© Universiti Tun Hussein Onn Malaysia Publisher's Office

J-SUE

http://publisher.uthm.edu.my/ojs/index.php/j-sue

e-ISSN : 2821-2851

Journal of Sustainable Underground Exploration

Analysis of Geosynthetic – Reinforced Stone Piles – Supported Embankments

Ali RamazanBorujerdi[1*]

[1]Department of Civil Engineering,
Qom University of Technology, Tehran, 1651958171, IRAN

*Corresponding Author

DOI: https://doi.org/10.30880/jsue.2023.03.01.006
Received 24 July 2023; Accepted 30 July 2023; Available online 31 July 2023

Abstract: The low bearing capacity, high compressibility, and lack of lateral resistance of stone pile-supported embankments on soft clay deposits pose design challenges. To overcome these difficulties, geosynthetics have been widely favored by geotechnical engineers in recent years. A two and three dimensional (2D, 3D) finite element model study that simulates a geosynthetic-reinforced and geosynthetic-encased stone pile-supported embankment on soft ground is presented in this paper. To study the effect of reinforcement and encasing on the vertical displacement of stone piles and soft soil, numerical analyses are performed. The results show a significant reduction in settlement with the casing, which is believed to be a direct result of the additional containment pressure created by the geosynthetic casing. With the help of soil reinforcement, the surface settlement values of the soft soil could be significantly reduced.

Keywords: Stone piles, geosynthetic – reinforced, embankment, finite element model, soft soil

1. Introduction

The construction of embankments on soft soil presents several difficulties related to the weak soil strength. In recent years, with increasing demand, the stone pile technique has been used to improve the bearing capacity, which depends on the surrounding soil [1-6]. However, due to insufficient lateral confinement, it is impossible to erect the stone pillars of very soft clay. In such soils, the required lateral containment can be achieved by encasing the individual stone piles with a suitable geosynthetic over all or part of the height of the pile [7-12]. The general idea of encasing the stone piles with geotextiles was first recognized by Gabr et al. [13]. They presented analytical design techniques for evaluating the required tensile strength of geotextiles. The project, which used a seamless geotextile sock as the stone pile encasement, was successfully implemented in Germany in 1995. With the advancement of construction and geosynthetic production technology in the 1990s, new design methods were developed. Later, Ramazan Borujerdi, A. [7], studied the performance of geosynthetic-encased stone piles using numerical and analytical models and established an analytical design technique for evaluating stone pile settlement based on geotextile stiffness. Cowland [3] conducted an experimental study and reported the benefits of encasing stone piles. Ramazan Borujerdi [9] evaluated the concept of encasing individual stone piles with geosynthetics through numerical analysis and found that the encased stone piles are stiffer than conventional stone piles. Ramazan Borujerdi [10] studied the settlement of fully encased and isolated stone piles by small-scale laboratory testing and numerical modeling and presented a significant reduction with increasing geosynthetic stiffness. Dash et al. [11] presented the results of the full 3D model of geosynthetic-encased stone pile-supported and the applicability of continuum elements instead of membrane elements in 3D modeling. Dash et al. [12] performed load tests on single and group stone piles with and without encasement in a large test tank and developed design guidelines for the given load and settlement. Gabr et al. [13] presented fully coupled analysis results on the contribution of the geosynthetic encasement in enhancing the settlement reduction in the embankment reinforced with stone piles. Krishnaswamy et al. [14] performed three-dimensional finite element analysis of geosynthetic-encased stone pile-supported using three different forms of hyperbolic models for the encased granular material to more

