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# Analysis of Replacing High-Volume Fill Material on A Ramp With Expanded Polystyrene (Eps) Geofoam on Soft Soil

**Dewanggana Aksatriyakula P.[1*], Diar Hibatullah Tsabit[2], Rifqi Brillyant Arieft[3], Abdul Rochim[4]**
[1-4] Universitas Islam Sultan Agung, Semarang, Indonesia
*email: diarhibatullaht@gmail.com[2]*

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***Abstract***

*Bridge approach embankments constructed on soft soil are susceptible to excessive settlement and instability due to the low strength and bearing capacity of the foundation soil. This study aims to evaluate the performance of Expanded Polystyrene (EPS) Geofoam as an alternative to conventional soil-fill embankments in terms of settlement, differential settlement, stability, and consolidation time. Analytical calculations and numerical modeling using PLAXIS 2D were conducted based on soil parameters obtained from the Terboyo Kulon site, Genuk District. The results show that the EPS embankment produced a vertical settlement of 0.31 m, compared with 0.71 m for the conventional soil-fill embankment. Differential settlement was reduced from 0.37 m for the soil-fill embankment to 0.18 m for the EPS embankment, representing a reduction of approximately 51%. The EPS configuration also produced a safety factor of 3.77, considerably higher than the 1.52 obtained for the conventional soil-fill embankment. Furthermore, the EPS embankment reached 90% consolidation within approximately 9.5 years, whereas the conventional soil-fill embankment required 68.49 years. The use of EPS Geofoam therefore provides a lightweight embankment solution that can improve the overall performance of bridge approaches constructed on soft soil. These findings indicate that EPS Geofoam can effectively reduce settlement and differential deformation while improving embankment stability and accelerating the consolidation process on soft foundation soil.*

***Keywords:*** *Bridge Approach Embankment, Consolidation, EPS Geofoam, PLAXIS 2D, Settlement.*



## INTRODUCTION

Bridge approaches are embankment or fill structures constructed behind abutments, and their performance has become an increasingly important geotechnical concern as infrastructure development increasingly extends toward areas characterized by weak and highly compressible ground conditions. The construction of embankments over soft soil is particularly challenging because low shear strength and high compressibility can simultaneously affect bearing capacity, deformation, and long-term serviceability (Ameratunga et al., 2021). Settlement at bridge approaches remains a common problem because differences in stiffness between the bridge structure and the adjoining embankment can generate differential deformation that is subsequently transferred to the pavement system (Christopher et al., 2006). Classical soil mechanics establishes that foundation safety is governed by the relationship between applied loading, soil strength, bearing capacity, and deformation characteristics (Terzaghi, 1943). Inadequate compaction during construction can further intensify settlement when compacted layer thickness and material moisture conditions are not maintained within appropriate specifications. Modern bridge approaches are therefore no longer limited to conventional soil fills, but may incorporate lightweight geomaterials and composite foundation systems to modify load transfer and reduce the adverse effects of soft subsoil conditions (Aabøe et al., 2019).

Embankment stability represents a fundamental consideration in geotechnical planning because the bearing capacity of the foundation soil, shear strength, embankment height, and slope geometry collectively determine the magnitude and distribution of stresses transmitted to the underlying ground. The bearing capacity of the foundation soil provides the primary resistance against embankment loading, whereas embankment height and slope inclination directly influence the magnitude of applied stresses and the potential for instability (Hardiyatmo, 2002). Conventional foundation design distinguishes shallow and deep foundations according to their principal mechanisms of load transfer, with shallow foundations relying predominantly on near-surface resistance and deep foundations transferring substantial loads through shaft resistance and end bearing at greater depths (Coduto, 2001). Numerical research has demonstrated that variations in loading magnitude and soil characteristics can substantially modify shallow-foundation response, indicating that bearing capacity cannot be evaluated independently from the mechanical characteristics of the supporting soil (Hakro et al., 2022). Settlement analysis has consequently become an essential component of foundation assessment because a foundation may satisfy ultimate bearing-capacity requirements while still experiencing excessive deformation under service loading (Duncan & Buchignani, 1976). The magnitude of embankment loading can be controlled during design through geometric modification and the selection of appropriate fill materials. One increasingly relevant strategy is to reduce the self-weight of the embankment by replacing conventional fill with lightweight materials such as Expanded Polystyrene (EPS) Geofoam, thereby decreasing stress transferred to soft foundation soils.

Recent developments in lightweight embankment engineering indicate that EPS Geofoam has considerable potential for controlling deformation and reducing instability in infrastructure constructed over soft ground. EPS Geofoam blocks have been developed as lightweight civil engineering materials capable of substantially reducing dead loads compared with conventional soil and granular fills (Aabøe et al., 2019). Research on lightweight EPS Geofoam embankment systems has demonstrated that reducing embankment self-weight can improve settlement performance by limiting the additional stress imposed on compressible foundation soils (Puppala et al., 2019). The material has also been examined from a sustainability perspective, with studies indicating that EPS Geofoam can provide functional advantages in road construction while contributing to alternative approaches for managing problematic ground conditions (Srivastava et al., 2019). Its engineering performance is nevertheless influenced by its dimensions, thickness, and position within the embankment because these parameters determine the distribution of stresses transferred to the underlying soil. Indonesian infrastructure practice has increasingly incorporated technical requirements for EPS Geofoam, reflecting the growing recognition of lightweight fill as an alternative for transportation infrastructure constructed over difficult ground conditions (Direktorat Jenderal Bina Marga, 2023). The material properties used in design must also comply with standardized requirements governing rigid cellular polystyrene geofoam to ensure that the selected material provides predictable mechanical performance under field conditions (ASTM International, 2017).

Despite these developments, the existing literature remains fragmented because studies of soft-ground embankments frequently emphasize settlement reduction, slope stability, or material performance without simultaneously establishing the comparative bearing-capacity and settlement behavior of shallow and deep foundation systems. Recent investigations have shown that embankment stability and deformation on soft clay are strongly controlled by soil properties, loading conditions, and embankment geometry, confirming that deformation cannot be separated from the overall stability mechanism (Alashlam et al., 2024). Earlier foundation studies have provided established analytical procedures for estimating capacity and settlement, yet conventional approaches may not fully capture the response of foundation systems subjected to modified loading conditions created by lightweight embankments. Deep foundation systems introduce a different load-transfer mechanism from shallow foundations, meaning that the reduction of embankment weight may produce different effects on foundation demand and soil deformation depending on foundation depth. Existing engineering guidance provides comprehensive procedures for settlement evaluation, but these procedures still require appropriate interpretation when applied to highly compressible soils subjected to unconventional loading configurations (U.S. Army Corps of Engineers, 1994). Research concerning soft-ground construction further indicates that settlement develops through interacting mechanisms involving immediate deformation, consolidation, and secondary compression, making the selection of an appropriate foundation system particularly important for long-term performance (Rou Ni et al., 2025). This gap is particularly relevant for bridge approaches because acceptable structural capacity alone does not guarantee satisfactory serviceability when differential settlement continues to develop beneath the adjoining embankment.

The unresolved relationship between foundation type, soft-soil response, and lightweight embankment loading has substantial scientific and practical implications for bridge approaches and other transportation structures. Excessive settlement can generate differential elevation between the bridge deck and adjoining roadway, while insufficient bearing capacity can initiate shear failure, lateral deformation, or progressive instability that compromises pavement and structural performance. The problem becomes more critical when conventional fill is used because increasing embankment height increases the applied stress and may accelerate deformation within highly compressible foundation soils. The use of lightweight fill offers an alternative mechanism for reducing foundation stress without necessarily reducing the required embankment geometry, making EPS Geofoam particularly relevant for soft-ground construction (Gunawan, 2020). Soil stabilization and column-based improvement represent another established strategy for modifying the mechanical behavior of weak foundation soils and increasing their capacity to sustain structural loads (Direktorat Jenderal Bina Marga, 2024). A rigorous comparison between shallow and deep foundation systems can therefore clarify whether load reduction through lightweight embankment construction is sufficient to achieve acceptable performance or whether deeper load-transfer mechanisms remain necessary. Such evaluation is important for developing foundation designs that balance bearing capacity, settlement control, construction feasibility, and long-term serviceability rather than optimizing a single design criterion.

