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Numerical Analysis Of An Embankment On Basal Reinforced Soft Clay

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Abstract: Constructing embankments on soft clay deposits poses significant challenges in geotechnical engineering, especially in terms of ensuring stability and controlling settlement to meet design requirements. The observational method is commonly used in such cases, allowing for adjustments to the design during construction. Matsuo (1977) proposed a construction control chart that combines vertical and lateral displacements, making it particularly useful for predicting the failure of embankments on soft ground during construction. Soil properties, loading history, and environmental conditions all have a substantial impact on these predictions, even with small variations. To evaluate this, the paper compares field observations from a case history with results from finite element analysis (FEA) conducted using PLAXIS 2D. The finite element analysis shows a good agreement with the observed field data. The analysis of results shows that 22% and 36% of reduction in maximum settlement and lateral displacements respectively. Finally, the stability of the embankment is assessed using Matsuo's construction control chart which agrees with the construction stages.

Index Terms – Embankment, Soft clay, Finite element Analysis, Stability

1.INTRODUCTION

The construction of an embankment on soft soils presents significant challenges in geotechnical applications, such as highways, airport runways, containment dikes, flood protection levees, and earth dams. These embankments are essential for key infrastructure, including transportation, water storage, and flood control. However, constructing them on soft clay foundations is difficult due to the soil's high compressibility and low shear strength, which make it prone to excessive settlement and shear failure. This poor shear strength results in reduced bearing capacity and complicates construction efforts.

Numerous ground improvement techniques tackle the challenges of weak soils, with geosynthetic reinforcement emerging as an efficient and economical solution. For over three decades, geosynthetics have been essential in stabilizing embankments on soft soils. A recent advancement, geocell reinforcement, uses a honeycomb structure to provide 3D soil confinement, improving stability, erosion control, earth retention, and channel protection, especially on soft clay foundations.

Analyzing the stability of embankments on soft ground is crucial due to the weak shear strength and high compressibility of soft clay. Rapid embankment construction often risks instability, typically assessed through undrained (short-term) analysis. To enhance stability, geosynthetics such as geotextiles and geocells are widely used to improve the bearing capacity and safety factor. Geocells, a recent advancement, are effectively applied in foundations, retaining walls, slopes, and embankments. Limited researchers have studied the performance of cellular reinforcement provided at the base of earthen embankments founded on soft soil through experimental and numerical studies (Jenner et al. 1988, Bush et al. 1990, Bathurst and Karpurapu 1993, Cowland andWong 1993, Bathurst and Knight 1998, Krishnaswamy et al. 2000, Madhavi Latha 2008, Hegde 2013, Lalima Banerjee 2019, Farshad Astaraki et al. 2020). Rowe (1984) reported that the use of geotextile reinforcement increases the failure height of the embankment by 57%. Matsuo (1977) proposed a construction control chart based on the combination of vertical and lateral displacements and it is suitable to predict the failure of embankments on soft ground during construction, while finite element methods reliably predict failures (Potts et al., 1990). This study employs PLAXIS 2D to analyze geocell-reinforced embankments, comparing their performance to unreinforced embankments and evaluating stability using Matsuo's construction control chart.

2 .METHODOLOGY

2.0 Case Study

This paper presents the Brazilian Highway Research Institute (IPR) built an instrumented trial embankment near Rio de Janeiro, Brazil. The test site was located in a flat, swampy area with an 11-meter-thick clay deposit underlain by sand and gravel layers. The clay's plastic limit ranged from 80% at the surface to 60% at the base. Ortigao et al. (1980) conducted a stability analysis of the unreinforced embankment to evaluate the strength of the soft foundation. The second case study was The Muar trial embankment, located on the Muar flat in the Muar River valley, west Peninsular Malaysia, which was built to study the behavior of soft marine clays. This coastal plain has 10–20 meters of low-shear-strength clay, often causing instability during embankment construction. A large-scale trial embankment was constructed with extensive instrumentation to monitor soil response. The construction, completed over 100 days at a rate of 0.4 meters per week, collected detailed data. Before construction, the Malaysian Highway Authority (MHA) invited researchers to make "Class A" predictions (Lambe, 1973) of deformation and failure height, determined later as 5.4 meters. The findings were presented at the 1989 symposium, Trial Embankment on Malaysian Marine Clays, hosted by MHA.

2.1 Soil Profile and Geometry

2.1.1 Case 1: Rio de Janeiro

The geotechnical investigation by the Brazilian Highway Research Institute revealed that the in situ water content slightly exceeded the liquid limit, indicating the presence of high-sensitivity clay. Soil properties are depicted in Figure 1. The trial embankment was designed with a base width of 40 meters and a base length of 80 meters. It featured a stable 1V:6H slope on the left side and a steeper 1V:2H slope on the right, as shown in Figure 2. The embankment height was incrementally increased by adding 0.5-meter layers of fill, with failure occurring at a height of 2.8 meters.

