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Numerical Analysis of Upcycled Iron Ore Tailings in Ballast Columns for Hydrocarbon Storage Tanks

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Abstract

The upcycling of iron ore tailings (IOT) as an alternative material for ballast columns presents a sustainable and cost-effective solution for ground improvement. This study investigates the performance of limestone-based and shale-based IOT ballast columns in controlling vertical displacement and reducing the settlement of hydrocarbon storage tanks. A numerical analysis was conducted to compare their effectiveness against conventional ballast columns under a 67 m diameter tank, subjected to an operational pressure of 184 kPa. The results indicate that limestone-based IOT columns reduced maximum settlement to 128.94×10^{-3} m, representing a 55.6% decrease compared with conventional ballast columns (290.51×10^{-3} m), and a 59.7% reduction relative to shale-based IOT columns (319.47×10^{-3} m). This improvement highlights the enhanced mechanical behaviour of limestone-based IOT, making it a promising alternative for geotechnical applications. The findings confirm that IoT-based ballast columns, particularly those using limestone, can serve as an environmentally friendly alternative to conventional materials while contributing to sustainable waste management. By upcycling mining waste, this approach not only improves ground stability but also minimises the environmental impact of tailings disposal. These results encourage further research into the optimisation of IOT mixtures and their application in large-scale construction projects. The use of IOT in geotechnical engineering aligns with global efforts to promote sustainability in infrastructure development.

Keywords

Upcycled mine tailings; Sustainable geotechnics; Ballast columns; Hydrocarbon storage tanks; Settlement; Numerical modelling.

1. Introduction

Hydrocarbon storage tanks are critical infrastructures in the energy sector, used for storing large quantities of petroleum products, natural gas, and other hydrocarbons. Given their massive size, with diameters exceeding 100 m, and the significant loads they impose on the ground, ensuring a stable foundation is essential for structural integrity, operational safety, and environmental protection. Inadequate foundation design can lead to differential settlement, structural failure, or even catastrophic leakage, posing severe economic and environmental risks (Nelson & Miller, 1997; Zumrawi, 2014). Stability is particularly crucial in areas with weak or variable soil conditions (Manzoor & Yousuf, 2020), where proper ground improvement techniques, such as ballast columns, are required to enhance load-bearing capacity and reduce settlement. Additionally, hydrocarbon storage facilities are often located in coastal or industrial zones where soil conditions may be suboptimal, necessitating innovative solutions like the use of mine tailings as a sustainable alternative construction material. Ensuring foundation stability not only extends the service life of storage tanks but also mitigates risks related to soil liquefaction, excessive deformations, and long-term maintenance costs (Sharari et al., 2022; Lupunga et al., 2024).

Ballast columns are a ground improvement technique widely used in geotechnical engineering to enhance the stability and load-bearing capacity of weak or compressible soils (Boutahir Born Bencheikh et al., 2020). The principle behind ballast columns involves the installation of compacted granular materials, such as gravel, crushed stone, or recycled aggregates, into the soil to create reinforced load-bearing elements (Al Saoudi et al., 2015). These columns function by distributing vertical loads more effectively, increasing soil strength, and improving drainage characteristics, thereby reducing excessive settlement and enhancing overall stability (Bziaz et al., 2023; Basack et al., 2022). In terms of applications, ballast columns are commonly used for foundation support in infrastructure projects, including hydrocarbon storage tanks, embankments, industrial facilities, and roadways. They are particularly beneficial in areas with soft clay, loose sand, or high groundwater levels, where traditional foundation solutions may be inadequate. By reducing differential settlement and enhancing soil stiffness, ballast columns help prevent structural deformation and long-term performance issues.

Traditional foundation materials used in ballast columns, such as crushed stone and gravel, face several challenges in terms of availability, cost, and environmental impact (Serridge, 2005). High-quality aggregates are often sourced from quarries, leading to significant extraction costs, depletion of natural resources, and environmental degradation (Přikryl, 2021). Additionally, transportation expenses can be substantial, especially in remote areas where suitable materials are not readily available. Geotechnically, conventional materials may not always provide optimal performance, particularly in weak or highly compressible soils, requiring additional stabilisation techniques (Tobal et al., 2026).

In contrast, the use of mine tailings as construction materials for ballast columns presents multiple advantages. Economically, mine tailings are often available as a by-product of mining operations, reducing material costs and lowering reliance on expensive quarried aggregates (Araujo et al., 2022). Environmentally, using mine tailings has gained increasing attention as a sustainable construction material due to its economic and environmental advantages (Benghazi et al., 2024). Geotechnically, certain types of mine tailings, depending on their composition and engineering properties, can offer comparable or even superior load-bearing capacity and drainage characteristics, making them a viable alternative to traditional materials (Chlahbi et al., 2023). By integrating mine tailings into foundation systems, infrastructure projects can achieve cost-effective, sustainable, and high-performance solutions for hydrocarbon storage tank stability.