The present study is positioned within the continuing development of geotechnical engineering approaches for evaluating foundation performance on soft soil, with particular emphasis on the relationship between bearing capacity and settlement in shallow and deep foundation systems. The research treats bearing capacity and settlement as complementary performance criteria rather than independent design parameters, enabling alternative foundation configurations to be assessed from both ultimate and serviceability perspectives. The analytical framework connects established principles of soil mechanics and foundation design with the contemporary requirement for more efficient management of weak and compressible ground conditions. Particular attention is directed toward understanding how differences in foundation depth and load-transfer mechanisms influence the ability of the supporting soil to sustain imposed loads while limiting deformation to acceptable levels. The study aims to analyze and compare the bearing capacity and settlement characteristics of shallow and deep foundations on soft soil and to establish the implications of these responses for foundation selection and geotechnical design. The theoretical contribution lies in strengthening the integrated interpretation of capacity and deformation behavior under soft-ground conditions, while the methodological contribution lies in providing a comparative analytical basis for identifying foundation configurations that can achieve an appropriate balance between structural safety and settlement control.

## RESEARCH METHODS

This study employed a non-empirical quantitative research design based on numerical geotechnical modeling using the finite element method (FEM) implemented in PLAXIS 2D, with the analysis structured to compare the bearing capacity and settlement behavior of conventional soil-fill and Expanded Polystyrene (EPS) Geofoam embankments constructed over soft soil. The conceptual model represented a bridge approach embankment at the Kaligawe toll-road bridge area in Semarang, Indonesia, where the foundation system was evaluated under soft-clay conditions using secondary field and laboratory data obtained from soil investigations, including borehole and N-SPT data from the Terboyo Kulon area, Genuk District. The modeled embankment geometry followed the field-based design configuration, consisting of a 26 m roadway crest width, a 6 m embankment height, and a 1:1.5 side slope, while the traffic loading was represented by a uniformly distributed load of 15 kN/m². The conventional embankment model used the available soil parameters from the site investigation, whereas the alternative configuration replaced the conventional fill with EPS Geofoam having a density of 22 kg/m³, consistent with the application of lightweight geofoam as a means of reducing stresses imposed on soft foundation soils (Direktorat Jenderal Bina Marga, 2023). The foundation soil was represented using the Mohr–Coulomb constitutive model to capture its strength and deformation response, while EPS Geofoam was represented using a linear-elastic material formulation based on its lightweight structural behavior. The numerical framework incorporated staged construction to reproduce the sequential placement of the embankment and the development of stresses within the foundation soil. The model configuration was established to evaluate both ultimate stability and serviceability behavior because foundation performance on soft soil must consider bearing capacity together with deformation and consolidation effects (U.S. Army Corps of Engineers, 1994).

The technical analysis was conducted by running the numerical models through sequential construction and consolidation stages in PLAXIS 2D, allowing excess pore-water pressure dissipation and time-dependent deformation of the soft foundation soil to be represented throughout the simulated construction process. Two principal configurations were analyzed under equivalent geometric and loading conditions, namely the conventional soil-fill embankment and the EPS Geofoam embankment, so that differences in foundation response could be attributed primarily to the change in embankment material and associated self-weight. The simulation outputs were evaluated using vertical displacement as the primary deformation metric, differential settlement as an indicator of serviceability risk, the time required to reach 90% degree of consolidation (U90) as a measure of consolidation performance, and the slope safety factor as an indicator of global stability. Bearing-capacity behavior was interpreted from the stress distribution and failure response obtained from the numerical model, with particular attention to whether the applied loading could be sustained without reaching an unacceptable failure condition. The predicted settlement response was examined throughout the construction and consolidation stages to identify differences in the magnitude and development rate of deformation between the two embankment configurations. Model interpretation was supported by established principles of settlement analysis and foundation behavior to ensure that the numerical outputs remained consistent with accepted geotechnical mechanisms (Hardiyatmo, 2010). The final evaluation compared all performance indicators between the two configurations to identify whether EPS Geofoam could provide a more stable and deformation-controlled embankment solution than conventional soil fill on soft soil.

## RESULTS AND DISCUSSION

### Geometry of the Bridge Approach and Material Parameters

The geometry of the bridge approach embankment was established using a geometric approach based on measurements obtained through Google Maps. The measurement process utilized the distance and surface-contour features to estimate the length, width, and elevation of the bridge approach under investigation. The resulting dimensions were 200 m in length, 26 m in width, and 6 m in height. These dimensions were used as the basic geometric configuration for modeling the embankment in PLAXIS 2D. The selected dimensions represent the approach configuration used in the analysis and provide a consistent geometric basis for comparing conventional soil fill with EPS Geofoam. The geometric approximation of the bridge approach is presented in Figures 1 and 2.

**Figure 1. Height of the Tanjungmas–Srondol Toll Road Approach from Google Maps**
Source: https://www.google.com/maps

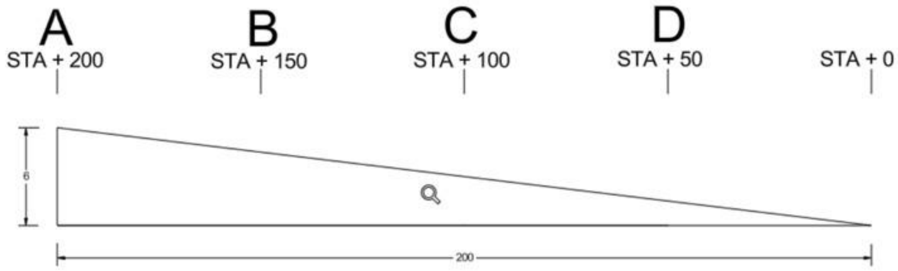


**Figure 2. Approximation of Bridge Approach Dimensions**
Source: Author's Documentation, 2026

The embankment geometry was subsequently modeled using a slope ratio of 1:1.5 in the vertical-to-horizontal direction. This configuration was applied to represent the slope geometry of the approach embankment and was maintained for the numerical analysis. Three cross sections were developed for the conventional soil-fill configuration, namely Cross Sections A, B, and C. The same cross-sectional approach was also applied to the EPS configuration to maintain comparable geometric conditions between the two alternatives. The cross-sectional models provide the geometric basis for determining the stress distribution and deformation response at different portions of the embankment. Figures 3-8 present the cross-sectional configurations used for the soil-fill and EPS embankments.

