 3D simulation result of 382 millimeters. Finally, at 114 meters distance (Section B-B), the experimental data recorded a displacement of 180 millimeters, whereas Plaxis 3D simulations indicated a displacement of 161 millimeters.

These comparisons highlight the importance of considering real-world experimental data alongside computational simulations to accurately assess settlement behavior in tunnel structures, particularly above TDA layers.

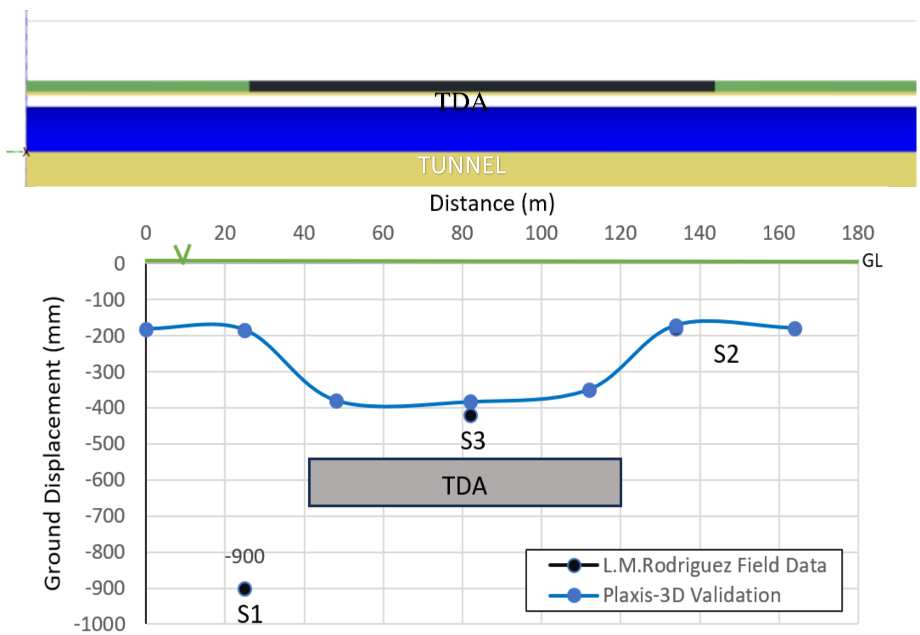



**Figure 3-18: Longitudinal settlement profile just above TDA with experimental Data** (Rodríguez et al., 2018)

## 3.18 Parametric Study: Numerical Analysis of Different TDA Layer Arrangements

In our comprehensive exploration of the extensive body of literature on tire-derived aggregate (TDA), a myriad of studies conducted by distinguished researchers such as Bosscher, Edil, Eldin, Mahgoub, El Naggar, Smith, Johnson, Gupta, and many others has provided profound insights into the versatile applications of TDA in diverse civil engineering structures. These studies have consistently emphasized the significant role of TDA in mitigating static loads due to its lightweight properties, offering a promising avenue for sustainable and efficient construction practices.

Our parametric study builds upon this foundational knowledge, seeking to unravel the nuanced influence of TDA distribution above a cut-and-cover tunnel. the study endeavors to assess the benefits of integrating TDA into its fill material. Employing a sophisticated 3D finite difference model crafted through PLAXIS-3D software, our research methodology ensures a meticulous representation of the tunnel's geometry and construction process.

To capture the intricate mechanical response of TDA under static loading conditions, our study diligently evaluates various constitutive models. From fundamental isotropic linear elasticity models to nuanced formulations involving anisotropic behavior, each model undergoes rigorous calibration grounded in empirical field measurements. This calibration process fine-tunes the predictive accuracy of these models, enabling them to faithfully simulate the intricate mechanical response of TDA.

Our parametric study meticulously explores three configurations of TDA placement above the tunnel, including a single layer positioned 1.5 meters above the tunnel crown, a stratified two-layer configuration with TDA above the tunnel, and an enveloping surrounding TDA configuration encompassing the tunnel arch. This systematic comparison aims to unravel the underlying mechanisms dictating the impact of TDA placement on mitigating static loads exerted on the tunnel lining.

In-depth analyses of settlement profiles above the TDA layer reveal intriguing insights into the subtle yet profound influence of TDA configuration on surface settlement patterns. The meticulously orchestrated two-layer configuration consistently exhibits lower surface settlements compared to its enveloping counterpart, indicating a tangible reduction in the stresses permeating through the TDA material.

Furthermore, tunnel convergence metrics, critical for the structural integrity of tunnels, witness a palpable reduction with the judicious introduction of TDA into the equation. Both configurations of TDA placement yield decreased tunnel convergence metrics compared to scenarios devoid of TDA. However, the enveloping TDA configuration emerges as the frontrunner in effecting substantial reductions in tunnel convergence, hinting at a more efficient redistribution of stresses encircling the tunnel lining.

Examining bending moment envelopes provides profound insights into structural stability. The stratified two-layer TDA configuration emerges as a harbinger of structural stability, boasting a notable reduction in positive bending moments, particularly at the tunnel crown. Conversely, the enveloping TDA configuration showcases minimal improvements in bending moments, underscoring the critical role of strategic TDA placement in optimizing tunnel design under the rigors of static loading conditions.

In conclusion, our parametric study serves as a comprehensive exploration of TDA's potential in alleviating static loads exerted on tunnel linings. These findings underscore the pivotal role of TDA configuration in achieving optimal performance, with the stratified two-layer configuration emerging as the superior choice compared to its enveloping counterpart. Armed with these insights, tunnel design and construction practices stand poised to embrace TDA as a potent solution for bolstering the sustainability and performance benchmarks of tunnel infrastructure. Nonetheless, the journey towards widespread adoption of TDA beckons further research endeavors and field demonstrations to validate these findings and catalyze its global proliferation in tunnel construction projects.

Building upon this, the literature on tire-derived aggregates (TDA) reveals a comprehensive understanding of their application in various civil engineering projects, providing valuable insights into soil-structure interaction, especially concerning cut-and-cover tunnels.

Studies by (El Naggar, 2018; Mahgoub, 2019; Mahgoub & El Naggar, 2019) focus on TDA as a backfill material for reducing stresses on buried pipes. Mahgoub and El Naggar's research demonstrate that TDA acts as a stress-reducing cushion, mitigating stress concentrations on pre-existing pipes by up to 50%. Smith and Johnson's findings showcase a linear reduction trend in pipe stresses with increasing TDA thickness, suggesting the potential for tailored design considerations.

In the context of culverts, (Mahgoub, 2019) explore the impact of TDA on corrugated steel plate culverts. (Mahgoub & El Naggar, 2019) study highlight the role of TDA in stress bridging over buried metal pipes. Similarly, Islam 2023 et al.'s research investigates various configurations of TDA around CSP culverts, emphasizing its ability to modify stress-settlement relationships and improve culvert performance under different loading conditions.

(Pincus et al., 1994) shed light on TDA's potential in shallow foundations. They highlight TDA as a cost-effective and environmentally friendly alternative to conventional backfill aggregates, making it a viable option for stabilizing shallow foundations on soft soils.

In conclusion, the collective findings from these studies underscore the promising role of TDA in soil-structure interaction, particularly in the context of cut-and-cover tunnels. By leveraging TDA's unique properties and exploring its diverse applications across various civil engineering projects, researchers have contributed valuable insights into optimizing soil-structure interaction and enhancing the performance of underground structures.