2.1.2 Case 2: Muar Trial Embankment

The soil profile at the site comprises a 2.0-meter thick weathered crust, followed by 5.0 meters of very soft clay and 8.0 meters of soft clay. Below this layer, there is a 0.5-meter thick peat layer, 3.5 meters of sandy clay, and finally dense sand. The actual results from field and laboratory tests are illustrated in Fig. 4. In this analysis, the 20-meter clay deposit is segmented into four layers, with their properties detailed in Table 1.

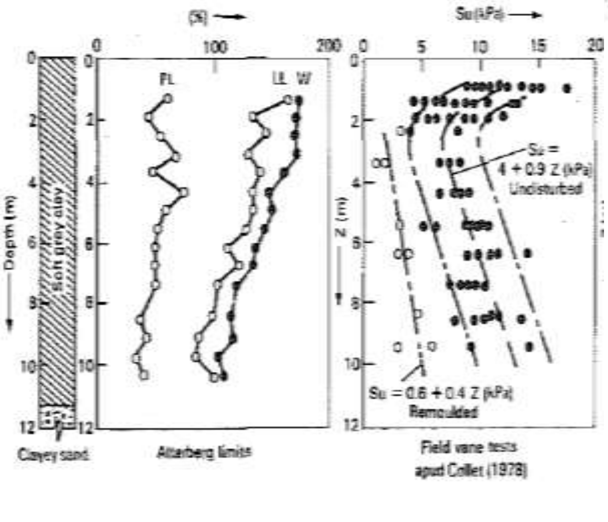


Fig.1. Geotechnical properties (Ortigao et al. 1983)

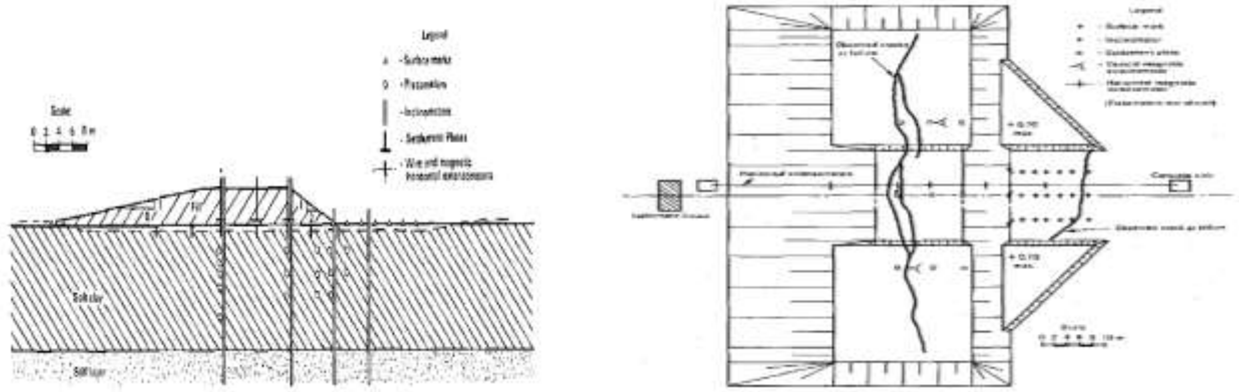


Fig. 2.Plan and Instrumentation scheme of the embankment (Ortigao et al. 1983)