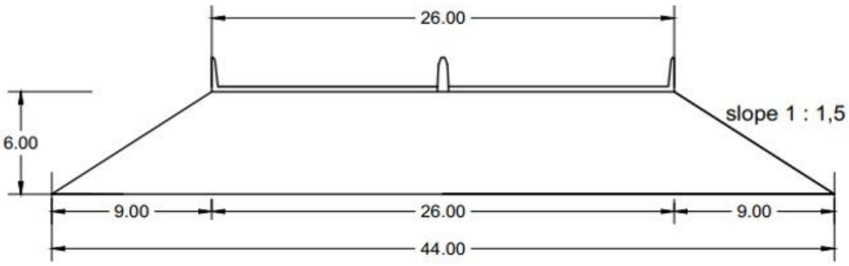


**Figure 3. Cross Section A of Soil-Fill Embankment**
Source: Author's Documentation, 2026

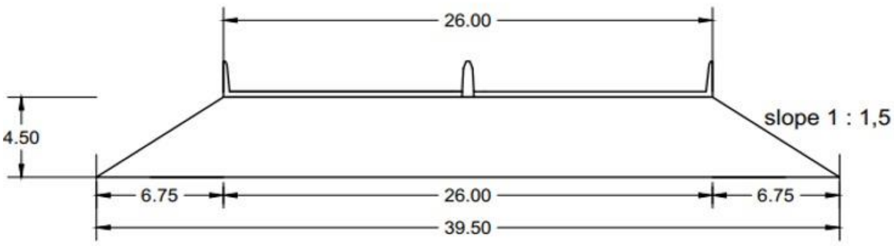


**Figure 4. Cross Section B of Soil-Fill Embankment**
Source: Author's Documentation, 2026

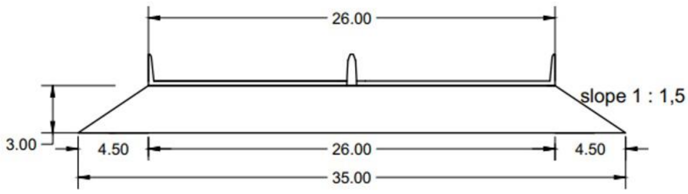


**Figure 5. Cross Section C of Soil-Fill Embankment**
Source: Author's Documentation, 2026

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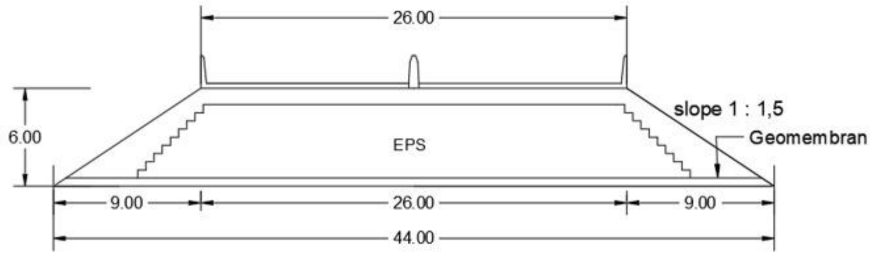


**Figure 6. Cross Section A of EPS Embankment**
Source: Author's Documentation, 2026

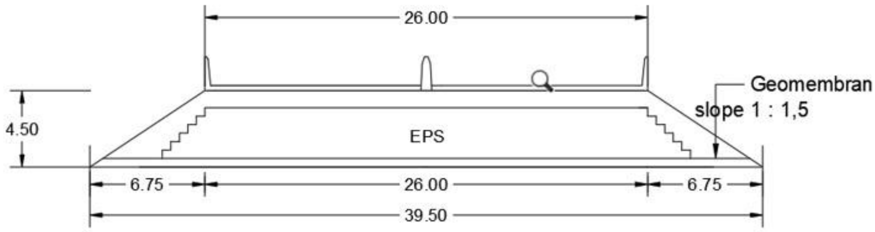


**Figure 7. Cross Section B of EPS Embankment**
Source: Author's Documentation, 2026

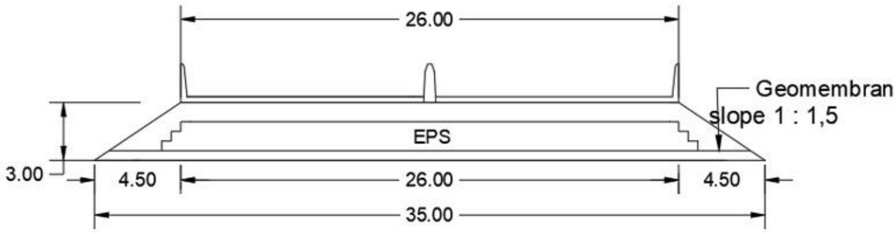


**Figure 8. Cross Section C of EPS Embankment**
Source: Author's Documentation, 2026

The foundation soil was divided into four layers extending to a depth of 25 m for the numerical analysis. Layer 1 extends from 0–6 m and consists of sand, while Layers 2, 3, and 4 consist of clay at depths of 6–8 m, 8–20 m, and 20–25 m, respectively. The N-SPT values were 38, 5, 2, and 5 for Layers 1 through 4, respectively, indicating a marked reduction in soil resistance within the clay layers. The elastic modulus also decreased from 30,300 kN/m² in Layer 1 to 6,000 kN/m² in Layer 2 and 2,400 kN/m² in Layer 3. The combination of low N-SPT values and relatively low stiffness in the deeper clay layers indicates that these layers are important in evaluating the deformation response of the embankment. The complete foundation soil parameters used in the analysis are presented in Table 1.

**Table 1. Soil Parameters**

| Parameter | Layer 1 | Layer 2 | Layer 3 | Layer 4 |
|---|---|---|---|---|
| Depth | 0–6 m | 6–8 m | 8–20 m | 20–25 m |
| Layer Thickness (m) | 6 | 2 | 12 | 5 |
| Soil Type | Sand | Clay | Clay | Clay |
| γ unsat (kN/m³) | 15.34 | 14.34 | 15.29 | 14.87 |
| γ sat (kN/m³) | 16.20 | 15.32 | 16.15 | 15.76 |
| e | 1.341 | 1.892 | 1.342 | 1.458 |
| c (kN/m²) | 0 | 30 | 12 | 30 |
| N-SPT | 38 | 5 | 2 | 5 |
| φ (°) | 42.5 | 25 | 21.3 | 25 |

| | | | | |
|---|---|---|---|---|
| E (kN/m²) | 30300 | 6000 | 2400 | 6000 |
| Cc | 0.351 | 0.396 | 0.2655 | 0.27 |
| Cv (m²/year) | 6.10 | 5.09 | 9.49 | 9.49 |

The material properties of the conventional soil-fill embankment were defined using the parameters obtained from laboratory testing and supplemented through empirical correlations. The soil-fill material has an unsaturated unit weight of 18.465 kN/m³, a saturated unit weight of 19.89 kN/m³, an elastic modulus of 88,949 kN/m², a void ratio of 0.655, and a friction angle of 30°. These parameters were incorporated into the PLAXIS 2D model to represent the mechanical response of the conventional embankment material. The EPS Geofoam configuration was modeled separately using a linear-elastic material representation. EPS has a density of 0.22 kN/m³, a Young's modulus of 6,910 kN/m², and a Poisson's ratio of 0.16, resulting in a substantially lower self-weight than the conventional soil fill.

**Table 2. Soil-Fill Parameters**

| Parameter | Value |
|---|---|
| γ unsat (kN/m³) | 18.465 |
| γ sat (kN/m³) | 19.89 |
| E (kN/m²) | 88949 |
| e | 0.655 |
| φ (°) | 30 |

**Table 3. EPS Parameters**

| Parameter | Value |
|---|---|
| Density, γ (kN/m³) | 0.22 |
| Young's Modulus, E (kN/m²) | 6910 |
| Poisson's Ratio, ν | 0.16 |

The difference in unit weight between the two embankment materials is a major parameter in assessing their influence on the soft foundation soil. The conventional soil fill has a unit weight of 18.465 kN/m³, whereas EPS Geofoam has a unit weight of only 0.22 kN/m³. This substantial difference indicates that replacing part of the conventional fill with EPS can considerably reduce the self-weight transmitted to the foundation. The lower modulus of EPS, however, also indicates that its deformation characteristics differ from those of conventional soil fill and therefore need to be evaluated together with the reduction in applied stress. The traffic load was specified as 15 kN/m² and applied as a uniformly distributed load in the analysis. Maintaining the same traffic loading for both configurations ensures that the comparison primarily reflects the different characteristics of the embankment materials.