# CHAPTER-4 EXPLORATION OF ALTERNATIVE TDA CONFIGURATIONS IN PARAMETRIC STUDIES

In exploring alternative configurations of tire-derived aggregate (TDA) in parametric studies, my focus is specifically on addressing the challenge of mitigating vertical stress at the tunnel crown level, a crucial aspect of tunnel engineering. Initial findings from a field test revealed that a single TDA layer resulted in only modest reductions in vertical stress, highlighting the necessity for more nuanced configurations. Consequently, two new models were developed to represent distinct geometrical arrangements of TDA material within the tunnel structure.

These models were meticulously crafted to simulate realistic scenarios aimed at optimizing stress distribution and alleviating the effects of static loads. Through thorough analysis, I am investigating the impact of different elastic material models of TDA, particularly isotropic formulations. Each model is undergoing comprehensive simulations under static loading conditions to assess its effectiveness in redistributing stress within the tunnel structure.

Additionally, as part of this exploration, I am analyzing scenarios involving the placement of two TDA layers (**Figure 4-1)** and investigating the configuration where the tunnel is surrounded by TDA layers **(Figure 4-2)**. These configurations aim to maximize the potential benefits of TDA in mitigating stress and enhancing the structural integrity of the tunnel under various loading conditions. Through detailed analysis and comparison with traditional construction methods, the goal is to determine the most effective TDA configurations for optimizing tunnel performance and sustainability.

Finally, the study includes dedicated analyses for the following configurations:

- Two TDA layers
- Tunnel surrounded with TDA layers.

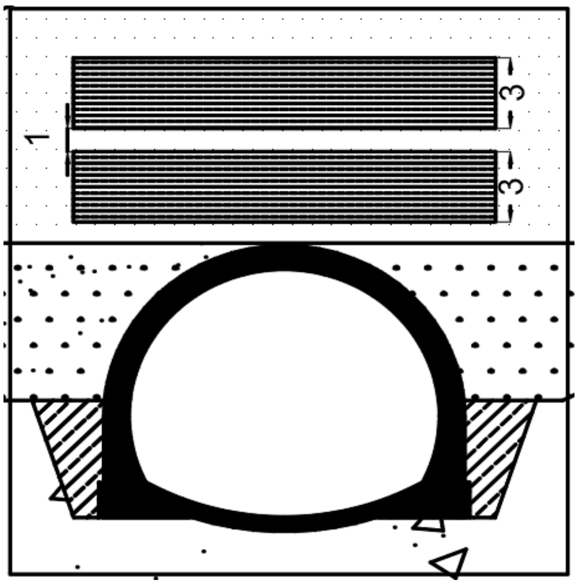



Figure 4-1: TDA Layer

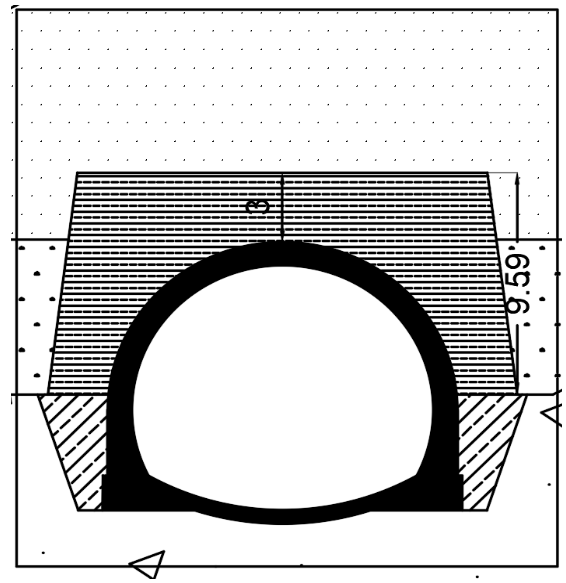



Figure 4-2: Surrounded With TDA

### 4.1 Two TDA Layers

Expanding on the configuration involving two TDA layers, this setup represents a thicker variation compared to the single TDA layer previously constructed, approaching the upper limit of class II TDA fills as defined by (ASTM D6270, 2008). In this configuration, two TDA layers are utilized, each designed with specific dimensions and placements to optimize their effectiveness in mitigating vertical stress within the tunnel structure.

The dimensions of each TDA layer are meticulously determined to ensure adequate coverage and support while adhering to established standards. Each layer spans 65 meters in length and 17 meters in width, maintaining symmetry about the tunnel axis to ensure uniform stress distribution. Additionally, the thickness of each layer is set at 3 meters, providing substantial material depth to accommodate the desired stress-reducing properties.

In terms of placement, the lower TDA layer is strategically positioned 1 meter above the tunnel crown, ensuring proximity to the areas experiencing the highest stress concentrations. This placement allows the lower TDA layer to effectively absorb and redistribute vertical stress, thereby enhancing the structural integrity of the tunnel lining. Furthermore, the upper TDA layer is situated 1 meter above the lower layer, maintaining a consistent separation distance to optimize stress distribution across both layers.

Considering the Plaxis-3D analysis results, it is evident that the configuration with TDA layers above the tunnel crown significantly reduces displacement, bending moment, and axial force compared to scenarios without TDA layers. With TDA layers in place, the displacement at the tunnel crown is reduced to 13.9 mm, the bending moment decreases to 465 kN m/m, and the axial force is -825 kN/m. In contrast, without TDA layers, the displacement at the tunnel crown increases to 18.5 mm, the bending moment rises to 980 kN m/m.

These findings underscore the effectiveness of the two-TDA-layer configuration in mitigating vertical stress and enhancing the structural stability of the tunnel. By incorporating specific dimensions, placements, and rigorous analysis through Plaxis-3D simulations, this configuration demonstrates promising results in optimizing tunnel performance and sustainability.

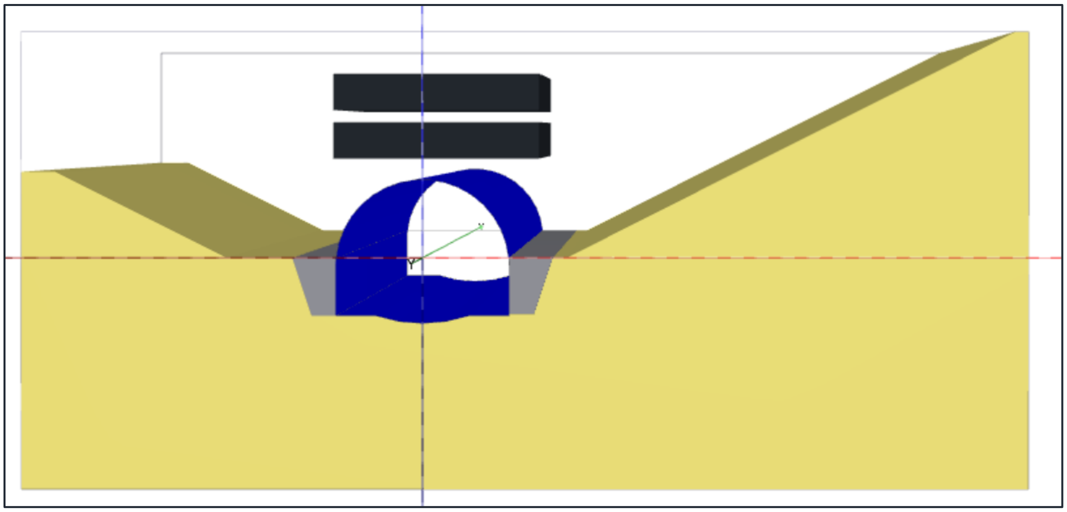


**Figure 4-3: Plaxis 3D model with 2 TDA layer distribution above Crown**

## 4.2 Surrounding with TDA Layer

Exploring the configuration where the tunnel is surrounded by TDA provides valuable insights into its efficacy in stress mitigation within the tunnel structure.