This work assesses the feasibility and performance of iron ore tailing (IOT) in ballast columns, which requires a comprehensive evaluation of its geotechnical properties under hydrocarbon storage tanks. The primary objective is to determine whether IOT can effectively replace conventional materials without compromising structural integrity. Numerical modelling using the finite element method was utilised to simulate settlement behaviour, stress distribution, and overall performance of IOT ballast columns compared with conventional ones. This study aims to develop a cost-effective and sustainable foundation solution while ensuring the structural stability of hydrocarbon storage tanks.

2. Materials and Methods

2.1. Material Characterisation

The Rouina iron ore mine was chosen as a case study for applying solid waste characterisation to the construction of ballast columns. The Rouina iron deposit was discovered in the late 19th century, with the first concession granted in 1872.

The mine is situated in the wilaya of Ain Defla, 120 km west of Algiers, 17 km west of the provincial capital, and 4.5 km south of the town of Rouina (Figure 1). The mining process generates an average of 320,000 tons of IOT each year (Figures 2 and 3).

Figure 1. Satellite view of Rouina iron ore mine (Google Earth, 2025). Source: Google Earth (2025), Image © CNES / Airbus, Maxar Technologies, and other providers. Used under Google Earth Terms of Service.

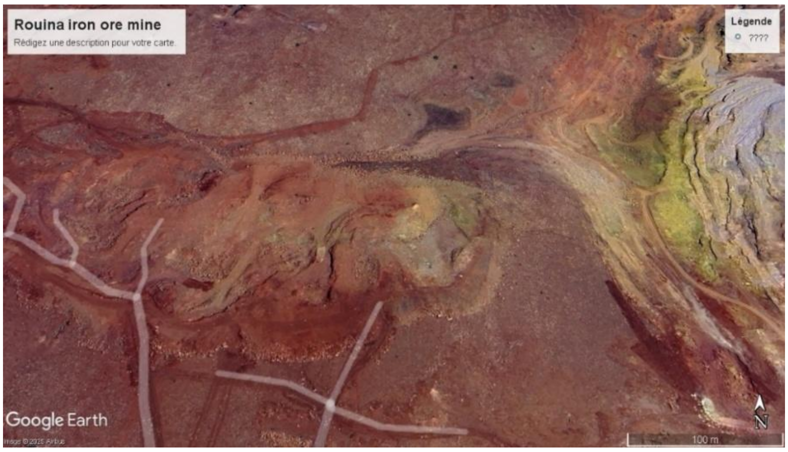


Figure 2. Satellite view of Rouina IOT deposit (Google Earth, 2025). *Source*: Google Earth (2025), Image © CNES / Airbus, Maxar Technologies, and other providers. Used under Google Earth Terms of Service.

Figure 3. Rouina IOT deposit. *Source*: Authors' field documentation (2025).

The IOT was sampled from the Rouina mine deposits and analysed in the Kolea LNHC laboratory (Algeria). It has been found to have two major types: limestone and shale. The geotechnical properties are presented in Table 1. The California Bearing Ratio (CBR) is an index widely used to express the supporting strength of granular materials; higher CBR values indicate better resistance to penetration and improved load-bearing performance. Young's modulus (E), measured in megapascals (MPa), represents the stiffness of a material and reflects how much it deforms under load. The higher the modulus, the stiffer the material. These parameters help illustrate how the limestone and shale IOT differ in their mechanical behaviour and suitability for use in ballast columns.

Table 1. Geotechnical characteristics of IOT (Source: Authors).

	Unite weight (kN/m3)	Frictional angle (°)	Cohesion (kN/m2)	California Bearing Ratio	Young's modulus (MPa)	Poisson's ratio
Limestone	25	35	24	57.5	92.07	0.32
Shale	21	25	20	10	49.34	0.43

2.2. Overview of Bejaia Port

The Port of Bejaia, one of Algeria's 13 major commercial ports, is a deep-water oil port and a key hub in the western Mediterranean. Located 180 km east of Algiers, it is managed by "Enterprise Portuaire de Bejaia". The port connects to Hassi Messaoud oil fields via pipelines and supports industrial sectors like cork and textiles.

With a 13.7-meter channel depth, it accommodates large vessels, including Panamax and Super-Panamax ships. Its primary exports include hydrocarbons and petroleum products. The port features a 400,000 m² container ground, 180,000 m² storage yards, and specialised facilities for handling dangerous goods, making it a strategic trade and logistics hub.

Figure 4. Satellite view of hydrocarbon storage tanks – Bejaia port (Google Earth, 2025). (Source: Google Earth (2025), Image © CNES / Airbus, Maxar Technologies, and other providers. Used under Google Earth Terms of Service.)