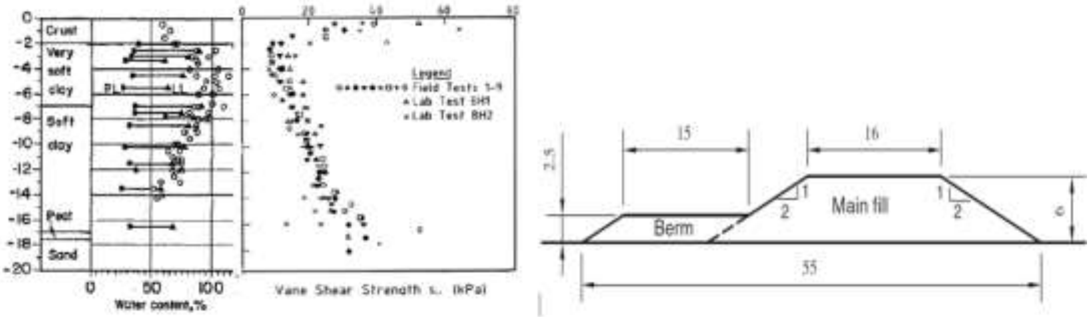


Fig.3. Soil Profile and geometry

2.1.3 Finite element analysis

Finite element analysis using PLAXIS 2D software was conducted under plain strain conditions to simulate real-world conditions, as shown in Figure 4. The model used the Mohr-Coulomb criterion for both the foundation and embankment soil, considering different drainage conditions (undrained and drained). The model was set up with 15-noded triangular elements, employing a medium to coarse mesh, refined in high-stress areas. Soil parameters, including bulk unit weight (γ), undrained shear strength (Su), undrained modulus of elasticity (Eu) for soft clay, drained modulus of elasticity (E) for embankment soil, and Poisson's ratio (ν), are listed in Table 1. The geocell's tensile strength was assumed to be 1000 kN/m. The deformation results for the basal-reinforced embankment were compared with unreinforced data and plotted on the Matsuo Construction Control chart to evaluate the embankment slope's factor of safety. The Matsuo plot (1977) uses settlement (d) at the embankment centre and horizontal displacement (δ) at the toe, as shown in Figure 5. Failure occurs when deformation reaches the topmost failure criteria curve in the Matsuo chart.

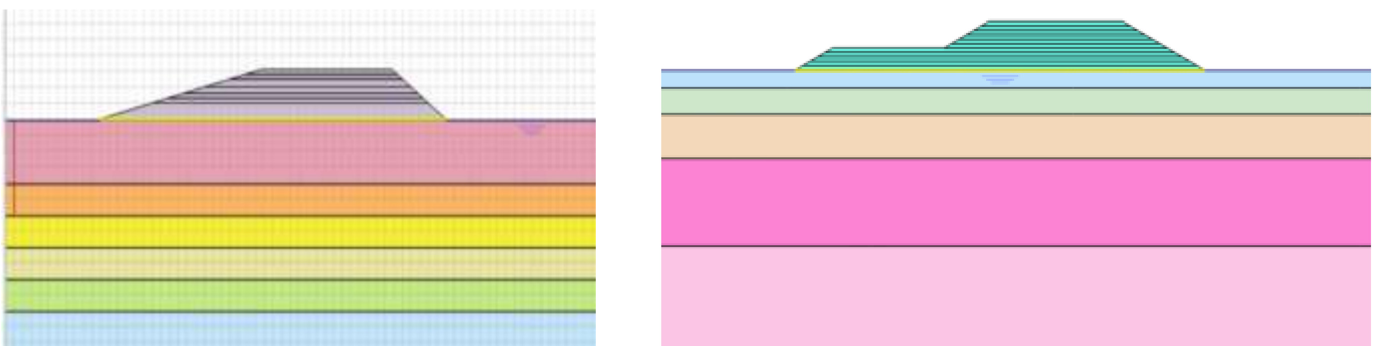


Fig 4. PLAXIS Model of Embankments

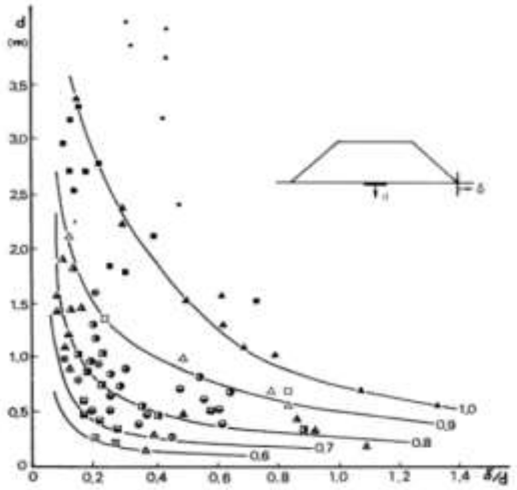


Fig 5. .Matsuo stability chart (Matsuo,1977)

Table 1. Soil parameters for Foundation and Embankment soil in FEA

Name of the embankment	Depth (m)	Unit weight of soil,g (kN/m^3)	Undrained Young's modulus E_u (MPa)	Poisson's ratio (ν)	Undrained shear strength (kPa) S_u	Effective friction angle,ϕ (°)
Rio De	0.0 -4.0	15	1.44	0.499	9	-
	4.0 -6.0	15	1.53		9	-
	6.0 -8.0	14.8	2.3		10	-
	8.0 -10.0	14.5	2.1		14	-
	10.0 -12.0	14.5	15.0	0.35	5.4	28
	12.0-200.0	15.2	50	0.3	5	36
	Embankment	18	25	0.3	10	30
Maur	0.0 – 2.0	15.5	8.7	0.495	35.0	0
	2.0 – 5.0	14.5	1.8	0.495	8.0	0
	5.0 – 10.0	15	4.1	0.495	18.0	0
	10.0 – 20.0	15.5	4.4	0.495	22.0	0
	20.0 – 40.0	18	35	0.495	13.2	37
	Embankment	20	5.1	0.3	14	31