This configuration involves strategically placing TDA material around the tunnel arch, encompassing it in a single layer. The volume of TDA used in this configuration amounts to 6630m$^3$, calculated to provide adequate coverage while adhering to established standards. Unlike the previous configuration involving two TDA layers, where the TDA was placed above the tunnel crown, this setup surrounds the entire tunnel perimeter with TDA material.

Incorporating the results from PLAXIS-3D analysis and simulation offers detailed insights into the effectiveness of the surrounding TDA configuration in reducing stress within the tunnel structure.

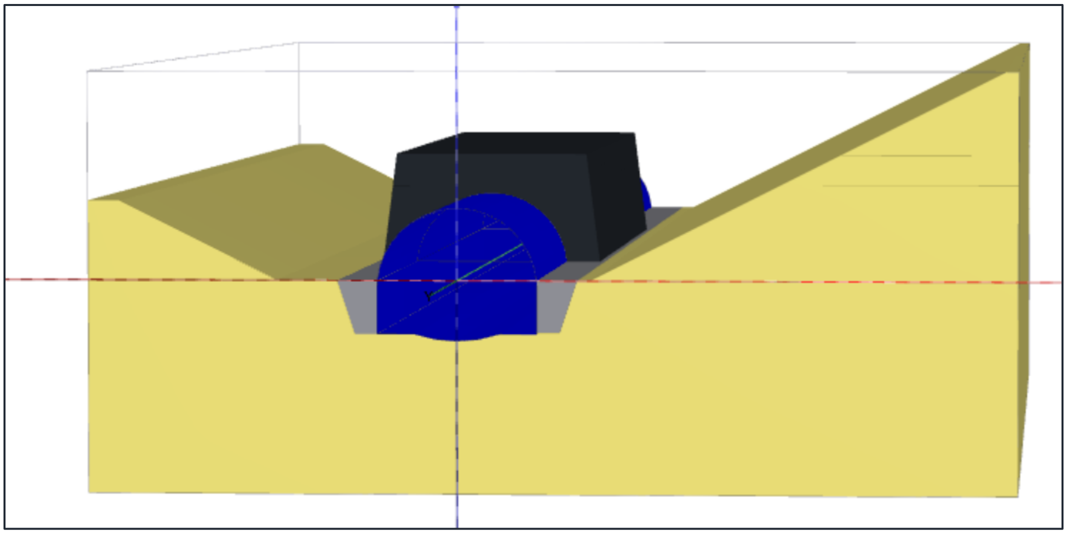


**Figure 4-4: Plaxis 3D model with Surrounded with TDA layer distribution above Crown**

With the surrounding TDA configuration, the analysis reveals a displacement of 13.5 millimeters at the tunnel crown, accompanied by a bending moment of 772 kN m/m. These findings highlight a significant reduction in displacement and bending moment compared to scenarios without TDA layers.

Conversely, without TDA layers, the analysis yields a displacement of 18.2 millimeters at the tunnel crown, with a corresponding bending moment of 980 kN m/m. These results underscore the substantial impact of surrounding TDA in reducing displacement and bending moment, thereby enhancing the structural stability and performance of the tunnel lining under static loading conditions.

## 4.3 Comparing displacement of 2TDA and Surrounded with TDA Layer Configuration

After conducting thorough Plaxis-3D analysis and simulation to assess the effectiveness of different configurations of tire-derived aggregate (TDA), we obtained insightful results regarding the deformation (displacement) at the tunnel crown across various TDA configurations.

In the absence of any TDA layer, the observed displacement at the tunnel crown, located at coordinates Y=112m, X=0, Z=6m, was measured at 18.5 millimeters. This displacement value represents the deformation experienced by the tunnel structure under the applied static loading conditions. Introducing a single TDA layer into the configuration resulted in a noticeable reduction in displacement, with the value decreasing to 15 millimeters. This reduction of approximately 18.9% compared to the configuration without TDA highlights the capacity of TDA to mitigate deformation and stabilize the tunnel structure.

Expanding on the effectiveness of TDA configurations, the introduction of two TDA layers further reduced the displacement to 13.9 millimeters. This additional reduction of approximately 7.9% compared to the configuration with a single TDA layer emphasizes the cumulative impact of multiple TDA layers in minimizing deformation. It showcases the synergistic effect achieved by strategically layering TDA within the tunnel structure to enhance its stability and resilience against static loading.

Notably, when the tunnel was enveloped by a TDA layer, the displacement decreased significantly to 13.5 millimeters. This configuration, surrounding the tunnel with TDA, demonstrated the most substantial reduction in displacement, representing a remarkable reduction of approximately 27.0% compared to the configuration without TDA. The surrounding TDA layer effectively distributed stress and mitigated deformation, showcasing its potential as a viable solution for optimizing tunnel performance and durability.

These findings underscore the critical role of TDA configurations in mitigating deformation and stabilizing tunnel structures under static loading conditions. The progressive reduction in displacement observed with the introduction of TDA layers highlights the importance of strategic placement and layering of TDA material to achieve optimal performance."