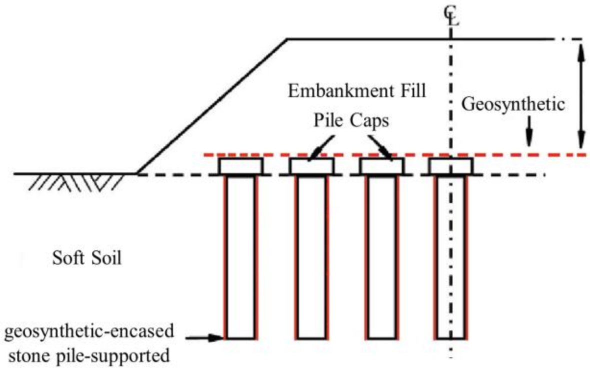
**Corresponding author: aliborujerdi1371@gmail.com*

realistically study the lateral response of geosynthetic-encased stone pile-supported during loading and found that modelling the behaviour of near-ground failures is essential for properly simulating the behaviour of geosynthetic-encased stone pile-supported. Latha et al. [15] performed field-scale load tests to investigate the improvement in bearing capacity and settlement reduction of a geosynthetic-encased stone pile-supported, with a focus on the effect of the encasement length and pile strain. This has been observed in the available studies, which revealed that mainly unreinforced soft-soil embankments were studied with geosynthetic-encased stone pile-supported and the effect of basal reinforcement in the embankment was not considered. The work presented in this paper aims to improve the axisymmetric unit cell model of reinforced embankments constructed on soft ground reinforced with geosynthetic-encased stone pile-supported. To compare the performance of the basal reinforcement, parallel analyses were also performed on unreinforced embankments. In addition, the effectiveness of the geosynthetic stiffness on settlement behaviour is investigated by parametric analysis.

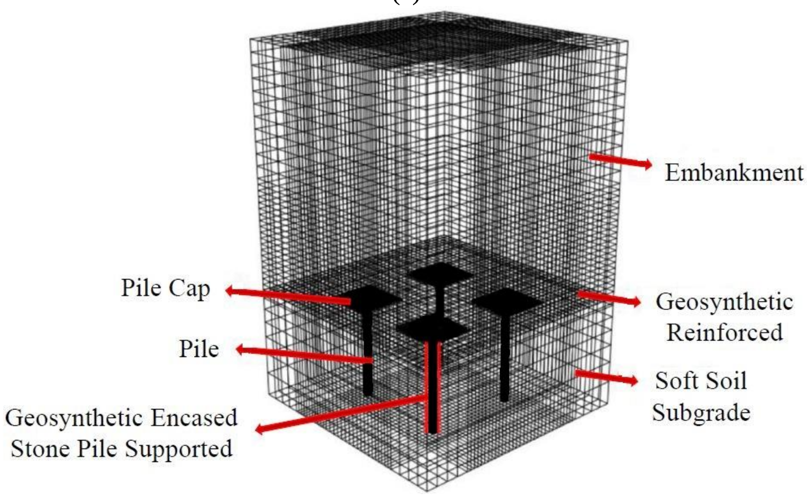
2. Numerical Analyses

PLAXIS 2023 [16] is the finite element code used in the numerical analyses of this work. In all numerical analyses performed, it is assumed that the height of the embankment reinforced with geosynthetics on soft ground is 3 m. The soft ground is 10 meters thick and lies on top of a rigid and firm layer. The water level is on the surface of the earth, see Fig. 1. Stone piles with a diameter of 0.8 m (D) are arranged in a square grid pattern on 2.4 m centres, which corresponds to an area replacement ratio of 9%. All cairns are encased in geosynthetics. At the base of the embankment, there is a layer of geosynthetic for basal reinforcement.