2.3. Geotechnical context

The southern area of the city of Bejaia, where the port is located, presents significant geotechnical challenges, particularly regarding liquefaction and low bearing capacity. Given its alluvial nature, this zone demands specialised foundation solutions, making the use of ballast columns a well-justified and effective approach. The site contains sixteen cylindrical metal tanks, each with a height of 16 meters (Figure 4). Twelve of these are located at the northern terminal, with a storage capacity of 35,000 m³ and a diameter of 56 meters, while the remaining four are at the southern terminal, with a storage capacity of 50,000 m³ and a diameter of 67 meters (R13, R14, R20, and R21 tanks) (Zidelmal, 2011).

For this study, Tank R21 was selected as an application example, with the relevant geotechnical data presented in Table 2.

Table 2. Geotechnical characteristics of different materials (Zidelmal, 2011).

Soils	**Depth (*m*)**	**Unite weight (*kN/m³*)**	**Frictional angle (°)**	**Cohesion (*kN/m²*)**	**Young's modulus (*MPa*)**	**Poisson's ratio**
Clay	0 - 3	19.3	13	40	4	0.4
Sand	3 - 27	16.6	34	11	5	0.3
Marl	27 - 40	20.9	20	80	400	0.33
Ballast	-	20	40	0	100	0.33

2.4. Methodology and Study Framework

This study aims to evaluate the geomechanical performance of stone columns constructed using IOT originating from the limestone and shale lithologies of the Rouina iron ore mine (Algeria). The methodology integrates material characterization, numerical modelling, and comparative analysis to quantify the settlement response, stiffness contribution, and potential applicability of the proposed materials in ground-improvement works for large storage tanks.

First, the mechanical properties of both IOT mixtures are characterized to establish their suitability for use in ground-improvement applications. A finite-element model in PLAXIS 2D is then developed to simulate the behaviour of a single column subjected to operational tank loading. Using this model, the settlement response of the two mixtures is compared under identical boundary and loading conditions to assess their relative performance.

2.5. Numerical modelling setup

Three numerical models based on the finite element method were developed. The first model evaluates the impact of ordinary ballast columns, the second investigates limestone-based IOT ballast columns, and the third examines shale-based IOT ballast columns, all in relation to settlement behaviour. Given the circular shape of the tank's foundation with a diameter of 67 meters, the modelling is conducted using a 2D axisymmetric approach, with a pressure of 184 kPa applied to represent the ultimate limit state. The different characteristics of the foundation are presented in Table 3. The modelled columns have a diameter of 1 m, a length of 20 m, and a centre distance of 4 m.

Table 3. Characteristics of the foundation (Zidelmal, 2011).

Soils	**Thickness (*m*)**	**Unite weight (*kN/m³*)**	**Interface rigidity factor**	**Young's modulus (*MPa*)**	**Poisson's ratio**
Foundation	0.25	24	0.5	30 × 103	0.2