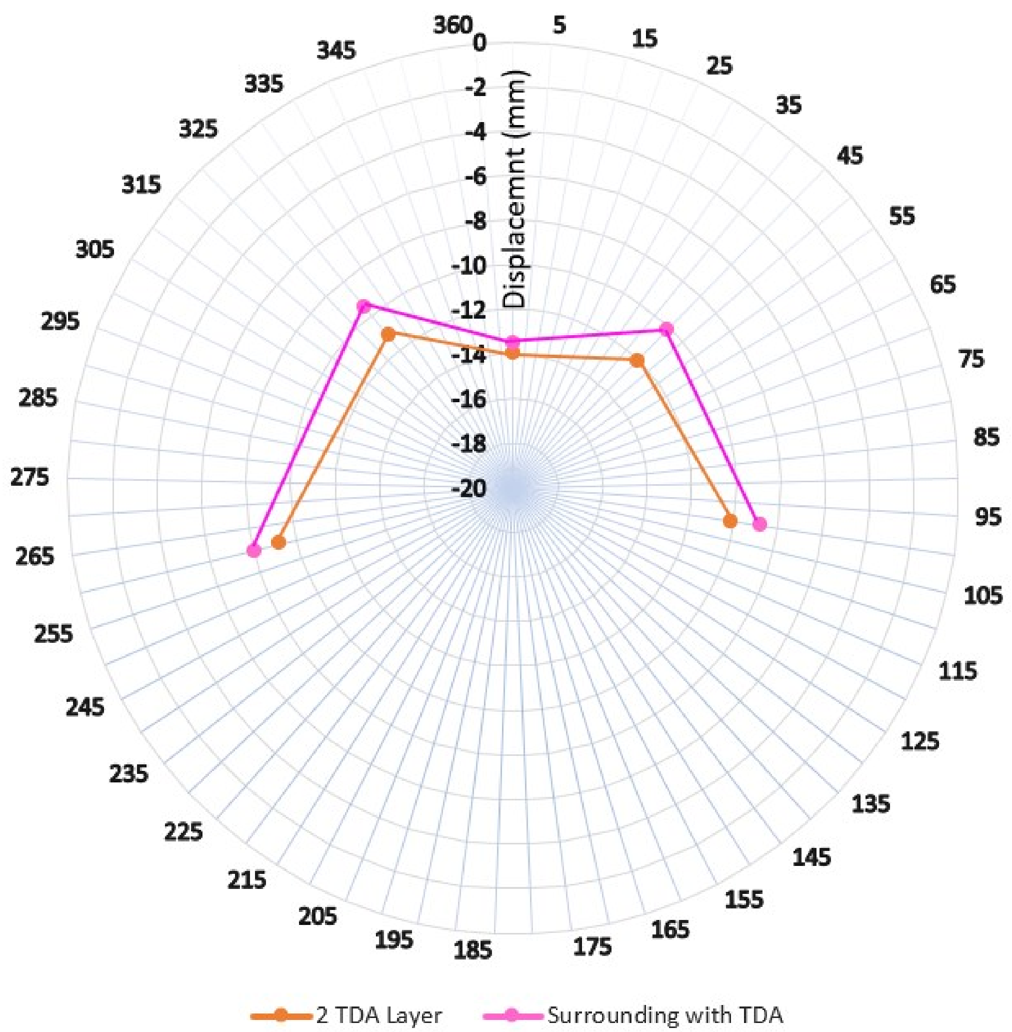



**Figure 4-5: Tunnel lining displacement Comparison between 2 TDA layer and Surrounding with TDA Layer configuration.**

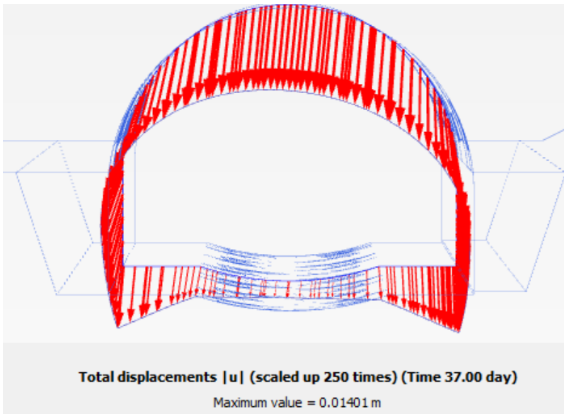



**Figure 4-6: 14mm Displacement at crown with 2 TDA Layer (Section A-A)**

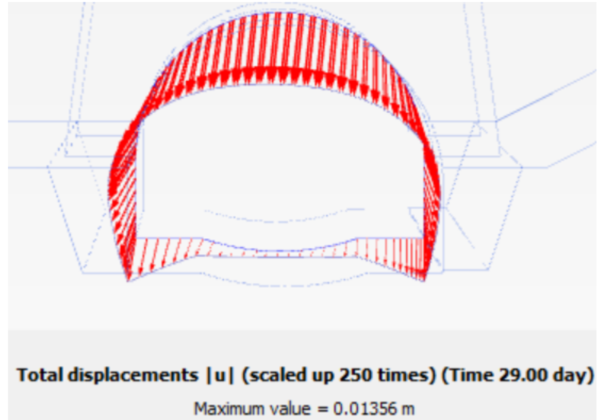



**Figure 4-7: 13.5mm Displacement at Crown with Surrounded TDA Layer Section (A-A)**

### 4.4 Comparing Bending Moment of 2TDA and Surrounded with TDA Layer Configuration:

After conducting extensive Plaxis-3D analysis and simulation, we evaluated the bending moment at the tunnel crown across different configurations of tire-derived aggregate (TDA). The bending moment, a measure of the bending stresses experienced by the tunnel structure, is a critical parameter in assessing structural stability and integrity. In the absence of any TDA layer, the bending moment measured a significant 1160 kN m/m, indicating considerable bending stresses exerted on the tunnel lining. Introducing a single TDA layer into the configuration resulted in a notable reduction in bending moment (BM), with the value decreasing to 575 kN m/m. This reduction of approximately 50.4% compared to the configuration without TDA highlights the effectiveness of TDA in reducing bending stresses and stabilizing the tunnel structure.

Furthermore, the introduction of two TDA layers further decreased the bending moment to 465 kN m/m, showcasing the additional benefits of layering TDA for enhanced structural stability. By strategically placing multiple TDA layers within the tunnel structure, we observed a synergistic effect in minimizing bending stresses and distributing loads more effectively. This layered approach demonstrated its efficacy in optimizing structural performance and resilience against static loading conditions.

Additionally, surrounding the tunnel with a TDA layer also significantly reduced the bending moment to 600 kN m/m. This configuration, known as the "tunnel surrounded by TDA layer," effectively distributed stress and minimized bending forces exerted on the tunnel lining. The surrounding TDA layer acted as a buffer, absorbing, and redistributing loads to enhance the overall structural integrity of the tunnel. These findings underscore the crucial role of TDA configurations in reducing bending stresses and improving the overall structural integrity of tunnels under static loading conditions. By mitigating bending stresses, TDA configurations contribute to the longevity and safety of tunnel infrastructure, offering valuable insights for engineers and practitioners in tunnel design and construction.

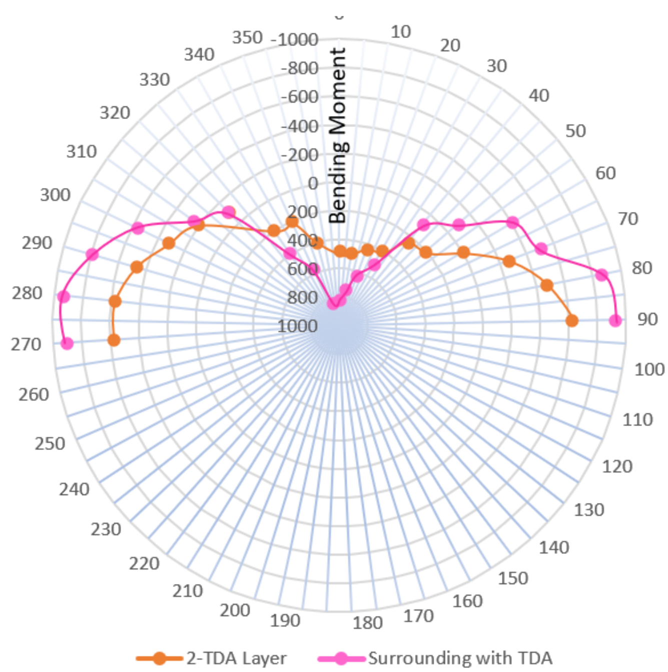



**Figure 4-8: Bending Moment Comparison between 2 TDA layer and Surrounding with TDA Layer configuration Tunnel**

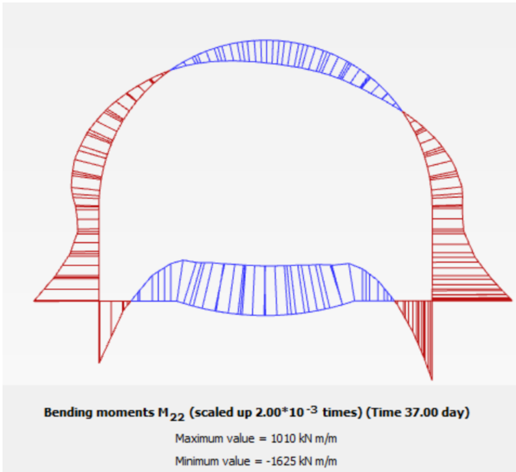



**Figure 4-9: BM corresponding at tunnel lining @82m (Section A-A) with 2TDA Layer**

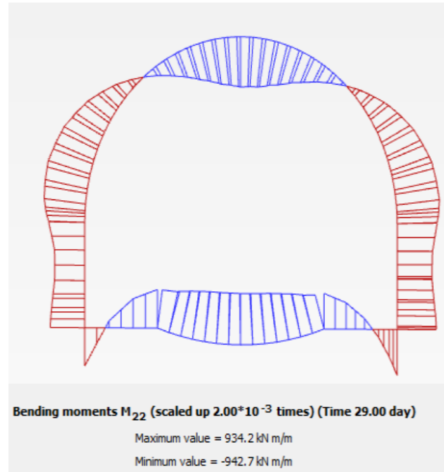



**Figure 4-10: BM corresponding at tunnel lining @82m (Section A-A), surrounded with TDA layer**

## 4.5 Longitudinal Displacement Comparison of Two TDA Layer and Surrounded with TDA Layer

The comparison between the configuration with two TDA layers and the configuration surrounded by TDA layers reveals distinct characteristics in terms of displacement and structural behavior, with implications for tunnel construction projects.