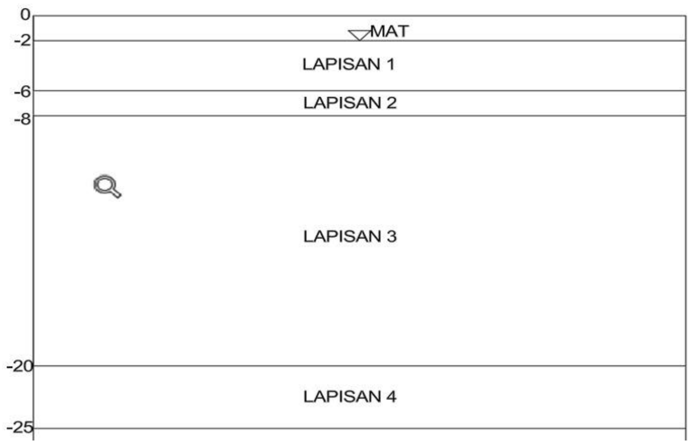


**Figure 9. Foundation Soil Layers**
Source: Author's Documentation, 2026

| Fungsi | Sistem Jaringan | Lalu Lintas Harian Rata-rata (LHR) | Beban Lalu Lintas (kN/m2) |
|---|---|---|---|
| Primer | Arteri | Semua | 15 |
| | Kolektor | > 10.000 | 15 |
| | | < 10.000 | 12 |
| Sekunder | Arteri | > 20.000 | 15 |
| | | < 20.000 | 12 |
| | Kolektor | > 6.000 | 12 |
| | | < 6.000 | 10 |
| | Lokal | > 500 | 10 |
| | | < 500 | 10 |

Sumber: Panduan Geoteknik 4 No Pt T-10-2002-B (DPU, 2002b)

**Figure 10. Traffic Load**

The parameter configuration indicates that the modeled foundation contains a relatively weak clay zone that is particularly relevant to embankment deformation. Layer 3 has an N-SPT value of 2, an elastic modulus of 2,400 kN/m², a cohesion of 12 kN/m², and a friction angle of 21.3°, distinguishing it from the stronger upper sand layer. The coefficient of consolidation for this layer is 9.49 m²/year, which is also used in the subsequent consolidation analysis. The conventional embankment introduces a substantially greater material weight than the EPS configuration because its unit weight is more than eighty times that of EPS. Consequently, the material parameters established in this section provide the principal input for assessing the differences in stress, settlement, consolidation behavior, and stability between the two embankment alternatives. These parameters were subsequently implemented in the PLAXIS 2D numerical model for the staged construction analysis.

**Stress and Settlement Analysis of Soil-Fill and EPS Embankments**

The stress analysis was initiated by determining the initial effective vertical stress within the four foundation soil layers. The calculated effective stresses were 38.6 kN/m² in Layer 1, 60.52 kN/m² in Layer 2, 114.742 kN/m² in Layer 3, and 166.04 kN/m² in Layer 4. The progressive increase in effective stress with depth reflects the increasing overburden stress generated by the overlying soil layers. These values provide the initial stress condition required for evaluating the additional stress generated by the embankment. The stress condition of the foundation is particularly important because the deeper clay layers have relatively low stiffness and are more susceptible to deformation. The effective stress calculations therefore establish the initial condition for the subsequent settlement assessment.

**Table 4. Initial Effective Vertical Stress**

| Foundation Layer | Effective Vertical Stress, σ'v0 (kN/m²) |
|---|---|
| Layer 1 | 38.60 |
| Layer 2 | 60.52 |
| Layer 3 | 114.742 |
| Layer 4 | 166.04 |

The additional vertical stress generated by the conventional soil-fill embankment was calculated for Cross Sections A, B, and C. For the uniform loading condition, the total stress contribution from the 6 m soil embankment together with the road and pavement loads reached 131.79 kN/m². The resulting stress increment decreased with depth in each cross section because the additional embankment-induced stress was distributed through the foundation soil. In Cross Section A, the calculated stress increments were 66.346, 64.829, 58.147, and 48.082 kN/m² for Layers 1–4, respectively. Cross Section B produced values of 52.360, 50.989, 45.139, and 36.730 kN/m², while Cross Section C produced 38.380, 37.210, 32.423, and 25.915 kN/m². The larger stress increments in Cross Section A indicate that this configuration produces the greatest additional loading on the foundation compared with Sections B and C.

**Table 5. Recapitulation of Stress Due to Soil-Fill Embankment Loading**

| Cross Section | Layer | $\Delta\sigma z$ (kN/m²) |
|---|---|---|
| A | 1 | 66.346 |
| A | 2 | 64.829 |
| A | 3 | 58.147 |
| A | 4 | 48.082 |
| B | 1 | 52.360 |
| B | 2 | 50.989 |
| B | 3 | 45.139 |
| B | 4 | 36.730 |
| C | 1 | 38.380 |
| C | 2 | 37.210 |
| C | 3 | 32.423 |
| C | 4 | 25.915 |

The EPS configuration generated substantially lower additional stresses than the conventional soil-fill configuration. The calculated uniform loads for EPS Sections A, B, and C were 58.72, 58.35, and 58.13 kN/m², respectively, which are considerably lower than the 131.79 kN/m² obtained for the conventional soil-fill configuration. In Cross Section A, the stress increments were 29.306, 28.636, 25.684, and 21.238 kN/m² from Layers 1 to 4. Cross Section B produced values of 29.110, 28.348, 25.096, and 20.420 kN/m², while Section C produced 28.986, 28.102, 24.487, and 19.572 kN/m². The relatively small differences among Sections A, B, and C indicate that the lightweight EPS configuration maintains a more uniform reduction in additional foundation stress across the evaluated cross sections. The reduction in applied stress is directly associated with the substantially lower unit weight of EPS compared with conventional soil fill.

**Table 6. Recapitulation of Stress Due to EPS Embankment Loading**

| Cross Section | Layer | $\Delta\sigma z$ (kN/m²) |
|---|---|---|
| A | 1 | 29.306 |
| A | 2 | 28.636 |
| A | 3 | 25.684 |
| A | 4 | 21.238 |
| B | 1 | 29.110 |
| B | 2 | 28.348 |
| B | 3 | 25.096 |
| B | 4 | 20.420 |
| C | 1 | 28.986 |
| C | 2 | 28.102 |
| C | 3 | 24.487 |
| C | 4 | 19.572 |

The immediate settlement results demonstrate the effect of the different stress levels generated by the two embankment configurations. For the conventional soil fill, the largest immediate settlement occurred in Layer 3 of Cross Section A, reaching 193.2 mm, while Layers 2 and 4 produced 77.31 mm each. Cross Section B produced immediate settlements of 54.82 mm, 137 mm, and 54.82 mm for Layers 2, 3, and 4, respectively. Cross Section C generated lower values of 35.65 mm, 89.12 mm, and 35.65 mm for the corresponding layers. For the EPS configuration, immediate settlement in Cross Section A decreased to 34.4 mm in Layer 2, 86.1 mm in Layer 3, and 34.4 mm in Layer 4. The same reduction was observed in Sections B and C, confirming that the lower embankment loading produced smaller immediate deformation of the foundation soil.

**Table 7. Recapitulation of Immediate Settlement Due to Soil-Fill and EPS Embankment Loading**

| Cross Section | Layer | Soil Fill (mm) | EPS (mm) |
|---|---|---|---|
| A | Layer 2 | 77.31 | 34.4 |
| A | Layer 3 | 193.2 | 86.1 |
| A | Layer 4 | 77.31 | 34.4 |
| B | Layer 2 | 54.82 | 31.1 |
| B | Layer 3 | 137.0 | 77.8 |
| B | Layer 4 | 54.82 | 31.1 |
| C | Layer 2 | 35.65 | 27.1 |
| C | Layer 3 | 89.12 | 67.8 |
| C | Layer 4 | 35.65 | 27.1 |

The primary consolidation settlement further demonstrates the influence of embankment loading on the soft foundation layers. Under the conventional soil-fill configuration, the largest primary consolidation settlement occurred in Layer 3 of Cross Section A, reaching 242.21 mm, followed by 196.00 mm in Section B and 147.03 mm in Section C. In comparison, the corresponding EPS values were 119.3 mm, 116.9 mm, and 114.3 mm for Sections A, B, and C, respectively. The reduction is also apparent in Layer 2, where the conventional soil-fill values ranged from 57.00 to 86.60 mm, whereas the EPS values remained between 45.4 and 46.1 mm. Layer 4 showed the same tendency, with conventional soil-fill settlement ranging from 34.59 to 60.66 mm compared with 26.6–28.7 mm for EPS. The results indicate that the lower stress imposed by EPS reduces the magnitude of primary consolidation, particularly within the soft clay layers that dominate the foundation response.