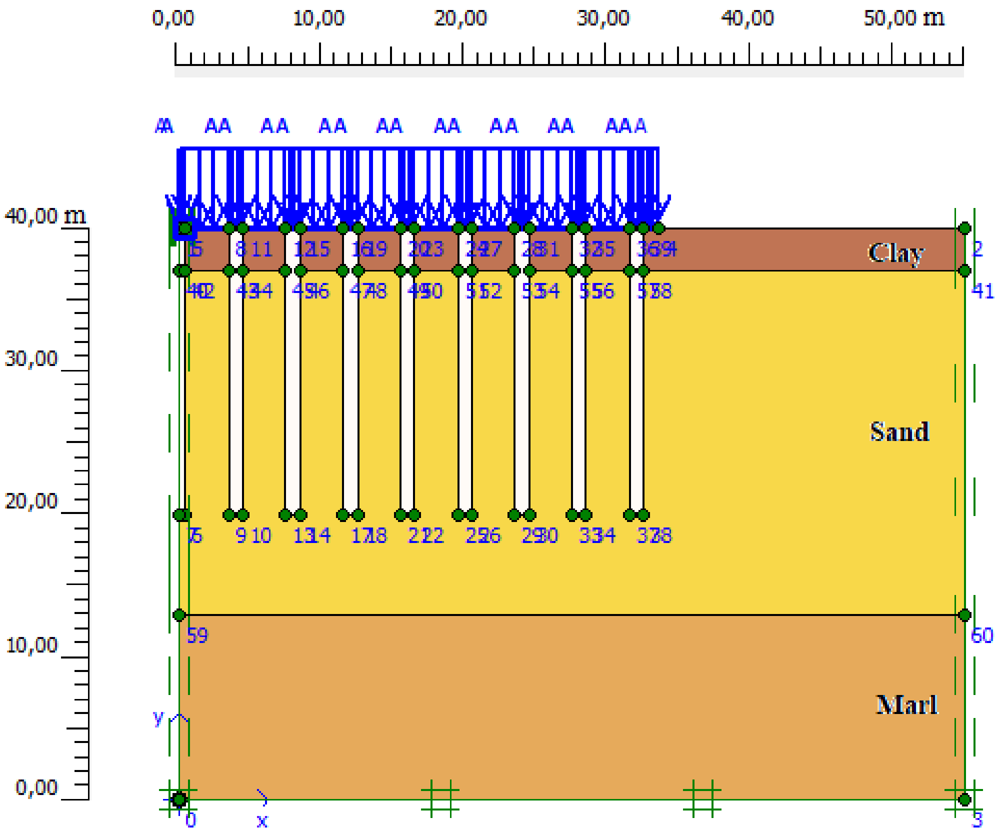


Figure 5. Geometry and boundary conditions of the numerical model (Source: Authors).

The numerical modelling was conducted using the finite element software PLAXIS 2D. PLAXIS is specifically designed for geotechnical engineering analysis. The improved soil was discretised using 15-node triangular finite elements to enhance the accuracy of stress-strain calculations. Figure 5 illustrates the geometry and boundary conditions of the numerical model. A refined mesh was applied around the column and tank centre to capture stress gradients. The average element size near the column was 0.05–0.1 m.

All soil layers and column materials were modelled primarily using the Mohr–Coulomb constitutive law due to its simplicity and suitability for preliminary performance assessments. However, the clay layer underlying the tank was assigned the Soft Soil model, which provides a more accurate representation of its compressibility and nonlinear consolidation behaviour. This combination ensures a realistic simulation of both the stiffer granular materials and the highly compressible clay strata.

3. Results

3.1. Analysis of Stress Distribution Patterns

Figure 6 shows the total stress fields for the three ballast column configurations. In the case of ordinary ballast columns (Figure 6a), the stress distribution develops symmetrically beneath the tank centre with a maximum mean stress of –729.79 kN/m², indicating a moderate concentration of stresses within the improved zone. With limestone-based IOT columns (Figure 6b), the maximum stress increases to –764.20 kN/m² and becomes more vertically channelled along the column axis. This reflects the higher stiffness of limestone IOT, which attracts a larger share of the applied load and limits lateral stress diffusion into the surrounding soil. Conversely, shale-based IOT columns (Figure 6c) display a maximum mean stress of –726.57 kN/m² and a wider lateral dispersion of stresses, consistent with the lower modulus of shale IOT. These results indicate that limestone IOT provides the most efficient stress confinement, ordinary ballast shows intermediate performance, and shale IOT results in the weakest load transfer efficiency. These differences directly influence the settlement response discussed in subsequent sections.