In the configuration with two TDA layers, the displacement at the TDA surface is measured at 745 millimeters. This setup involves stacking two TDA layers, each 3 meters thick, with a total of 3 meters of fill above the TDA layers acting as a static load. While the displacement is significant, it falls within the upper limit of class II TDA fills as defined by ASTM D6270-08 standards. This configuration offers increased load-bearing capacity and structural stability due to the presence of multiple TDA layers, thereby potentially reducing settlement and minimizing the risk of structural damage over time.

On the other hand, in the configuration surrounded by TDA layers, the displacement at the TDA surface is observed to be 868 millimeters. Here, the same volume of TDA as in the previous case is disposed in a single layer encircling the tunnel arch. This disposition may slightly exceed ASTM D6270-08 standards by allowing free air access into the TDA fills, potentially affecting the thermal properties of the surrounding soil and the overall settlement behavior. However, detailed analyses by Arroyo et al. (2011) suggest minimal heat generation when exposed steel is limited according to ASTM provisions, and facilitating air circulation within such fills has been found to reduce eventual temperature rise. The surrounding TDA layer configuration offers ease of access for air circulation and maintenance but may require additional measures to mitigate settlement and ensure structural integrity.

While both configurations result in substantial displacements at the TDA surface, the configuration surrounded by TDA layers exhibits a slightly higher displacement compared to the configuration with two TDA layers. This difference may be attributed to the distribution of the TDA material and the effects of surrounding air circulation on settlement behavior. Further analysis and comparison of stress distribution, settlement patterns, and long-term structural performance would provide valuable insights into the suitability of these configurations for tunnel construction projects, taking into account factors such as soil composition, environmental conditions, and project-specific requirements.

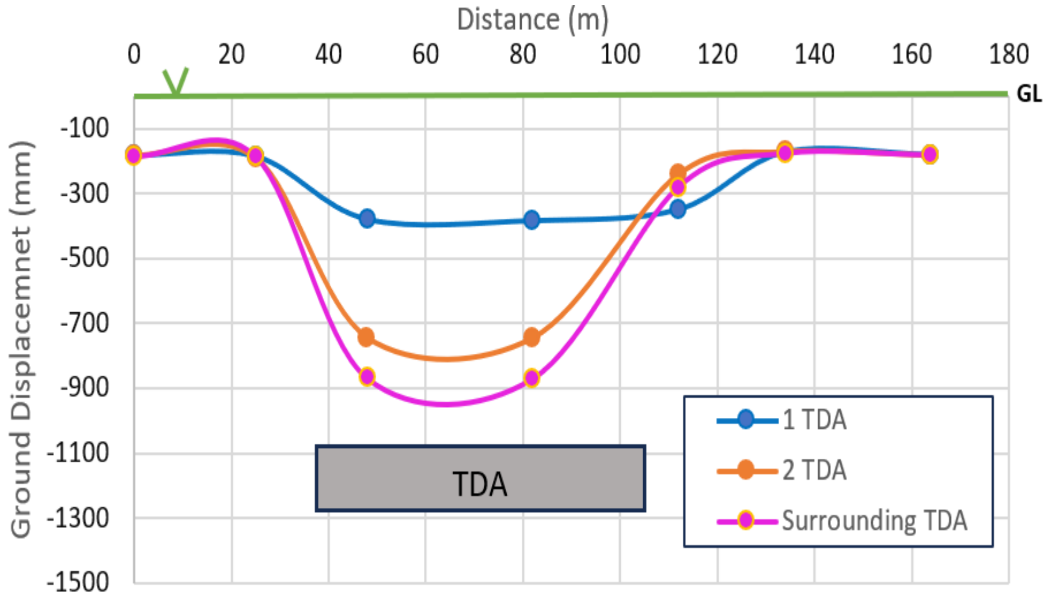


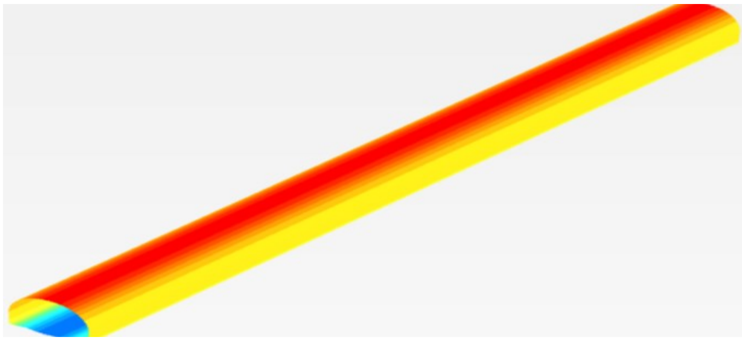

**Figure 4-11: Longitudinal Displacement Above three different TDA layer Distribution**

## 4.6 Contours at Tunnel lining

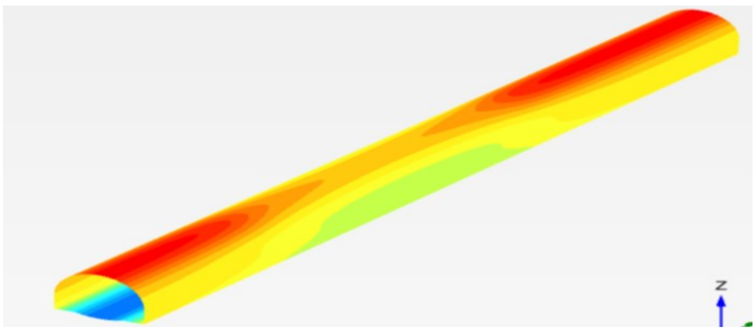
In the PLAXIS 3D analysis of the concrete tunnel lining, stress distribution is visually represented through contour plots, indicating varying stress levels with different colors. Without a Tire-Derived Aggregate (TDA) layer, the contour plots show intense red coloring at the tunnel crown, indicating significant stress concentrations. However, introducing one TDA layer above the crown results in a more uniform stress distribution, with fewer areas of high stress. Configurations featuring two TDA layers or complete encasement of the tunnel with TDA exhibit even lower stress levels across the structure. These findings suggest that the presence of TDA layers helps mitigate stress concentrations and optimize the tunnel's structural performance.

- **No TDA Layer:** Intense stress concentrations observed at the tunnel crown, indicated by prominent red areas on the displacement contours.
- **1 TDA Layer:** Improved stress distribution compared to the absence of TDA, with reduced prominence of high-stress areas and more uniform displacement contours.
- **2 TDA Layers:** Further reduction in stress concentrations, showcasing a significant enhancement in stress distribution and overall structural stability.
- **Surrounded with TDA:** Optimal stress mitigation achieved, as evidenced by the displacement contours, indicating a robust and resilient tunnel structure supported by TDA layers.