**Table 8. Recapitulation of Primary Consolidation Settlement Due to Soil-Fill and EPS Embankment Loading**

| Cross Section | Layer | Soil Fill (mm) | EPS (mm) |
|---|---|---|---|
| A | Layer 2 | 86.60 | 46.1 |
| A | Layer 3 | 242.21 | 119.3 |
| A | Layer 4 | 60.66 | 28.7 |
| B | Layer 2 | 72.68 | 45.7 |
| B | Layer 3 | 196.00 | 116.9 |
| B | Layer 4 | 47.67 | 27.7 |
| C | Layer 2 | 57.00 | 45.4 |
| C | Layer 3 | 147.03 | 114.3 |
| C | Layer 4 | 34.59 | 26.6 |

The settlement analysis indicates that the difference between the two embankment configurations originates primarily from the magnitude of additional stress transmitted to the foundation. The conventional soil-fill configuration produces considerably greater immediate and primary consolidation settlement because its higher unit weight generates a larger increase in vertical stress. The effect is most pronounced in Layer 3, which has the lowest N-SPT value of 2 and the lowest elastic modulus of 2,400 kN/m² among the clay layers. The calculated combined coefficient of consolidation was 8.8 m²/year, while the theoretical time required to reach 90% consolidation was approximately 34.7 years based on the calculation presented in the initial analysis. The substantial deformation potential of soft clay is consistent with established settlement behavior, in which additional loading can induce both immediate deformation and time-dependent consolidation. These results provide the analytical basis for comparing the subsequent PLAXIS predictions of long-term settlement and consolidation behavior for the two embankment alternatives.

**PLAXIS Modeling and Evaluation of Embankment Performance**

The numerical analysis was conducted using PLAXIS 2D to simulate the behavior of the bridge approach embankment under conventional soil-fill and EPS Geofoam configurations. Before the numerical calculation was performed, the initial geometry was prepared using CAD software to facilitate the modeling process. The CAD geometry included the embankment profile and the underlying soil layers based on the configuration established in the previous section. The CAD file was saved in .dxf format and subsequently imported into PLAXIS for further modeling. The soil material parameters, including elastic modulus, Poisson's ratio, unit weight, cohesion, friction angle, and permeability, were then assigned to the corresponding soil layers.

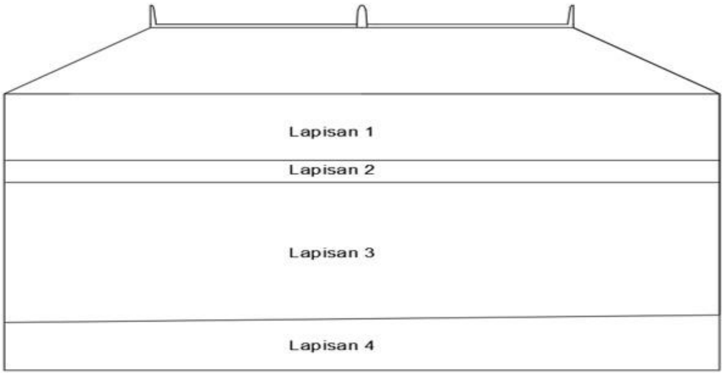


**Figure 11. CAD Modeling**

The meshing stage was performed after the geometry and material parameters had been assigned to the model. A very fine mesh configuration was selected to divide the model domain into smaller elements. The use of a very fine mesh was intended to provide greater numerical accuracy by reducing the size of individual calculation elements. The groundwater table was subsequently positioned at a depth of −2 m, corresponding to the available SPT-based field data. After the groundwater condition was defined, the construction sequence was established through the staged construction feature in PLAXIS. This procedure allowed the numerical model to represent the construction process progressively rather than applying the complete embankment load in a single calculation stage.

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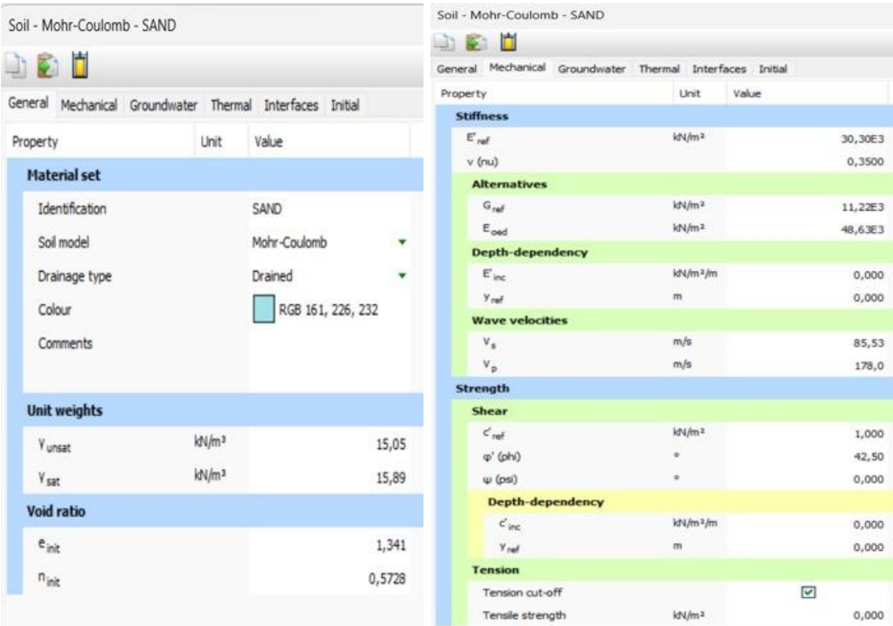