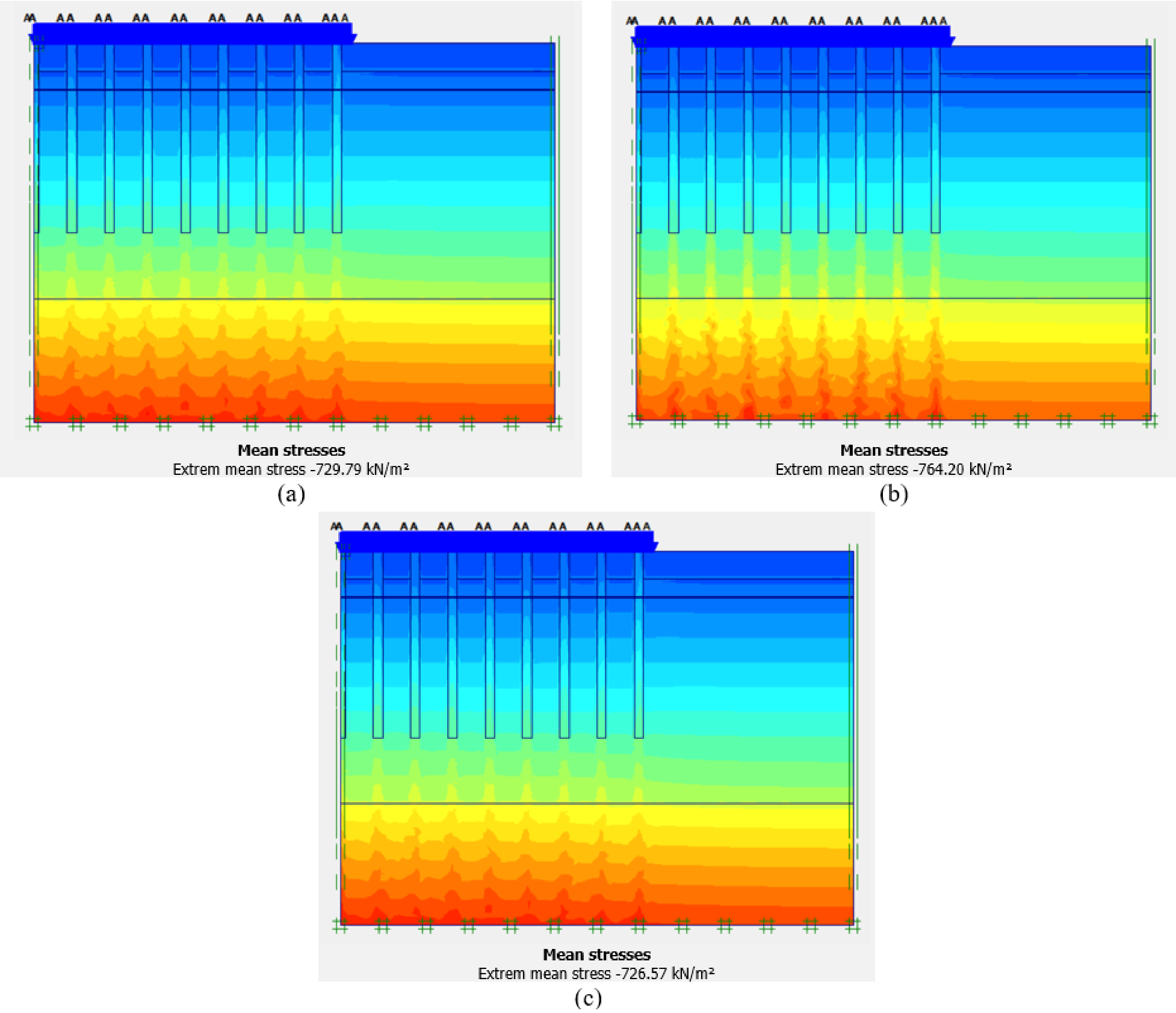
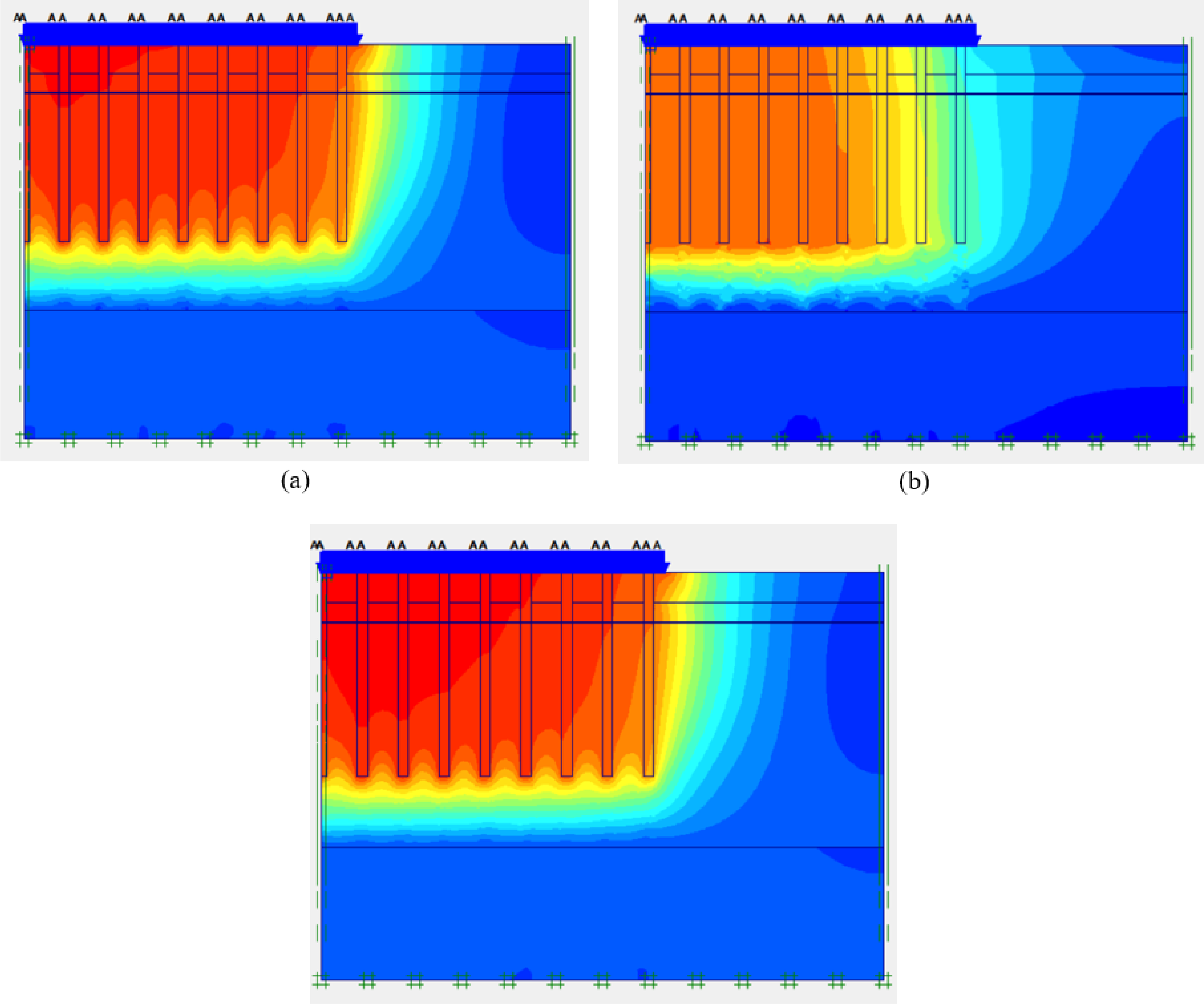