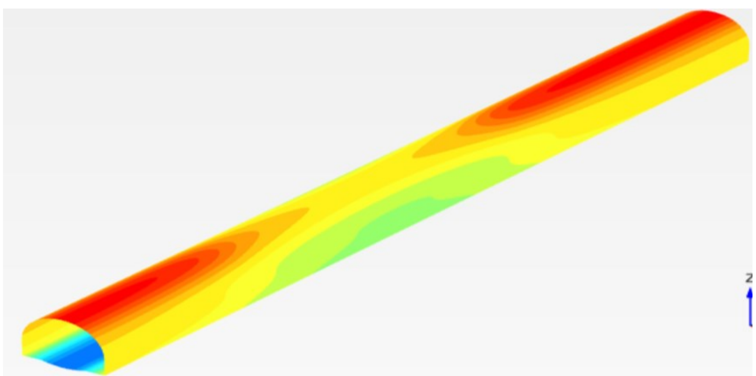
For detailed 3d visualization, refer to **Figure 4-12** for displacement contours.



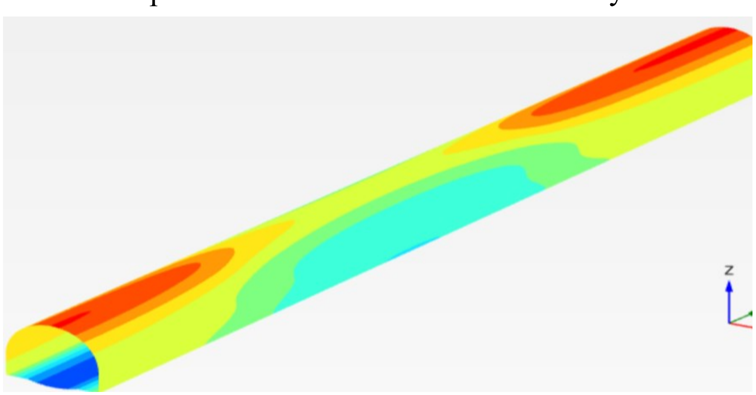
Displacement Contours with No TDA Layer



Displacement Contours with 1 TDA Layer



Displacement Contours with 2 TDA Layer



Displacement Contours Surrounded with TDA Layer

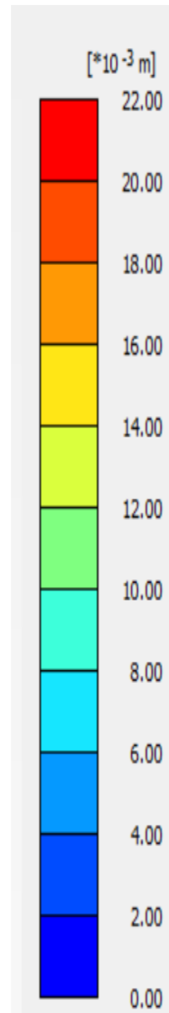



**Figure 4-12: A 3D representation of Displacement contours with 4 different consecutive models with and without TDA**

# CHAPTER-5 DISCUSSION AND RESULTS

## 5.1 Interpretation of Results and Findings from the Research

The research findings underscore the potential of tire-derived aggregate (TDA) as a viable solution for reducing the weight of fill materials above cut-and-cover railway tunnels. Through meticulous field testing and numerical analyses, it was observed that the incorporation of TDA into tunnel construction projects can lead to significant reductions in lining bending moment, thereby indicating its effectiveness in mitigating static loads on tunnel linings.

The comprehensive comparison of different constitutive models for TDA revealed that while the choice of model had some influence on the behavior of the tunnel, the overall impact on tunnel lining loads was relatively minor. This suggests that empirical calibration of numerical models with field measurements is crucial for accurate predictions, highlighting the practical importance of validating computational models in geotechnical engineering applications.

Furthermore, the study demonstrated that TDA layered fills, when strategically placed above the tunnel crown, offer notable benefits in terms of reducing static loads on tunnel linings. The analysis of various TDA configurations revealed that the two-layer TDA configuration consistently outperformed other configurations in terms of minimizing settlement profiles and bending moments in the tunnel lining.

### *5.1.1 Bending Moment Interpretation*

The analysis of bending moments at the tunnel crown provides crucial insights into how the structural behavior of the tunnel lining is influenced by different configurations of Tire-Derived Aggregate (TDA). Without TDA, the bending moment is measured at 957 kN/m², indicating significant stress concentrations at the tunnel crown. However, with the introduction of one TDA layer, positioned strategically above the tunnel crown, the bending moment decreases to 597 kN/m², reflecting a notable reduction of about 37.6%. This reduction underscores the effectiveness of incorporating TDA in alleviating stress on the tunnel lining.

Furthermore, when two TDA layers are employed, each placed at a distance above the tunnel crown, the bending moment further diminishes to 477 kN/m². This represents a more substantial reduction of approximately 50.2% compared to the scenario without TDA. The significant decrease in bending moment with the addition of two TDA layers highlights the considerable benefits of this configuration in minimizing stress and optimizing the structural integrity of the tunnel lining.

In contrast, surrounding the tunnel with TDA, while maintaining the same volume as the previous configurations, results in a bending moment of 772 kN/m². While this value is lower than that of the scenario without TDA, it is not as effective as employing two TDA layers. This suggests that the arrangement and positioning of TDA layers play a crucial role in mitigating bending moments on the tunnel lining, emphasizing the importance of careful planning and design considerations.

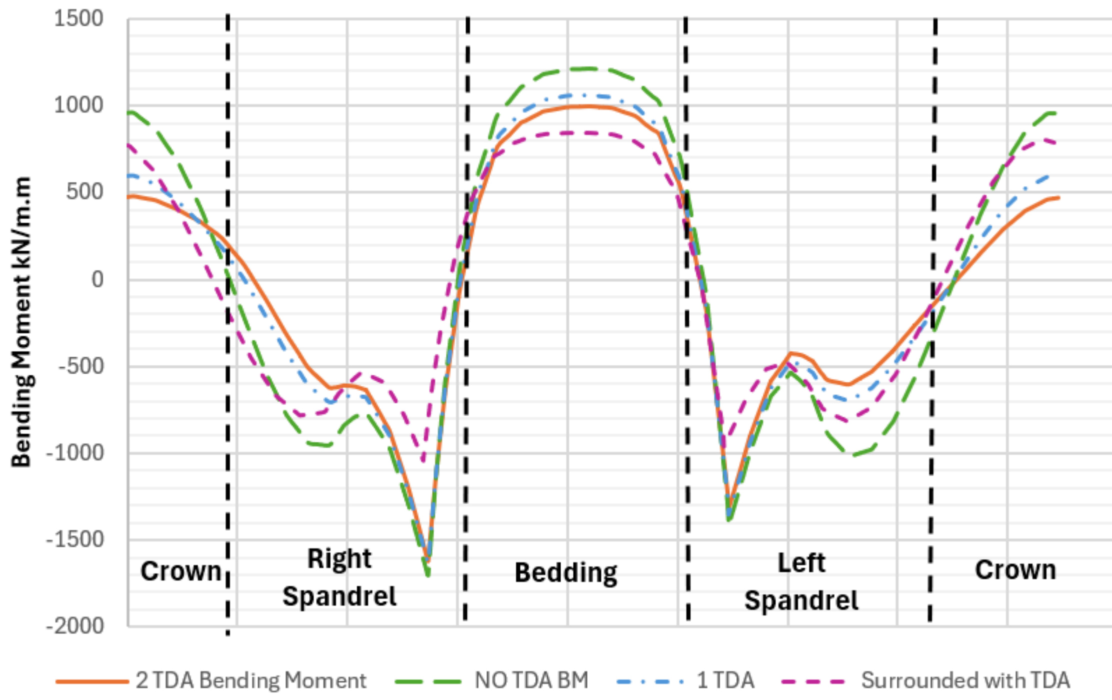



**Figure 5-1: Effect of Different TDA distribution on Computed Bending Moment**

**Table 5-1: Maximum Bending Moment (kN.m/m)**

| Model | Bending Moment (kN.m/m) |
|---|---|
| No TDA | 957 |
| 1 TDA | 597 |
| 2 TDA | 477 |
| Surrounded with TDA | 772 |