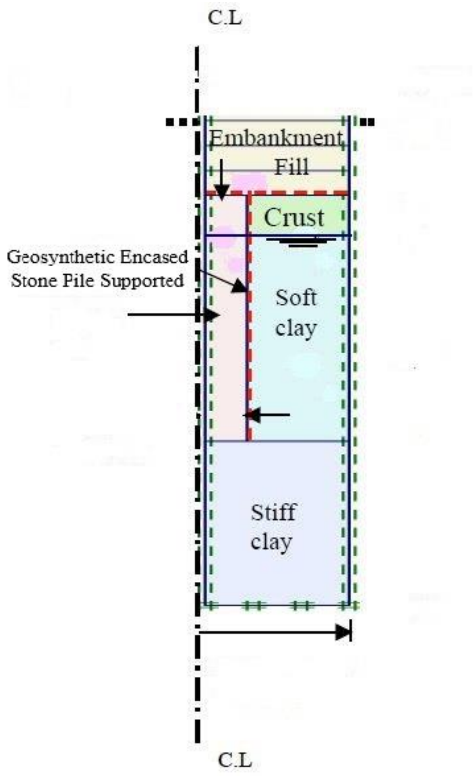
Fig. 1c shows an axisymmetric finite element unit cell model in which the total radius of the cylinder was chosen to be 1.2 m. The finite element mesh used in the numerical simulations was developed using 15-point triangle elements. The accumulations between soil and piles were refined twice due to the expected severe deformation. No horizontal displacement was allowed on the vertical boundaries, while the lower boundary is fully fixed in both vertical and horizontal directions. The soil surface is a drainage boundary (zero value of excess pore pressure), while the vertical and lower boundaries of the mesh are assumed to be impermeable.



(a)



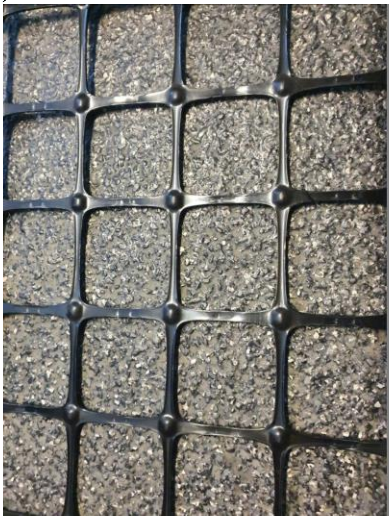
(b)



(c)

(d)

(e)



(f)

Fig. 1 - (a) Actual field condition; (b) 3D models adopted for analysis; (c) unit cell idealization concept; (d) installation of geosynthetic-encased stone pile-supported and geosynthetic-reinforced over soft soil embankment; (e) geosynthetic-encased stone pile-supported; (f) geosynthetic-reinforced

The geosynthetics used for both the base reinforcement and the encasement were modelled as a linear elastic material with axial stiffness in elastic or elastoplastic forms, with an assumed Poisson's ratio of 0.3, e.g., [17-23]. The secant stiffness of the geosynthetic (J) was defined as the ratio of the tensile force per unit width to the average strain in the geosynthetic. To determine the geosynthetic modulus of elasticity, the initial tensile modulus at 3% axial strain was calculated. Dash et al. [11] documented that design values of tensile modulus (J) between 1000 and 4000 kN/m were required for the geosynthetic used to encase granular piles on various projects (sheathing tensile modulus, J, is also commonly referred to as geosynthetic stiffness). Consequently, in the numerical analyses, a value of J = 1000 kN/m was used for both the encasement and the reinforcement. To model the interaction behaviour between them, interface elements were used, which can be characterized by two parameter sets: between the geosynthetic and the granular pile and between the geosynthetic and the surrounding soft soil. The coefficient of sliding friction (μ) between the geosynthetic and the granular pile was chosen to be 0.5 (= 2/3 tan) [24-26], where the friction angle of the pile material to the interaction between the geosynthetic and the soft soil was assumed to be 0.3 (= 0.7 tan) [27-28], which is the friction angle of the soft soil. The parameters used in the numerical analyses are summarized in Table 1.

After determining the prestressing and the pore pressure under the appropriate boundary conditions, the stone pile, the geosynthetic encasement, and the geosynthetic reinforcement were activated on site as required. The dam construction was then simulated in equal stages with a 0.5-m backfill. It was assumed that each embankment fill should be completed within 10 days, followed by a 20-day consolidation period. In order to compare the performance of the reinforced and the cased pile-supported embankment, parallel analyses were also performed on both unreinforced stone piles. In the numerical analysis, four different basic reinforcement stiffnesses (1000, 2000, 3500, and 5000 kN/m) are used to investigate the influence of the basic reinforcement stiffness on the deformation behavior of stone piles.