3. RESULTS AND DISCUSSION

3.1.1 Settlements

Case 1. Rio de Janeiro

The analysis of the embankment construction phases showed that settlements decreased at each stage when compared to the unreinforced embankment, as illustrated in Figure 6. During the filling phase, significant settlement increases were observed in the field, particularly between the heights of 2.5 and 2.8 meters, with maximum settlements ranging from 238 to 250 mm. However, the geocell-reinforced embankment exhibited reduced settlements compared to the unreinforced case throughout the construction process. FEM analysis indicated that settlements gradually increased with the embankment height, as shown in Figure 6. Ultimately, the embankment reached its design height of 3.1 meters, resulting in an overall settlement reduction of 22% compared to the unreinforced embankment. The settlements are reduced to 11% in the case of a Geocell of 2000 kN/m as compared to the geocell strength of 1000 kN/m.

Case 2: Muar Trial Embankment

The settlements due to the embankment loading from the finite element analysis are shown in Figure 4.1. The settlements against each increment of fill for insitu and reinforced embankments are depicted in Figure 4.2. The settlements at the initial stages of filling, and the reinforced embankments are similar to the in-situ values till the height of 1.5m. The measured settlements at the end of the construction of the unreinforced embankment are 600 mm, which corresponds to a height of 5.0 m due to the cumulative effects of the applied load and the compressibility of the underlying soil of less cohesion. The embankment reinforced with geocell of 1000 kN/m and 2000 kN/m exhibits reduced settlement at a height of 5.0 m compared to unreinforced soil, with settlement reduction of 12 % and 15% respectively. The geocell confinement reduces the vertical stress on the underlying soil, minimizing soil deformation and compressibility. Additionally, the geocells help to distribute the applied loads more evenly across the embankment, which further helps to increase the embankment height from 5.0 m to 5.5m. The higher tensile strength of the geocells (2000 kN/m) provides even greater reinforcement, leading to a more significant reduction in settlement compared to the lower-strength geocells (1000 kN/m).