### *5.1.2 Displacement Interpretation*

Investigating crown displacement at a specific point within the tunnel, precisely at Section A-A, 82m along the tunnel axis and at a height of 11 meters from the base of the tunnel, provides crucial insights into the deformations experienced by the tunnel structure. Analyzing crown displacement at this particular location allows for a focused examination of the maximum deformation occurring at the tunnel crown, which is often a critical consideration in tunnel engineering.

Initially, without TDA, the crown displacement at this specific point is measured at 19.35mm. Upon introducing one TDA layer, 2 meters thick and positioned 1 meter above the tunnel crown, the displacement decreases to 14.855mm, indicating a reduction of approximately 23.1%. Furthermore, with the addition of two TDA layers, each 3 meters thick and separated by a 1-meter gap, the displacement further decreases to 13.84mm, representing a reduction of approximately 28.5% compared to the baseline scenario without TDA.

Intriguingly, when the tunnel is surrounded by TDA, maintaining the same volume of TDA as in the previous alternative method, the crown displacement at this specific point is recorded at 13.5mm. Although this configuration results in a reduction compared to the scenario without TDA, it is slightly less effective than having two TDA layers, indicating that the arrangement of TDA layers plays a crucial role in minimizing crown displacement.

Furthermore, it is noteworthy to mention that the displacement distribution across different sections of the tunnel varies. At a 45-degree inclination from the reference point, the displacement is observed to be approximately 2mm higher compared to measurements taken at 325 degrees. Similarly, significant displacement is detected along the tunnel side walls, particularly at 100 degrees and 260 degrees, where displacement values reach approximately 9-10mm.

These findings, complemented by the radar graph below in the thesis, underscore the significant influence of TDA configuration on crown displacement at specific points within the tunnel structure. The considerable reductions observed with the introduction of TDA layers highlight the potential of TDA as a viable solution for reducing deformations and enhancing the stability of tunnel systems, particularly at critical locations such as the tunnel crown and sidewalls. Moreover, the comparative analysis emphasizes the importance of optimizing TDA placement to maximize its beneficial effects on crown displacement and overall tunnel performance.

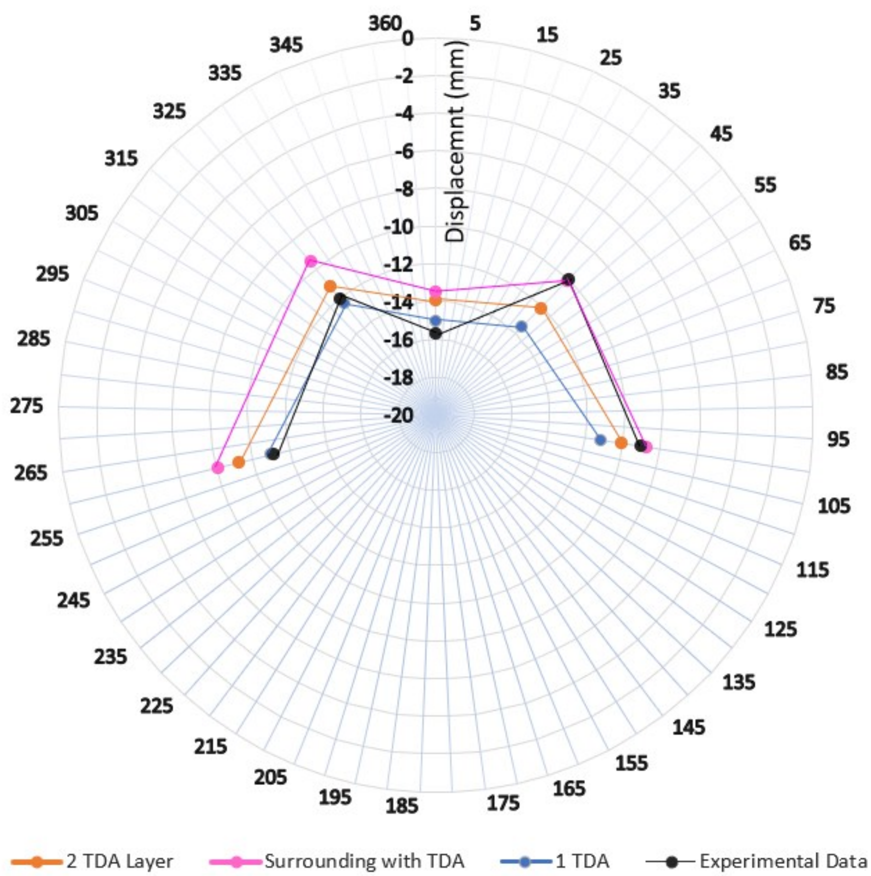



**Figure 5-2: Tunnel lining final displacements at five different angles, showing effect of alternative TDA distributions.**

### *5.1.3 Time vs Settlement curve on Tunnel Lining*

The settlement behavior over time in tunnel construction is a critical aspect that requires thorough investigation. The initial phase (0-5 days) typically demonstrates minimal settlement, around 1mm, attributed to the absence of backfill material. As fill-1 is progressively introduced along the tunnel's sides (4th-10th day), settlement gradually increases to approximately 3mm, indicating the initial accommodation of the applied load.

The pivotal moment arrives when fill-1 reaches a height of 1m above the tunnel crown (10th-15th day). At this juncture, settlement escalates to about 5mm, reflecting the intensified load distribution on the tunnel structure.

Comparing the settlement behavior among different constitutive models, noteworthy distinctions emerge. In the case of the No TDA and 1 TDA layer models, settlement progression closely mirrors the incremental addition of fill material. However, with the 2 TDA layers model, settlement exhibits a more restrained response, indicative of the mitigating effect of multiple TDA layers on load-induced deformations.

Remarkably, the TDA surrounded around the tunnel model presents a compelling narrative. Despite the dynamic construction environment, settlement remains relatively stable at 4mm, underscoring the efficacy of TDA as a protective medium against settlement.

The introduction of fill-2 marks a significant turning point, precipitating a surge in settlement across all models. Notably, the 2 TDA layers model demonstrates resilience, with settlement peaking at 13.9mm, emphasizing the importance of innovative solutions in mitigating settlement-induced risks in tunnel construction.

The time vs. settlement graph serves as a valuable tool for understanding settlement dynamics and informing future tunnel construction practices. This analysis underscores the critical role of material selection and construction sequencing in minimizing settlement and ensuring the long-term structural integrity of tunnels.

These findings are visually represented in **Figure 5-3** below, providing a comprehensive overview of the settlement trends observed across different constitutive models over time.