**Figure 12. Soil Material Input**

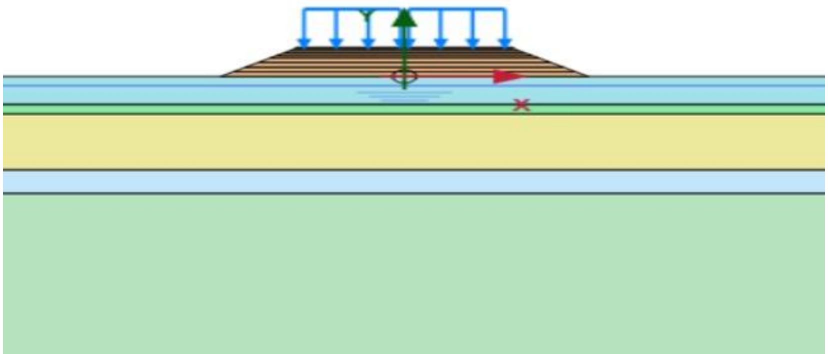

**Figure 13. Soil Parameter Input into Geometry**

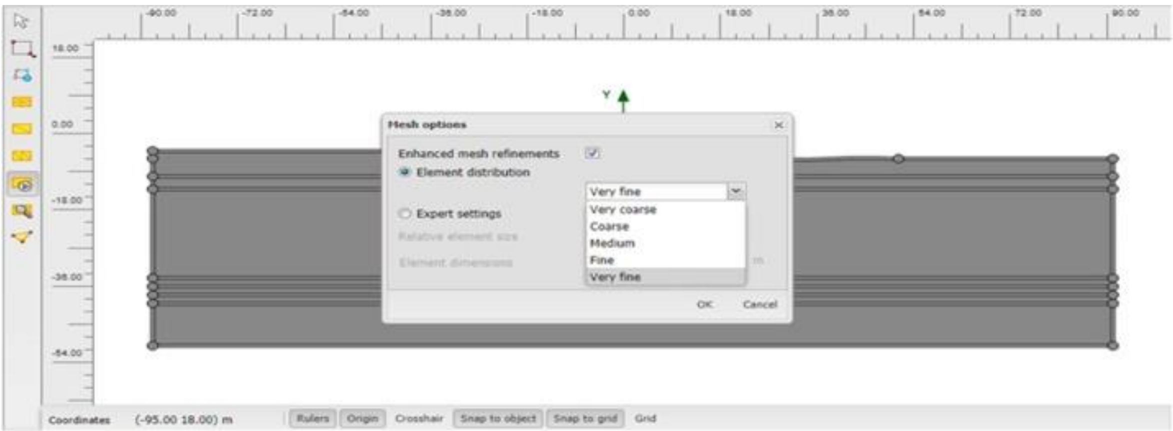


**Figure 14. Meshing**

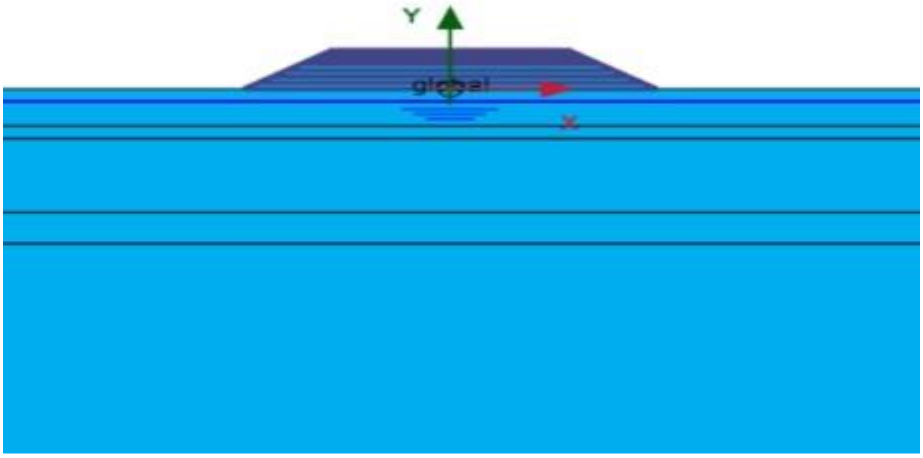

**Figure 15. Groundwater Table at −2 m**

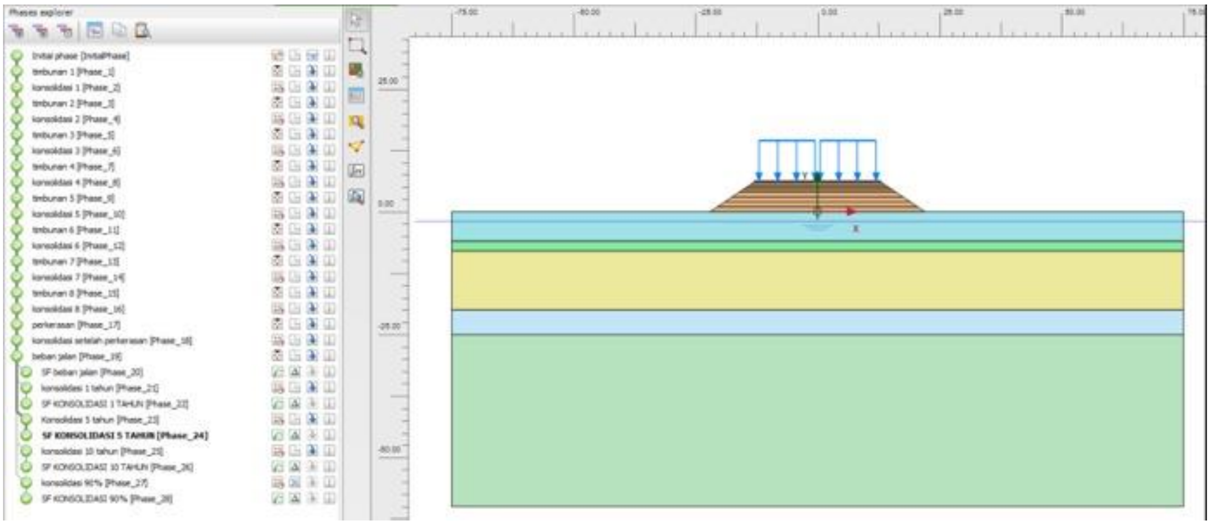

**Figure 16. Construction Stage**

The conventional soil-fill embankment was modeled as a drained material using the Mohr–Coulomb constitutive model. The material parameters included unit weight, cohesion, friction angle, elastic modulus, and Poisson's ratio, which were obtained from field investigations and laboratory testing. The embankment geometry has a base width of 44 m and gradually narrows to 26 m at the crest, producing a trapezoidal configuration consistent with the field geometry. The staged construction began with the placement of a 1 m thick first embankment layer over a 14-day interval, followed by 7 days of consolidation. The same 1 m thickness was maintained for Embankments 2, 3, and 4, while subsequent layers were reduced to 0.5 m and constructed with shorter time intervals. The complete construction sequence, including the final construction phase, reached a cumulative duration of 161 days.

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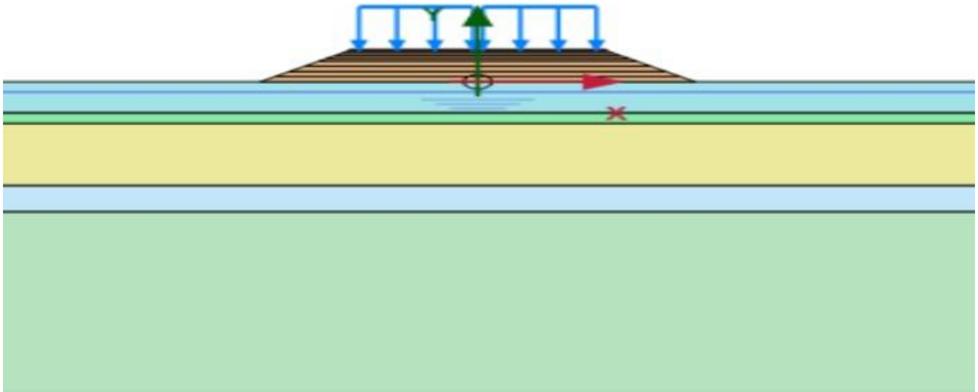

**Figure 17. Soil-Fill Embankment Modeling**

**Table 9. Construction Stages of Soil-Fill Embankment**

| No. | Analysis Stage | Interval (day) | Embankment Height (m) | Total Day |
|---|---|---|---|---|
| 1 | Embankment 1 | 14 | 1 | 14 |
| 2 | Consolidation | 7 | – | 21 |
| 3 | Embankment 2 | 14 | 1 | 49 |
| 4 | Consolidation | 7 | – | 56 |
| 5 | Embankment 3 | 14 | 1 | 63 |
| 6 | Consolidation | 7 | – | 70 |
| 7 | Embankment 4 | 14 | 1 | 84 |
| 8 | Consolidation | 7 | – | 91 |
| 9 | Embankment 5 | 7 | 0.5 | 98 |
| 10 | Consolidation | 3 | – | 101 |
| 11 | Embankment 6 | 7 | 0.5 | 108 |
| 12 | Consolidation | 3 | – | 111 |
| 13 | Embankment 7 | 7 | 0.5 | 118 |
| 14 | Consolidation | 3 | – | 121 |
| 15 | Embankment 8 | 7 | 0.5 | 128 |
| 16 | Consolidation | 3 | – | 131 |
| 17 | Final Construction | 30 | – | 161 |

The PLAXIS results for the conventional soil-fill model indicate a settlement of 0.47 m after one year and 0.58 m after ten years following completion of construction. The analysis also indicates that 90% consolidation was reached after 25,000 days, equivalent to approximately 68.49 years. The differential settlement was calculated from a settlement of 0.72 m at the center of the embankment and 0.35 m at its end, resulting in a differential value of 0.37 m. The safety factor evaluated at 90% consolidation was 1.5. These results indicate that the conventional embankment generates considerable long-term deformation, particularly in the soft foundation layers. The long consolidation period also demonstrates that the deformation process continues substantially beyond the 161-day construction period.