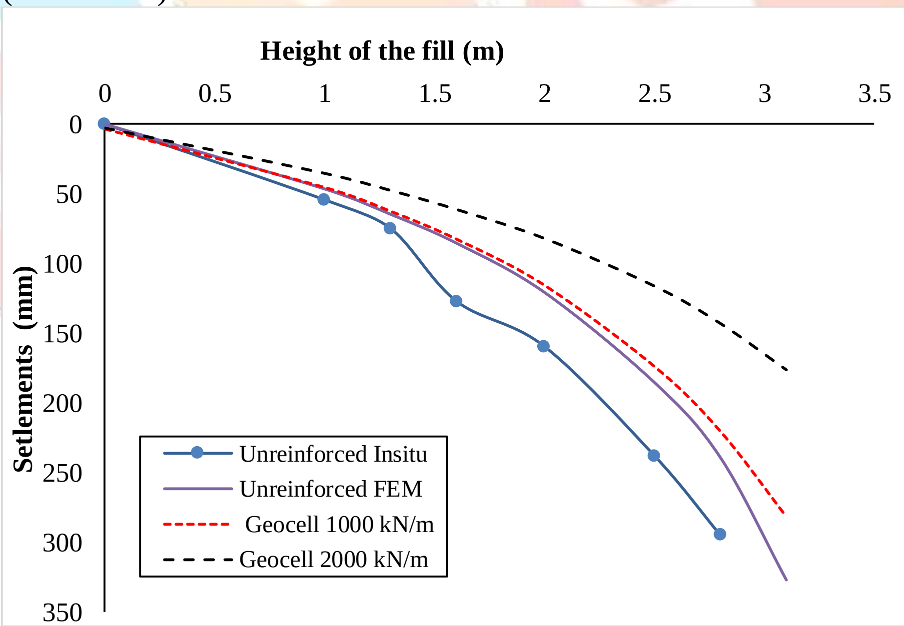


Fig.6 Settlements at the centre of the embankment

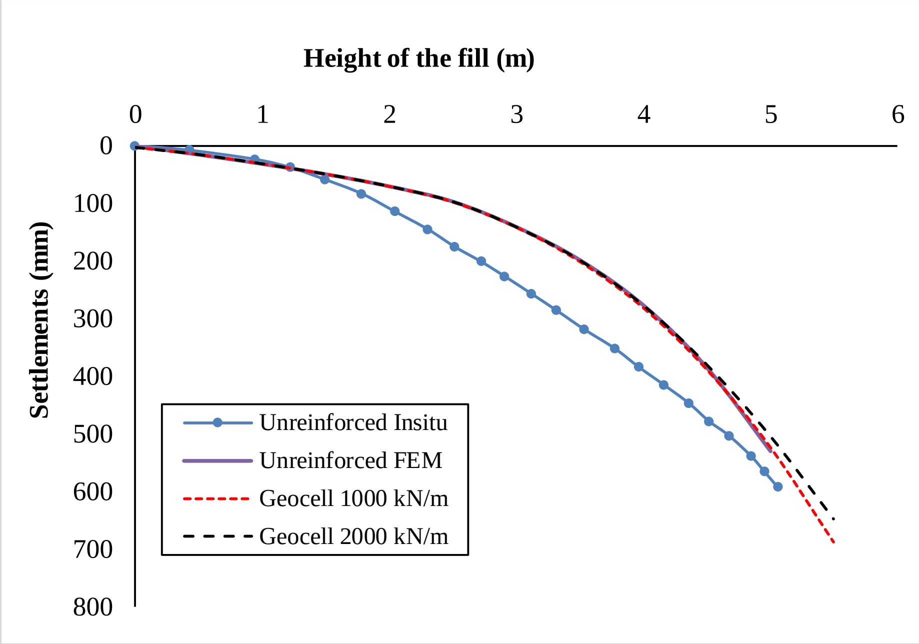


Fig.7 Settlements at the centre of the embankment

3.1.2 Lateral Displacements

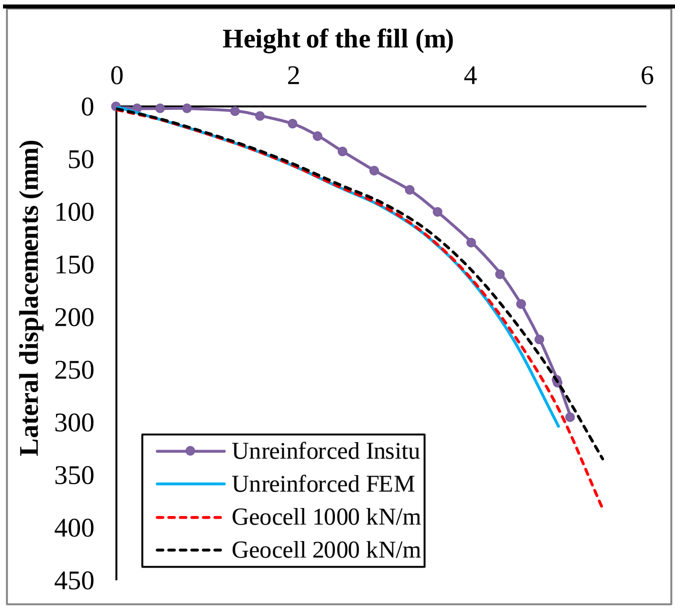
a) At the toe of the embankment

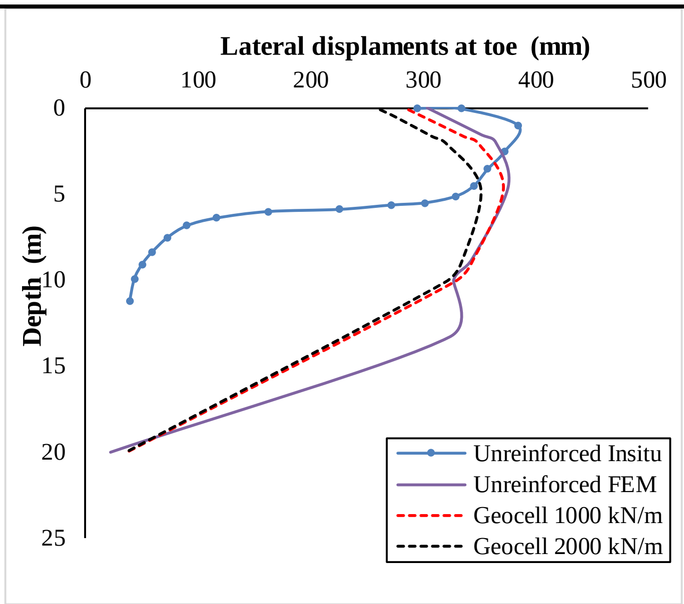
Lateral displacements at the toe of the embankment gradually increased in both the unreinforced and reinforced cases, as shown in Figure 8(a). In the unreinforced case, as the embankment height increased from 2.5 to 2.8 meters, there was a rapid rise in lateral displacement at the toe, ranging from 300 mm to 350 mm. However, in the reinforced case, these lateral displacements were reduced by 36% The Geocell-reinforced cases show much better control over lateral displacement. The Geocell 2000 kN/m case, in particular, demonstrates that reinforcement is effective even at higher fill heights with the same soil parameters. In case 2 as shown in Figure 9(a), the unreinforced embankment shows significant lateral displacements as the fill height increases, with minimal displacement (16 mm) up to 2 meters. At a height of 5 meters, the displacement reaches 295 mm. In contrast, the geocell-reinforced embankment experiences increased lateral movements initially up to 3 meters but shows reduced displacements at the end of construction. At the maximum height of 5 meters, lateral displacements are reduced to 287 mm for geocell with 1000 kN/m and 260 mm for 2000 kN/m reinforcement.