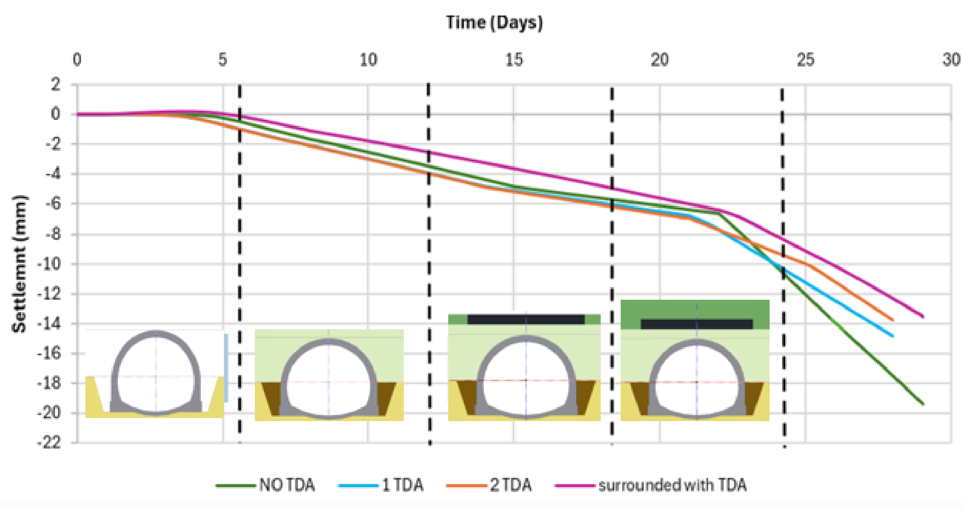



**Figure 5-3: Tunnel Crown displacements w.r.t Time @ section A-A, showing effect of alternative TDA distributions.**

**Table 5-2: Final displacement at crown with 3 different TDA**

| TDA Distribution at Crown @82m | Displacement (mm) |
|---|---|
| No TDA | -19.1 |
| 1 TDA Layer | -15 |
| 2 TDA Layer | -13.9 |
| Surrounded with TDA | -13.5 |

### *5.1.4 Comprehensive Analysis of Tunnel Lining Displacement with Varying Tire-Derived Aggregate (TDA) Configurations.*

The comprehensive tunnel lining displacement **Figure 5-4** incorporates all four models: No TDA layer, 1 TDA layer, 2 TDA layers, and surrounded with TDA layer. Employing a magnification of 150x, we enhance visualization, facilitating easy comparison of displacement levels across the different TDA configurations. Notably, the No TDA layer model exhibits the maximum displacement, while the surrounded with TDA layer model showcases the least displacement. Interestingly, the 2 TDA layers and surrounded with TDA models demonstrate nearly identical displacement, differing only by 1mm. This graph provides a holistic view of tunnel displacement, encompassing the beddings, spandrels, and crown, offering valuable insights into the structural behavior under varying TDA configurations.

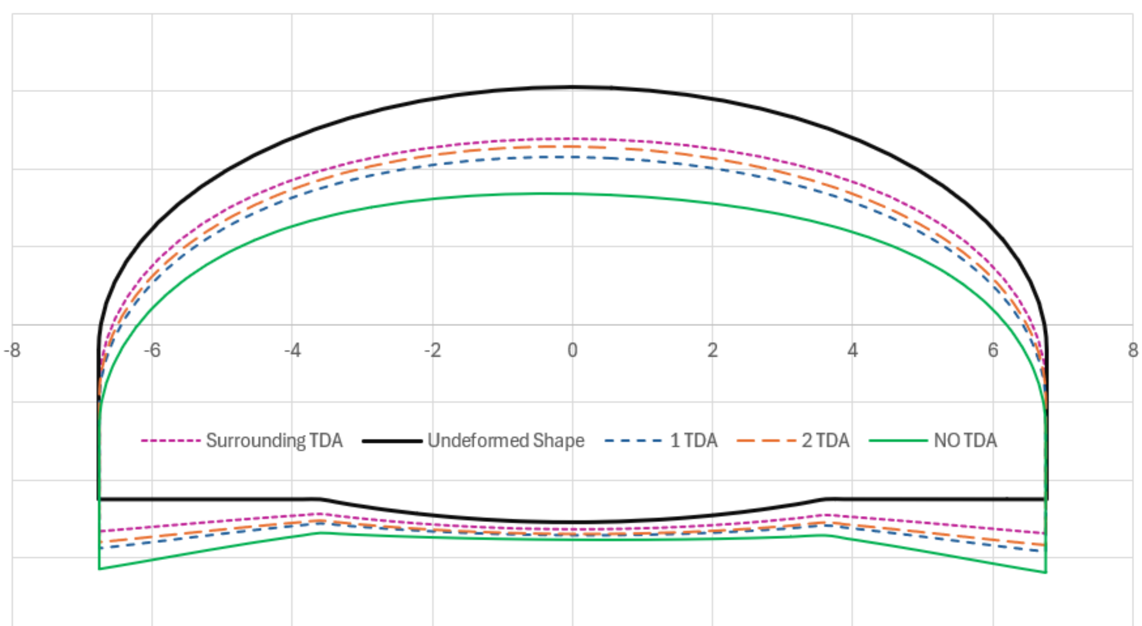



**Figure 5-4: Cross Sectional Displacement at Crown with a scale of magnified 150.**

# CHAPTER-6 CONCLUSIONS

This study investigated the potential of Tire-Derived Aggregate (TDA) as a stress-mitigating and deformation-reducing material in cut-and-cover tunnels. Utilizing three-dimensional finite element modeling, the research analyzed the effectiveness of various TDA configurations: one TDA layer, two TDA layers, and full TDA encasement.

The results revealed significant reductions in tunnel lining bending moments with strategically placed TDA layers. The inclusion of two TDA layers above the crown demonstrated the most promising outcome, achieving a notable reduction of up to 60% compared to scenarios without TDA. This finding highlights the transformative potential of TDA in mitigating stress on tunnel structures. While a single TDA layer also offered a substantial reduction in bending moments, full TDA encasement resulted in a higher bending moment, suggesting a need for further investigation into optimal deployment strategies.

Beyond stress reduction, the study examined the efficacy of TDA in minimizing displacements. The introduction of either one or two TDA layers significantly reduced displacements, with a second layer offering further mitigation. These findings demonstrate the potential of strategically placed TDA to enhance the overall structural stability and resilience of cut-and-cover tunnels.

In conclusion, this research establishes TDA as a viable approach for mitigating stress and deformations in cut-and-cover tunnels. The successful implementation of two strategically placed TDA layers above crown reduces the stress and deformations while promoting sustainable infrastructure solutions by incorporating recycled materials.

Future research can explore the potential benefits of TDA under dynamic loading conditions, given its inherent high damping properties. Additionally, investigating the efficacy of TDA in different tunnel geometries and foundation conditions is crucial for broader applicability. Furthermore, optimizing TDA layer configurations by exploring alternative placement strategies and material properties holds promise for maximizing its effectiveness.

This research paves the way for the wider adoption of TDA in cut-and-cover tunnel construction. The demonstrated effectiveness of strategically placed TDA layers in mitigating stress and deformations, coupled with its sustainability benefits, positions TDA as a valuable tool for geotechnical engineers. Further research efforts exploring dynamic loading, geometric variations, and TDA layer optimization can solidify the role of TDA in building more robust and sustainable underground infrastructure.

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