Table 1 - Model parameters

Property	Stone Column	Soft Clay	Embankment
	Model Type		
	Mohr-Coulomb	Modified Cam-Clay	Mohr-Coulomb
ϕ (°)	40	-	32
c' (kPa)	1	-	1
φ' (°)	10	-	2
E (kPa)	40000	-	15000
υ	0.3	0.3	0.3
K	-	0.02	-
λ	-	0.4	-
e	-	1.0	-
M	-	1.0	-
Permeability (m/s)	$1x10^{-2}$	$1x10^{-6}$	$1x10^{-2}$

3. Results and Discussion

Figs. 2 and 3 show the deformations and settlements at the bottom of the embankment after the construction period and at the end of the consolidation. These results show that at the end of construction, the maximum settlement of the soft soil is approximately 15% of the maximum long-term settlement at the end of consolidation. As expected, the settlements in the soft soil are higher than in the pile. Fig. 3 shows the development over time of the settlements at the base of the slope, in the middle of the top of the pile (x = 0), and on the soft soil at the edge of the unit cell (x = 1.2 m), where the maximum value occurs; the difference processing is also shown. The long-term settlement on the soft soil at the periphery of the unit cell is 13.6 cm, while in the centre of the pile it is 1.5 cm, and the differential settlement is 12.1 cm.

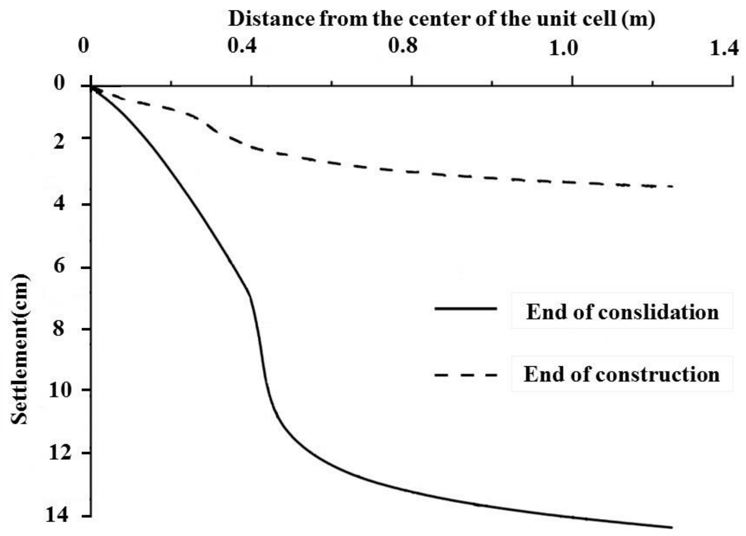


Fig. 2 - Settlement at the embankment base

Figure 3 compares the maximum settlement at the slope base for both reinforced and unreinforced cases at the end of the consolidation period. The results show that with reinforcement, there is a decrease in long-term maximum settlement from 13.6 cm to 4.1 cm, i.e., the settlement reduction ratio (ratio between settlements of the reinforced and unreinforced cases) is 0.3. Fig. 4 shows the settlement behaviour of soft soil for the reinforced embankment cases with different stiffness values. The results show that the settlement of soft soil with soil reinforcement decreases from 13.6 cm to 3.2 cm. As the reinforcement stiffness value increases (the sheath stiffness is constant, J = 1000 kN/m), the settlement value decreases, as expected. With small stiffness values of the reinforcement, the settlements decrease significantly more; with higher values, settlements become less noticeable and remain almost constant. The settlement value on the ground decreases from 4.1 cm to 3.2 cm.