b) Along the vertical plane at the toe

The maximum lateral displacements were observed along the vertical plane at the toe of the embankment, as shown in Figure 8(b). In the unreinforced case (Case 1), the maximum lateral deformation (ym) was recorded at a depth (z) of 3.6 meters from the ground level, measuring 348 mm. In contrast, the geocell-reinforced embankment exhibited reduced displacements of 290 mm at a greater depth of 5 meters. Overall, the maximum lateral displacements (y_m) were reduced by 16.5%, with significant displacements occurring at depths exceeding 1 meter. This higher-strength geocell controls lateral movement effectively, ensuring better stability throughout the embankment height. In case 2 as shown in figure 9(b), the maximum lateral displacement of 390 mm at 1.5 m depth in the unreinforced embankment decreases with geocell reinforcement, with displacements reduced to 370 mm at 4.5 m depth. The surface displacements decrease by 3% and 11% for 1000 kN/m and 2000 kN/m geocell reinforcements, respectively. Reinforcement significantly reduces lateral displacements, particularly at greater depths.

The inclusion of geocells at the base of the embankment plays a key role in strengthening the foundation soil within the plastically deformed zone. By mobilizing the strength of the foundation soil in this critical area, geocells significantly enhance the stability and overall performance of the embankment structure.

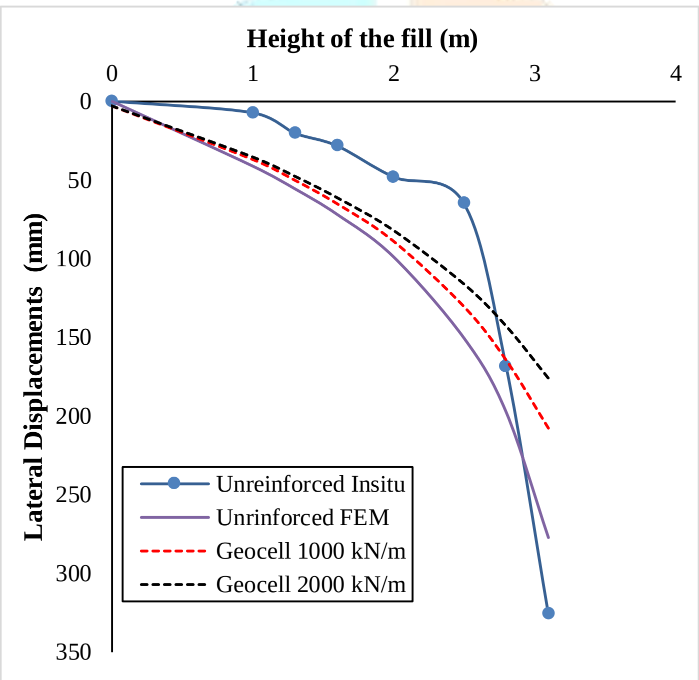


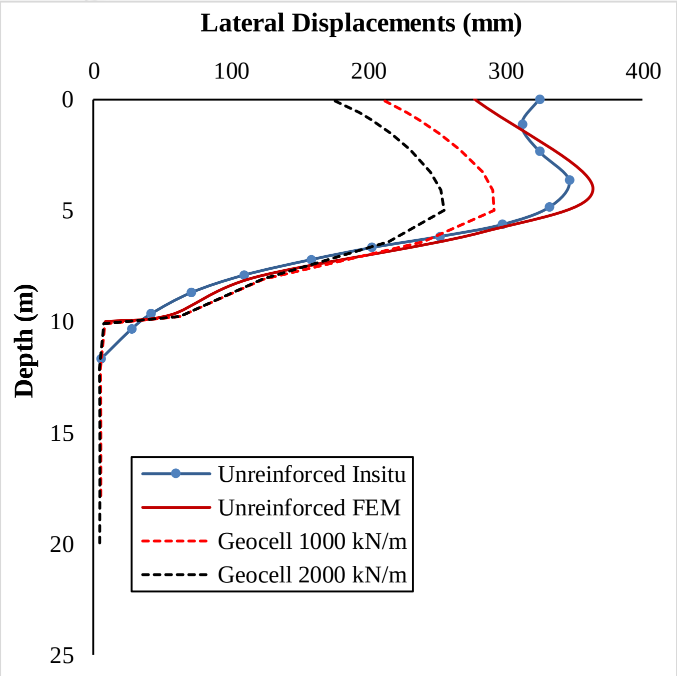


a) Initial to end of construction

b) Along the vertical plane at the end of Construction

Fig 8 Lateral displacements at the toe of the embankment





a) Initial to end of construction

b) Along the vertical plane at the end of Construction

Fig 9 Lateral displacements at the toe of the embankment

3.1.3 Factor of Safety

The FEM analysis for the geocell-reinforced embankment at Rio de janerio and Maur showed a factor of safety of 1.30 at a height of 3.1 m and 5.5 m respectively, whereas the unreinforced embankment had a factor of safety below one. The inclusion of geocells increases stability, enabling a higher embankment and enhancing safety. According to the Matsuo construction control chart, the reinforced embankment remains stable, while the unreinforced embankment exhibits accelerating deformations, signalling the risk of failure.