**Table 10. PLAXIS Output for Soil-Fill Embankment**

| Parameter | Result |
|---|---|
| Settlement after 1 year | 0.47 m |
| Settlement after 10 years | 0.58 m |
| 90% Consolidation | 25,000 days / 68.49 years |
| Settlement at center | 0.72 m |
| Settlement at embankment end | 0.35 m |

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| | |
|---|---|
| Differential settlement | 0.37 m |
| Safety Factor at 90% consolidation | 1.5 |

The EPS Geofoam embankment was subsequently modeled as a linear-elastic material with its own unit weight, elastic modulus, and Poisson's ratio parameters. The EPS configuration also used a base width of 44 m that gradually decreased to 26 m toward the crest, maintaining the same general geometry as the conventional embankment. The first construction stage consisted of a 1 m layer comprising 0.5 m of soil fill and 0.5 m of EPS blocks, followed by a 3-day consolidation period after the initial 7-day construction interval. Embankments 2 through 5 were each constructed at a thickness of 1 m with a 3-day construction interval and a 3-day consolidation period. The upper portions were then constructed using two 0.5 m soil-cover layers before a final 30-day construction phase was applied. The total cumulative construction duration for the EPS configuration was only 78 days.

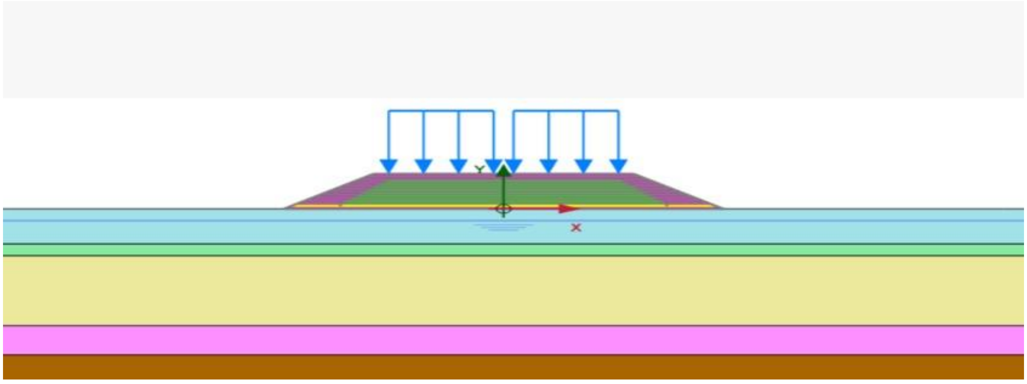

**Figure 18. EPS Embankment Modeling**

**Table 11. Construction Stages of EPS Embankment**

| No. | Analysis Stage | Interval (day) | Embankment Height (m) | Total Day |
|---|---|---|---|---|
| 1 | Embankment 1 | 7 | 1 | 7 |
| 2 | Consolidation | 3 | – | 10 |
| 3 | Embankment 2 | 3 | 1 | 13 |
| 4 | Consolidation | 3 | – | 16 |
| 5 | Embankment 3 | 3 | 1 | 19 |
| 6 | Consolidation | 3 | – | 21 |
| 7 | Embankment 4 | 3 | 1 | 24 |
| 8 | Consolidation | 3 | – | 27 |
| 9 | Embankment 5 | 3 | 1 | 30 |
| 10 | Consolidation | 3 | – | 33 |
| 11 | Upper Embankment 1 | 5 | 0.5 | 37 |
| 12 | Consolidation | 3 | – | 40 |
| 13 | Upper Embankment 2 | 5 | 0.5 | 45 |
| 14 | Consolidation | 3 | – | 48 |
| 15 | Final Construction | 30 | – | 78 |

The PLAXIS results for the EPS configuration show a settlement of 0.26 m after one year and 0.34 m after ten years following completion of construction. The time required to reach 90% consolidation decreased substantially to 3,746 days, equivalent to approximately 10.25 years. The settlement at the center of the embankment was 0.36 m, while the settlement at the end was 0.18 m, resulting in a differential settlement of 0.18 m. The safety factor at 90% consolidation reached 3.7, which is substantially higher than the value obtained for the conventional soil-fill model. The comparison indicates that the EPS configuration produces lower long-term settlement and a shorter consolidation period while also providing a higher calculated safety factor.

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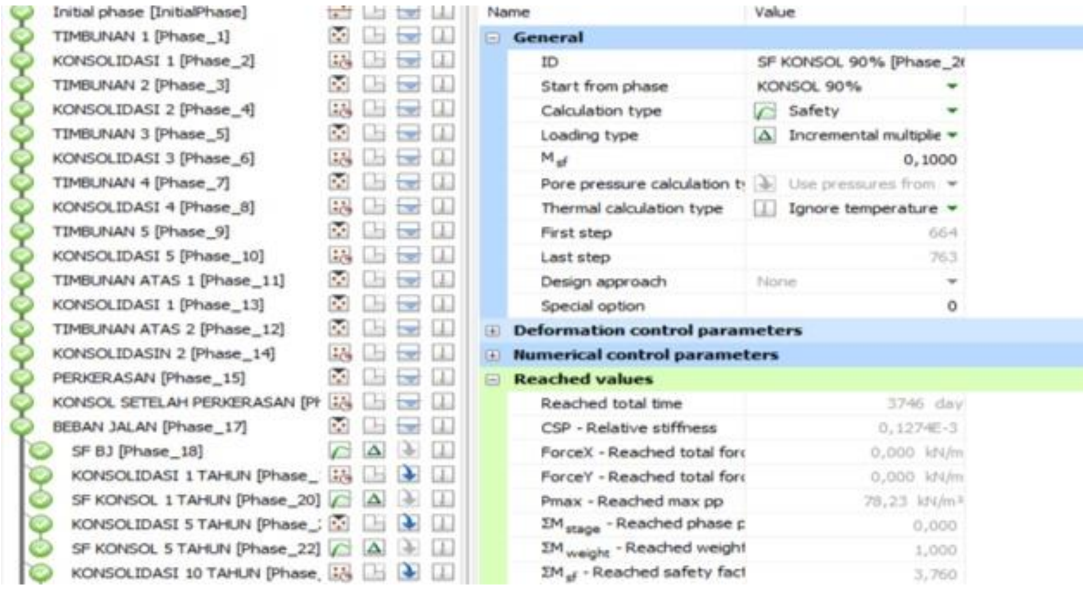


**Figure 19. Safety Factor of 3.7**

**Table 12. PLAXIS Output for EPS Embankment**

| Parameter | Result |
|---|---|
| Settlement after 1 year | 0.26 m |
| Settlement after 10 years | 0.34 m |
| 90% Consolidation | 3,746 days / 10.25 years |
| Settlement at center | 0.36 m |
| Settlement at embankment end | 0.18 m |
| Differential settlement | 0.18 m |
| Safety Factor at 90% consolidation | 3.7 |

The comparative PLAXIS results demonstrate a clear difference in the numerical response of the two embankment configurations. The conventional soil-fill model produced settlements of 0.47 m after one year and 0.58 m after ten years, whereas the EPS model produced values of 0.26 m and 0.34 m, respectively. The consolidation period also decreased from 25,000 days for soil fill to 3,746 days for EPS. The safety factor increased from 1.5 for the conventional embankment to 3.7 for the EPS configuration. The differential settlement was reduced from 0.37 m to 0.18 m, indicating a reduction of approximately half relative to the conventional configuration.

**Table 13. Comparison of PLAXIS Analysis Results**

| Modeling | Displacement 1 Year (m) | Displacement 10 Years (m) | 90% Consolidation (Day) | Safety Factor (SF) |
|---|---|---|---|---|
| Soil Fill | 0.47 | 0.58 | 25,000 | 1.5 |
| Expanded Polystyrene (EPS) Geofoam | 0.26 | 0.34 | 3,746 | 3.7 |

The difference in construction duration further supports the distinction between the two modeling approaches. The conventional soil-fill configuration required 161 days, including consolidation intervals between successive embankment layers. The EPS configuration required only 78 days, representing a substantially shorter modeled construction period. The shorter duration resulted from the lower weight of EPS and the corresponding reduction in loading applied to the foundation soil. The numerical results therefore show that the EPS configuration not only reduces settlement but also shortens the modeled construction and consolidation periods. The resulting increase in safety factor further indicates improved numerical stability under the analyzed consolidation condition.