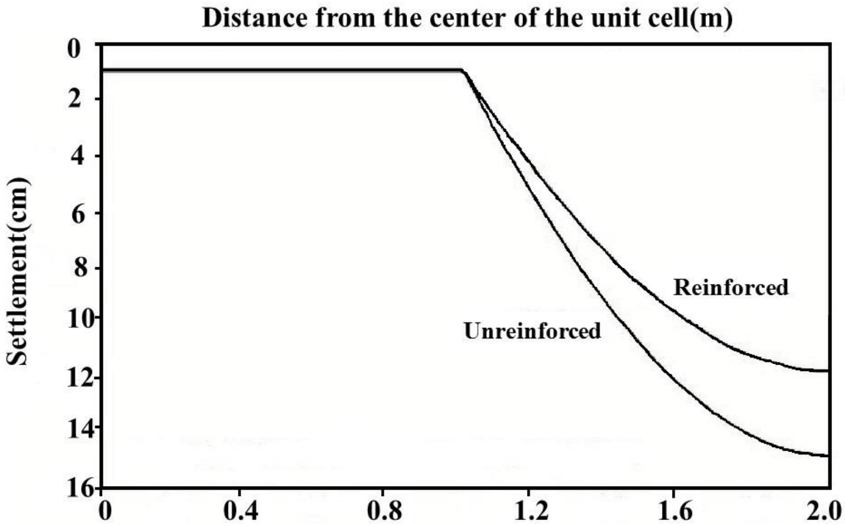


Fig. 3 - Settlement at the embankment base for the reinforced and unreinforced cases

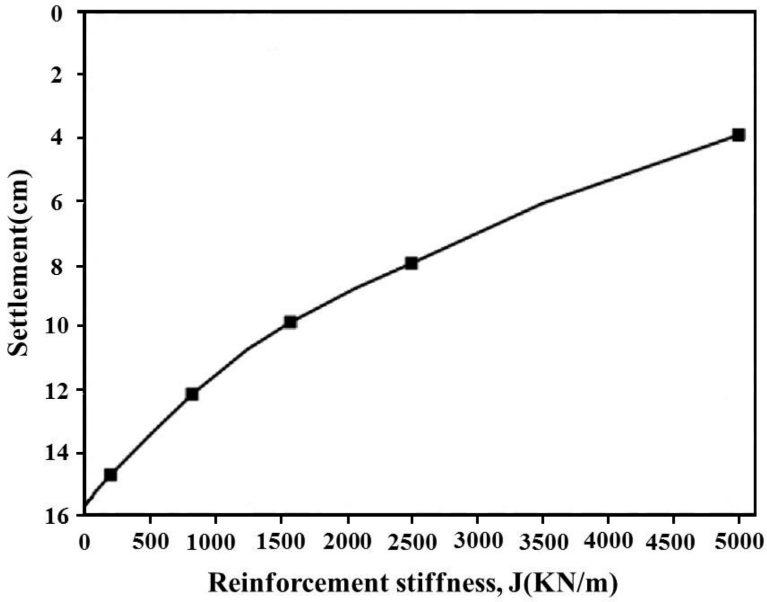


Fig. 4 - Settlement of soft soil under embankment reinforced with geosynthetics having different stiffness values

4. Conclusion

This paper presents numerical analyses of the reinforced and encased stone pile supported embankments built on soft soil. The effectiveness of basal reinforcement in embankment is investigated. The following consequences can be pointed out:

- Settlement is reduced by using a geosynthetic layer at the base of the embankment as a base reinforcement. The ratio between the settlements of the reinforced and unreinforced embankments is determined to be 0.3.
- The stiffness of the reinforcement does not have a considerable effect on the settlement behavior of geosynthetic-encased stone pile-supported.
- The stress-settling behavior of stone piles can be significantly improved by encasing them.
- Increasing the friction angle of stone pile infill led to an improvement in the bearing capacity of geosynthetic-encased stone pile-supported. This reinforcement is more pronounced with larger mandatory settlements.
- The deformation of the geotextile-covered pile was mainly concentrated at the top of the pile. The geotextile provided some confinement to the pile and reduced the pile's bulge deflection.