Figure 6. Total stress field: (a) for ordinary ballast columns; (b) for limestone IOT ballast columns; (c) for shale limestone IOT ballast columns (Source: Authors).

3.2. Settlement behaviour of different ballast column configurations

Figure 7 shows clear differences in the vertical displacement patterns produced by the three ballast column configurations. In the ordinary ballast case (Figure 7a), the displacement field forms a wide deformation bowl beneath the tank, indicating substantial downward movement extending into the surrounding soil. With limestone-based IOT columns (Figure 7b), the displacement contours become noticeably narrower and more confined around the column axis, reflecting improved stiffness and reduced deformation spread. The shale-based IOT columns (Figure 7c) display a broader and more diffuse displacement field, with deformation zones extending deeper and wider in the soil strata. This pattern suggests a less efficient load-carrying response compared with limestone IOT, which produces the most localised and controlled displacement field, whereas ordinary ballast and shale IOT result in wider deformation zones.



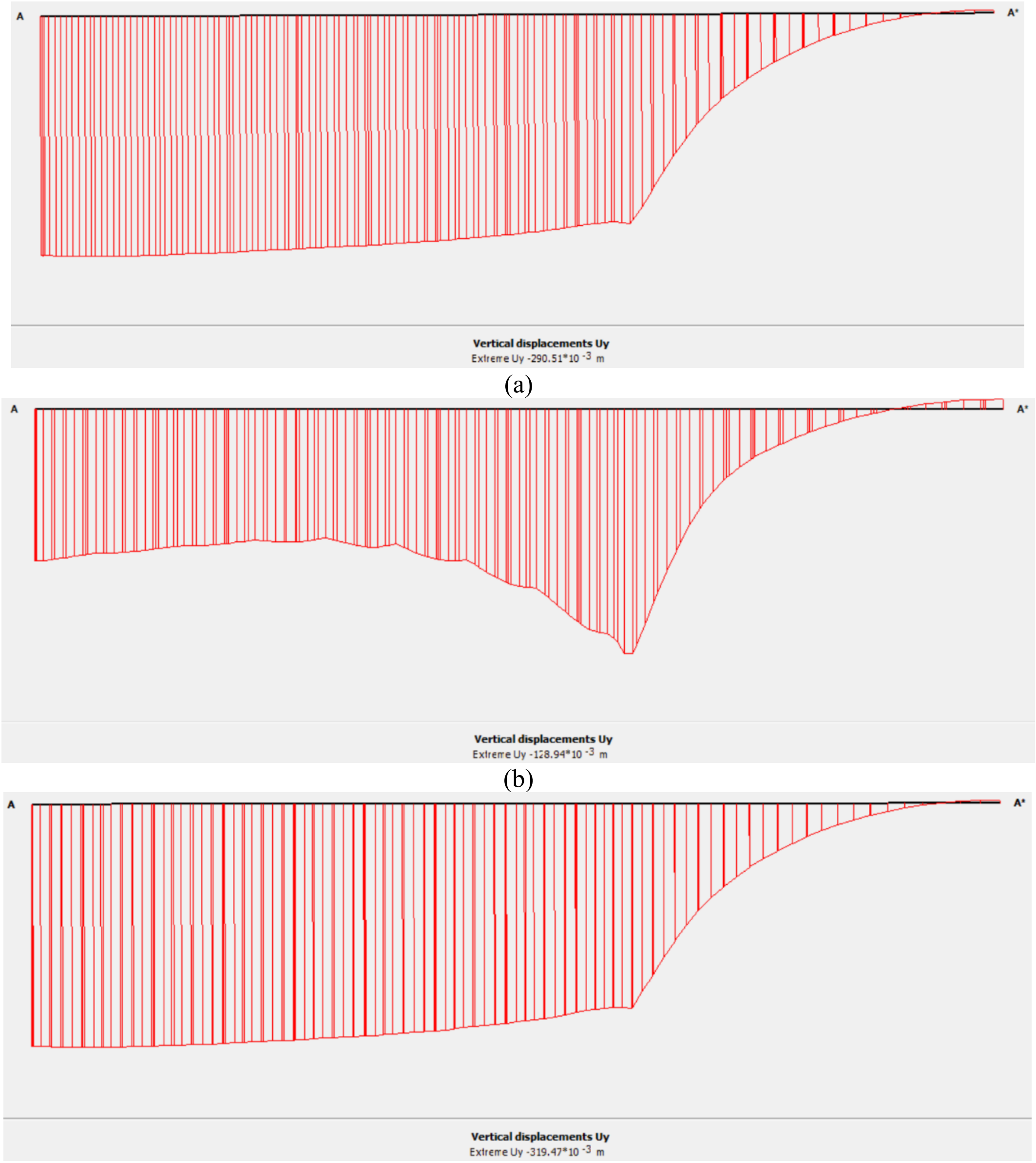
(a)