**Comparison of Embankment Performance and Discussion of Results**

The comparison of the PLAXIS results shows that the EPS Geofoam configuration provides better deformation performance than the conventional soil-fill embankment. The settlement after one year decreased from 0.47 m for the soil-fill model to 0.26 m for the EPS model. After ten years, the settlement decreased from 0.58 m to 0.34 m, indicating that the lower-weight EPS configuration continues to provide a reduction in long-term deformation. The differential settlement also decreased from 0.37 m for soil fill to 0.18 m for EPS. These results indicate that the use of EPS can reduce the deformation imposed on the soft foundation soil while maintaining the same general embankment geometry. The reduction in settlement is consistent with previous research reporting that EPS Geofoam can significantly reduce embankment settlement compared with conventional fill on soft ground.

The consolidation response provides another important distinction between the two embankment alternatives. The conventional soil-fill model required approximately 25,000 days, or 68.49 years, to reach 90% consolidation. In contrast, the EPS model reached 90% consolidation after only 3,746 days, equivalent to approximately 10.25 years. The difference of more than 21,000 days demonstrates the substantial influence of embankment weight on the consolidation process of the underlying soft soil. The lighter EPS configuration generates a smaller additional stress, which results in a lower deformation demand on the foundation and a shorter calculated consolidation period. The result is particularly relevant for bridge approaches because excessive long-term settlement can create elevation differences between the approach embankment and the adjacent structure. The use of lightweight embankment material therefore provides an alternative for reducing the potential consequences of long-term foundation deformation.

The stability results also show a substantial improvement when EPS Geofoam is incorporated into the embankment. The calculated safety factor at 90% consolidation increased from 1.5 for the conventional soil-fill configuration to 3.7 for the EPS configuration. The higher safety factor indicates a greater margin against failure under the modeled consolidation condition. This difference is closely related to the reduction in the load transmitted from the embankment to the underlying soil. The conventional embankment has a considerably greater self-weight, whereas EPS has a unit weight of only 0.22 kN/m$^3$, resulting in a much smaller additional load on the foundation. The numerical results therefore indicate that the lightweight characteristic of EPS contributes not only to settlement reduction but also to improved calculated embankment stability.

The construction sequence also demonstrates an advantage of the EPS configuration in terms of the modeled implementation period. The conventional soil-fill embankment required a total construction duration of 161 days, consisting of successive 1 m and 0.5 m fill layers separated by consolidation stages. The EPS configuration required only 78 days, with shorter construction and consolidation intervals because of its substantially lower weight. The conventional configuration required repeated 14-day construction intervals for the first four layers, followed by shorter 7-day intervals for the upper layers. In comparison, the EPS configuration generally used 3-day construction intervals for the main EPS layers and ended with a 30-day final construction phase. The shorter duration does not indicate that EPS eliminates the need for consolidation, but rather that the lower imposed load allows the staged construction sequence to be completed more rapidly in the model.

**Table 14. Comparison of Embankment Performance**

| Parameter | Soil Fill | EPS Geofoam | Difference |
|---|---|---|---|
| Construction Duration | 161 days | 78 days | 83 days |
| Settlement after 1 Year | 0.47 m | 0.26 m | 0.21 m |
| Settlement after 10 Years | 0.58 m | 0.34 m | 0.24 m |
| 90% Consolidation | 25,000 days | 3,746 days | 21,254 days |
| Differential Settlement | 0.37 m | 0.18 m | 0.19 m |
| Safety Factor | 1.5 | 3.7 | 2.2 |

The findings are consistent with the study by Zianal, Yusof, and Aziman, which used PLAXIS 2D to compare conventional embankments with EPS-reinforced embankments on soft soil. That study reported a settlement of 28 mm for the conventional model, while the EPS models produced smaller settlement values depending on EPS density. The study also indicated that increasing EPS density resulted in lower settlement, demonstrating the influence of EPS properties on embankment deformation. The present analysis shows the same general tendency, although the numerical values differ because the geometry, foundation conditions, material parameters, and loading configuration are specific to the bridge approach analyzed in this study. The comparison strengthens the interpretation that EPS can function effectively as a lightweight embankment material for controlling settlement on soft foundation soils. The observed reduction in settlement from 0.58 m to 0.34 m after ten years further supports the suitability of EPS for applications where long-term deformation is an important design consideration.

The results are also comparable with the study by Tommy Diaz Iskandar, which evaluated different EPS Geofoam configurations using PLAXIS 2D for embankments on soft soil. The previous study found that configurations with insufficient EPS content could fail to satisfy the required consolidation and safety criteria, whereas the 100% geofoam configuration provided improved stability under the investigated loading conditions. In the present analysis, the EPS configuration produced a safety factor of 3.7, compared with 1.5 for the conventional soil-fill configuration. The present model also showed a substantial reduction in differential settlement, from 0.37 m to 0.18 m. The results suggest that the effectiveness of EPS is associated with its ability to reduce the load transferred to the weak foundation while maintaining a stable embankment configuration. This finding is in line with the broader application of EPS Geofoam as a lightweight material for controlling settlement in embankments constructed over weak or compressible soils.

Overall, the numerical comparison indicates that EPS Geofoam provides better performance than conventional soil fill for the analyzed bridge approach. The most notable improvements occur in long-term settlement, consolidation duration, differential settlement, safety factor, and modeled construction duration. Settlement after ten years was reduced by 0.24 m, while the differential settlement decreased by 0.19 m. The time required to reach 90% consolidation was also reduced from 68.49 years to 10.25 years, representing a major improvement in the predicted consolidation response. The safety factor increased from 1.5 to 3.7, indicating a considerably greater stability margin in the EPS model. Based on these numerical results, EPS Geofoam can be considered a more effective embankment alternative for reducing deformation and improving stability on the soft foundation conditions represented in the model.

## CONCLUSION

Based on the analytical calculations and numerical analysis using PLAXIS 2D, the use of Expanded Polystyrene (EPS) as an embankment material provides better performance than conventional soil fill on the analyzed soft foundation soil. The numerical results show that the maximum vertical displacement $|u_y|$ for the soil-fill embankment reached 0.71 m, while the EPS embankment produced a total settlement of 0.31 m. These results indicate that the EPS configuration can substantially reduce vertical deformation compared with the conventional soil-fill configuration. The differential settlement for the soil-fill embankment was 0.37 m, based on settlements of 0.72 m at the center and 0.35 m at the end of the embankment. In comparison, the EPS embankment produced settlements of 0.36 m at the center and 0.18 m at the end, resulting in a differential settlement of 0.18 m. This represents a reduction in differential settlement of approximately 51% compared with the conventional soil-fill embankment. The results confirm that the lightweight characteristics of EPS can effectively reduce deformation and differential settlement of embankments constructed over soft soil.

The stability analysis further demonstrates the effectiveness of EPS in improving the performance of the embankment system. The calculated safety factor for the EPS embankment reached 3.77, whereas the conventional soil-fill embankment produced a safety factor of 1.52. The higher safety factor indicates that the EPS configuration provides a greater stability margin under the analyzed conditions. The numerical analysis also showed that the conventional soil-fill embankment required approximately 68.49 years to reach 90% consolidation after completion of construction. In contrast, the EPS embankment reached 90% consolidation in approximately 9.5 years, indicating a substantially shorter consolidation period. The construction duration was also reduced in the numerical model, from

161 days for the soil-fill configuration to 78 days for the EPS configuration. Based on the reduction in settlement, differential settlement, consolidation time, and the increase in safety factor, EPS Geofoam demonstrates better overall performance than conventional soil fill for the analyzed bridge approach. Thus, EPS can be considered an effective lightweight embankment alternative for controlling deformation and improving the stability of embankments constructed on soft foundation soil.

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