- The geotextile was effective in reducing the settlement of the foundation with the single pile, and the effect of reducing settlement became more pronounced as the stiffness of the geotextile increased.
- The effects of soil arching, stiffness of the stone pile included in the analysis. It has been observed that the use of reinforcement reduces the settlement of soft soil. For smaller distances between stone piles, the use of geosynthetic reinforcement is more advantageous. The settlement of the soft soil increases with increasing depth of the soft soil or height of the embankment. However, as the modulus ratio or stiffness of the geosynthetic layer increases, the soft soil settlement decreases.
- The geosynthetic exhibits greater efficacy when the soft soil exhibits high compressibility, as the axial force in the geosynthetic increases with the increase in the settlement of soft ground. The settlement exhibits a decrease with the increase in the soft ground elastic modulus and geosynthetic tensile stiffness, while the increase in embankment fill height and soft soil depth is consistent with the anticipated trend. Due to the reaction of soft ground to geosynthetic tensile stiffness, the full load carried by the piles decreases with increasing soft ground depth and geosynthetic tensile stiffness and increases with increasing embankment height and soft ground elastic modulus.

References

[1] Abu-Farsakh M, Chen Q, Sharma R (2013). An experimental evaluation of the behavior of footings on geosynthetic-reinforced sand. Soils and Foundations, 53 (2), 335–348. https://doi.org/10.1016/j.sandf.2013.01.001

[2] Barksdale, R. D., and Bachus, R. C. (1983). Design and construction of stone columns. Rep. No. FHWA/RD-83/026, Office of Engineering and Highway Operations Research and Development, Federal Highway Administration, Washington, D.C.

[3] Cowland, J.W., Wong, S.C.K., (1993). Performance of a road embankment on soft clay supported on a geocell cushion foundation. Geotextiles and Geomembranes, 12, 687–705.https://doi.org/10.1016/0266-1144(93)90046-Q

[4] Ramazan Borujerdi, A., and Jiryaei Sharahi, M. (2018). Seismic Bearing Capacity of Strip Footings Adjacent to Slopes Using Pseudo Dynamic Approach (Summary of MSc Thesis). Master of Science Thesis, Qom University of Technology. http://dx.doi.org/10.13140/RG.2.2.30142.15686.

[5] Ramazan Borujerdi, A., and Jiryaei Sharahi, M. (2021). Seismic Bearing Capacity of Strip Footings Adjacent to Slopes Using Pseudo Dynamic Approach. Journal of Mathematics and Computational Sciences, 2(1), pp. 17–41. https://dx.doi.org/10.30511/mcs.2021.137964.1009.

[6] Ramazan Borujerdi, A., Jiryaei Sarahi, M. And Amelsakhi, M. (2019). Seismic displacement of Cohesive-friction slopes using Newmark method. Proceedings of the 8th International Conference on Seismology and Earthquake Engineering (SEE8), International Institute of Earthquake Engineering and Seismology (IIEES), Tehran,Iran.

[7] Ramazan Borujerdi, A. (2023). Site Characterization of Alluvial Silty Sand Soils by Dynamic In-Situ and Laboratory Tests. International Journal of Sustainable Construction Engineering and Technology, 14(1), 260–269. https://doi.org/10.30880/ijscet.2023.14.01.023

[8] Ramazan Borujerdi, A. (2022). Numerical and Experimental Analysis of Seismic Soil Pile Structure Interaction. Emerging Advances in Integrated Technology, 3(2), 1–10. https://doi.org/10.30880/emait.2022.03.02.001

[9] Ramazan Borujerdi, A. (2023). Analysis of site liquefaction and lateral spreading based on in-situ Tests. International Journal of Sustainable Construction Engineering and Technology.

[10] Ramazan Borujerdi, A. (2023). Evaluation of a Mechanistic Model for Sub-Grade Material Performance under Cyclic Loading. The International Journal of Integrated Engineering.

[11] Dash, S.K., Krishnaswamy, N.R., Rajagopal, K., (2001). Bearing capacity of stone piless supported on geocell-reinforced sand. Geotextiles and Geomembranes, 19, 235–256. https://doi.org/10.1016/S0266-1144(01)00006-1

[12] Dash, S.K., Rajagopal, K., Krishnaswamy, N.R., (2007). Behavior of geocell reinforced sand beds under strip loading. Canadian Geotechnical Journal, 44, 905–916. http://dx.doi.org/10.1139/T07-035

[13] Gabr, M.A., Doson, R., Collin, J.G., (1998). A study of stress distribution in geogrid-reinforced sand. In: Proceeding of Geosynthetics in Foundation Reinforcement and Erosion Control Systems (GSP 76), ASCE, October 1998, Massachusetts, America, pp. 62–76.