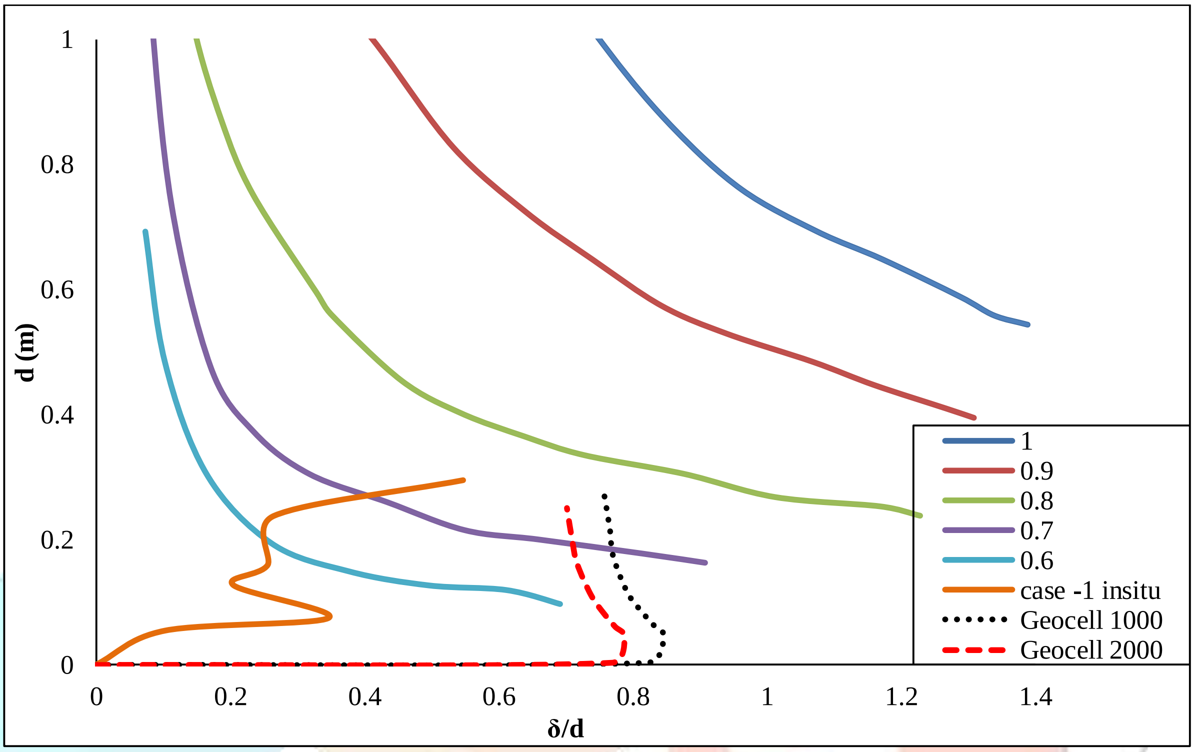


Fig 10. Stability chart Rio Mastuo

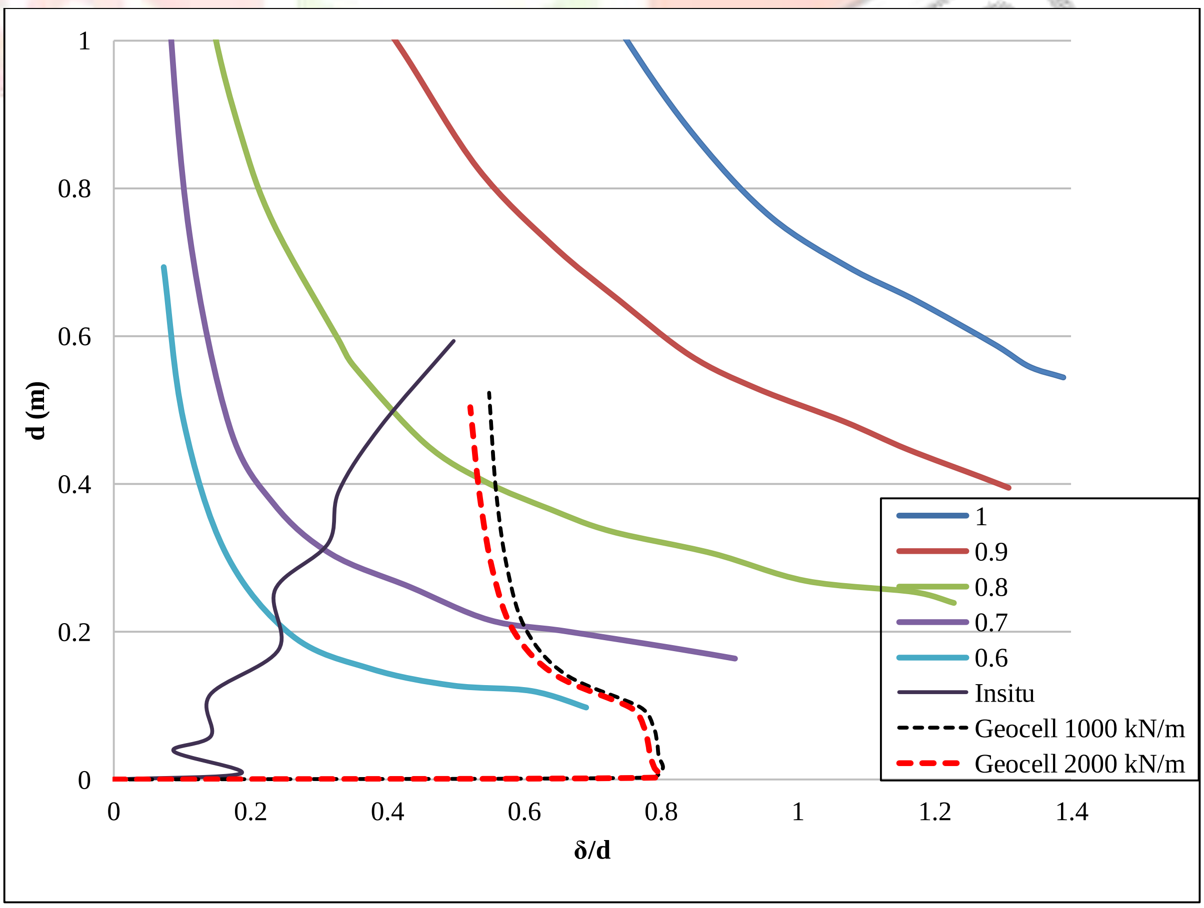


Fig 11. Stability chart Maur mastuo

Summary and Conclusions

The numerical simulations using finite element analysis to model a soft clay embankment reinforced with geocells led to the following conclusions:

- The Settlements were reduced by 22% and remained relatively limited in case 1, in case 2 it was around 15% compared to the unreinforced embankment.
- The Lateral displacement at the embankment toe was reduced by 36% with geocell reinforcement. The maximum lateral displacement along the vertical plane at the toe (ym) decreased by 16.5% in Case 1 compared to the unreinforced embankment, with notable displacement occurring at depths greater than 1 meter in Case 2. In case 2, it was reduced by about 11% and maximum lateral displacement along the vertical plane at the toe shifts from 2.5m to 4.5m compared to the unreinforced condition.
- The height of the Embankment increased when Geocell reinforcement provided a stable platform for construction, allowing for increased embankment heights. In case 2, the height increased from 5.0 m to 5.5 m, in case 2, and in case 1, it increased from 2.8 to 3.1m.
- The factor of safety during construction improved with the addition of geocell reinforcement at the embankment base, in line with the Matsuo plot. However, this result was inconsistent with actual field measurements, suggesting that additional parameters are needed for more accurate predictions.
- In summary, the incorporation of geocells enhances embankment stability by reducing settlement, and lateral displacement, and increasing the factor of safety, though further data is needed for consistency with field observations.

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