(b)

(c)

Figure 7. Vertical displacement field: (a) for ordinary ballast columns; (b) for limestone IOT ballast columns; (c) for shale limestone IOT ballast columns (Source: Authors).

Figure 8 illustrates the variations in settlement observed for each column type. The numerical results showed significant differences in settlement depending on the material used for the ballast column. Ordinary ballast columns exhibited a maximum settlement of 290.51 $\times 10^{-3}$ m (Figure 8a), while limestone-based IOT columns reduced settlement to 128.94 $\times 10^{-3}$ m (Figure 8b). In contrast, shale-based IOT columns produced a settlement of 319.47 $\times 10^{-3}$ m (Figure 8c). The settlement profiles beneath the tank base further confirm that limestone-based IOT columns are associated with substantially lower vertical displacements.



(a)

(b)

(c)

Figure 8. Vertical displacement values under the storage tank: (a) for ordinary ballast columns; (b) for limestone IOT ballast columns; (c) for shale limestone IOT ballast columns (Source: Authors).

4. Discussion

4.1. Comparative performance of IOT materials

The stress distribution generated beneath the two IOT column materials demonstrates distinct patterns reflecting their stiffness contrast. For the limestone columns (Figure 6b), the stress countours extend more deeply and remain narrow, indicating that a larger portion of the applied load is transferred vertically to the underlying competent layers (particularly the marl). This reflects efficient load spreading and vertical stress concentration, typical of systems with high-stiffness inclusions (Dheerendra Babu et al., 2013).

On the other hand, the shale columns (Figure 6c) exhibit a shallower and wider stress distribution, with greater stress dispersion into the surrounding sand layer. Because of the lower stiffness, the shale column is less effective at channelling stresses downward, causing more load to be distributed horizontally into the softer surrounding soils. This contributes directly to the larger settlements recorded in the shale-column model (Castro, 2017).

The limestone IOT columns consistently produced smaller settlements compared to the shale IOT columns. This behaviour is primarily attributed to the significantly higher stiffness of the limestone ballast ($E = 92.07$ MPa) relative to the shale ballast (E = 49.34 MPa). Because settlement in axisymmetric, ground-improvement systems is governed by the composite stiffness of the column–soil matrix, a stiffer column mobilizes a larger proportion of the applied load (Das & Deb, 2019). As a result, the limestone column undergoes smaller deformations and reduces overall ground compression. In contrast, the lower stiffness of the shale mixture leads to greater column deformation and a reduced ability to redistribute stresses to deeper, stiffer strata.

Additionally, the higher friction angle of the limestone ballast (35° versus 25° for shale) enhances lateral shear resistance, contributing to improved confinement and reduced axial strain. These mechanical advantages explain the distinctly lower settlement observed in the limestone-supported model. Similar findings were reported by Basack et al. (2022), who highlighted the decisive influence of column stiffness on settlement control in reinforced soft ground.

The stress distribution patterns highlight the dominant influence of material stiffness on the load-transfer behaviour of ballast columns. Limestone-based IOT columns attract higher stresses and maintain a concentrated vertical stress path, reflecting their superior modulus and confinement capacity. This efficient stress channeling reduces load transmitted to surrounding soft soils, contributing to improved overall foundation performance. Ordinary ballast columns display an intermediate response, with moderate stress concentration and noticeable lateral diffusion consistent with their average stiffness. In contrast, shale-based IOT columns show the widest stress dispersion and the weakest confinement, confirming their lower mechanical resistance. Their limited stiffness restricts vertical load transfer and increases lateral stress leakage into adjacent soils.

4.2. Geotechnical implications for hydrocarbon tank foundations

Settlement reduction is critical for cylindrical hydrocarbon tanks, where even small differential movements can induce wall buckling or leakage. The improved ground response obtained with the limestone IOT columns demonstrates compliance with recognized serviceability criteria. In particular, the maximum settlement remained below the 150×10^{-3} m limit recommended in previous case studies (Zidelmal, 2011), indicating that the limestone-based configuration provides adequate stiffness and load-transfer capacity for safe tank operation.