[14] Krishnaswamy, N.R., Rajagopal, K., Madhavi, L.G., (2000). Model studies on geocell supported embankments constructed over soft clay foundation. Geotechnical Testing Journal, 23, 45–54. ASTM.

[15] Latha, G.M., Rajagopal, K., Krishnaswamy, N.R., (2006). Experimental and theoretical investigations on geocell-supported embankments. International Journal of Geomechanics, ASCE, 6 (1), 30–35. http://dx.doi.org/10.1061/(ASCE)1532-3641(2006)6:1(30).

[16] PLAXIS 2D, 3D (2023). Reference manual. PLAXIS B.V.

[17] Rowe, R.K., Taechakumthorn, C., (2008). Combined effect of PVDs and reinforcement on embankments over rate-sensitive soils. Geotextiles and Geomembranes, 26 (3), 239–249. http://dx.doi.org/10.1016/j.geotexmem.2007.10.001

[18] Zhou, H.B., Wen, X.J., (2008). Model studies on geogrid or geocell-reinforced sand mattress on soft soil. Geotextile and Geomembranes 26, 231–238. http://dx.doi.org/10.1016/j.geotexmem.2007.10.002

[19] Braja, M.D., (2008). Advanced Soil Mechanics, third ed. Taylor & Francis, New York. BS8006. British standard: code of practice for strengthened/reinforced soils and other fills.

[20] Koerner, R.M., (1998). Designing with Geosynthetics. Prentice Hall, New Jersey.

[21] Lambe, T.W., Whitman, R.V., (1969). Soil Mechanics. John Wiley & Sons, New York.

[22] Latha, G.M., Murthy, V.S., (2007). Effects of reinforcement from on the behavior of geosynthetic reinforced sand. Geotextiles and Geomembranes, 25, 23–32. https://doi.org/10.1016/j.geotexmem.2006.09.002

[23] Rajagopal, K., Krishnaswamy, N.R., Latha, Madhavi, (1999). Behavior of sand confined with single and multiple geocells. Geotextiles and Geomembranes, 17 (3), 171–184. https://doi.org/10.1016/S0266-1144(98)00034-X

[24] Li, A.L., Rowe, R.K., (2008). Effects of viscous behaviour of geosynthetic reinforcement and foundation soils on embankment performance. Geotextiles and Geomembranes, 26 (4), 317–334. https://doi.org/10.1016/j.geotexmem.2007.12.002

[25] Ramazan Borujerdi, A., Jiryaei Sharahi, M, (2018). Pseudo-dynamic bearing capacity factor for strip footings considering Coulomb failure mechanism. The 4th International Conference on Structural Engineering, Tehran, Iran, ISSE. https://4th.irastconf.com/article_3821.html.

[26] Izadifar, M., Luo, N., Abu-Farsakh, M., Chen, S, (2023). Performance Evaluation of Design Methods for Geosynthetic-Reinforced Pile-Supported Embankments. Transportation Research Record: Journal of the Transportation Research Board, 1–18. https://doi.org/10.1177/03611981231165994

[27] Ikbarieh, A., Izadifar, M., Abu-Farsakh, M., Voyiadjis, G, (2022). A Parametric Study of Embankment Supported by Geosynthetic Reinforced Load Transfer Platform and Timber Piles Tip on Sand. Transportation Geotechnics. 38(4). https://doi.org/10.1016/j.trgeo.2022.100901

[28] Farhangi, V., Zadehmohamad, M., Monshizadegan, A., Izadifar, M., Moradi, M., Dabiri, H, (2023). Effects of Geogrid Reinforcement on the Backfill of Integral Bridge Abutments. 13(4), 1–17. https://doi.org/10.3390/buildings13040853