The shale IOT columns, however, exceeded this threshold by a significant margin. This performance gap highlights the sensitivity of large-diameter tank foundations to column stiffness, especially when underlain by compressible clay layers. The higher deformability of the shale mixture results in reduced shear confining resistance and less efficient stress transfer to deeper competent strata (Singh & Chamling, 2014). From a design perspective, this means that not all IOT materials are inherently suitable as ballast column replacements unless their mechanical properties are enhanced, either through mechanical stabilization, blending with stiffer aggregates, or cementitious improvement. Therefore, while the limestone mixture appears immediately applicable, shale tailings may require additional processing to meet settlement requirements for oil and gas storage infrastructure, especially in stratigraphic profiles similar to the storage tanks of Bejaia port.

4.3. Practical Implementation and Cost–Benefit Considerations

The IOT is locally available near mining operations, which reduces transportation costs and dependence on quarried aggregates. In industrial regions where limestone IOT is stockpiled, the cost of raw material acquisition may be reduced by 30–60% compared to natural crushed stone, depending on haul distance and processing requirements. This constitutes a significant economic incentive, given the large volumes of column material typically required for tank foundations.

Constructability considerations also influence real-world adoption. Limestone IOT exhibits compaction behaviour and angular particle geometry similar to granular fills, allowing it to be installed using standard vibro-replacement techniques without major modification of equipment or procedures.

In general, while limestone IOT shows strong numerical performance, its real-world use requires project-specific evaluation of availability, transport logistics, compaction characteristics, and quality control. Further field-scale trials would help quantify construction productivity, long-term durability, and life-cycle cost advantages, enabling more confident adoption in engineering practice.

4.4. Sustainability and Circular Economy Perspective

Beyond geotechnical considerations, the integration of IOT into ballast columns contributes to resource efficiency and waste valorisation. This reduces the environmental footprint associated with their disposal, which often involves large storage facilities, long-term environmental monitoring, and potential risks of contamination or tailing dams' instability. Using limestone IOT reduces the reliance on quarried aggregates, thereby lowering environmental impacts from raw material extraction and transport (Alam & Bawa, 2025). This supports recent sustainability frameworks (Benghazi et al., 2024), which encourage the integration of secondary raw materials into civil engineering applications to promote low-carbon, low-waste construction practices. In regions with extensive mining activity, mine tailing-based ground improvement solutions provide a promising pathway toward more circular infrastructure systems, transforming a waste stream into a high-value engineering resource. Moreover, the widespread adoption of such materials could contribute to national strategies for sustainable industrial development, reduce disposal burdens on mining operators, and provide cost-effective solutions for large tank foundations across the oil and gas sector.

4.5. Limitations and Future Research

The results indicate the potential of limestone IOT based on numerical modelling under static conditions. Field-scale validation is required to evaluate performance under cyclic loads, seismic activity, and chemical exposure to hydrocarbons. Investigation of, and should be prioritized in future research. Nonetheless, the research provides the first systematic comparison of limestone- and shale-based IOT ballast columns under large hydrocarbon storage tanks, quantifying settlement reduction and performance improvements. Future work should involve laboratory and field validation, cyclic/dynamic load testing, and parametric sensitivity analyses to generalize the findings across different soil and operational conditions. Blended limestone and shale IOT mixtures may optimize both material availability and geotechnical performance, and should also be prioritized in future research. Despite these limitations, the current results offer valuable preliminary insights into sustainable ground improvement using upcycled IOT, guiding both engineering design and further research

5. Conclusions

This study evaluated, through numerical modelling, the feasibility of using iron ore tailings (IOT) as an alternative material for ballast columns supporting hydrocarbon storage tanks. The findings confirm that limestone-based IOT columns significantly reduce settlement compared with both ordinary and shale-based materials.

While these results are scientifically consistent within the model framework, they remain limited in real-world applicability until validated by experimental and field investigations. Nonetheless, the study provides a valuable preliminary basis for developing sustainable and low-cost ground improvement solutions using mining by-products.

This study used finite element modelling to assess the performance of limestone- and shale-based iron ore tailings (IOT) as sustainable substitutes for conventional ballast materials beneath hydrocarbon storage tanks. The results show that limestone-based IOT significantly reduces settlement compared with ordinary ballast and shale-based tailings.

However, as a numerical and static investigation, the findings provide only an initial indication of the potential behaviour of these materials. Their real-world applicability remains limited until validated through laboratory testing and full-scale field studies. In particular, hydrocarbon tanks experience cyclic and dynamic loads that may alter settlement and stress transfer mechanisms over time.

The present study establishes a solid foundation for future experimental and field investigations and highlights the promising role of IOT in sustainable geotechnical engineering.

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Conflict of interest:

The authors declare that there is no competing interest.

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