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Evaluation of the accuracy of three design methods for reinforced piled embankments

Juan Felix Rodriguez Rebolledo, Ennio Marques Palmeira, Gregório Luís Silva Araújo*, Juliana Araujo da Cunha and José Melchior Filho

Department of Civil and Environmental Engineering, University of Brasilia, Brasília, Brazil

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EDITED BY
Mario Riccio,
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REVIEWED BY
Bruno Lima,
Rio de Janeiro State Federal University, Brazil

*CORRESPONDENCE
Gregório Luís Silva Araújo,
gregorio@unb.br

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The construction of road and railway embankments adheres to strict specifications, particularly regarding stability and limited settlements. Consequently, their foundations must be designed to ensure satisfactory stress redistribution, preserving the integrity of the structure to prevent failures and large deformations. In this context, both physical and numerical models can provide a detailed evaluation of soil response and load transfer. This study compares the predictions from two-dimensional Finite Element Method (FEM) numerical analysis with those from a large scale instrumented physical model. The instrumentation included load cells at the head of one of the piles and total stress cells at various depths. After validating the results, analyses were conducted to compare predictions from different standard design methods. The vertical stress applied to the pile caps, total stresses, and efficiencies predicted by each model were examined. The results indicated that the method which best predicted both the stress at the pile cap and the model's efficiency was the concentric arches.

KEYWORDS

reinforced piled embankments, geosynthetics, laboratory tests, numerical analysis, instrumentation

1 Introduction

Geosynthetic reinforced embankments on concrete piles have been utilized worldwide as an effective stabilization technique. Essentially, the reinforcement increases the stability of the embankment, while its stiffness enhances soil arching and favors the transfer of the majority of the embankment load to the piles. The piles then transfer the received load to a stiffer soil, thereby avoiding excessive differential settlements and potential embankment failure. To optimize pile foundation design, a cap is installed at the top of each pile, and the efficacy of stress transfer depends on the distance between pile caps (d) and the height of the embankment (H), among other factors.

Several investigations have evaluated the behavior of this type of construction through numerical analyses (Hosseinpour et al., 2015; Kadhima et al., 2018; Nguyen et al., 2023; Wang et al., 2023; Liu et al., 2024; Riccio et al., 2024; Agarwal et al., 2025) and laboratory experiments (Girout et al., 2016; Pham et al., 2018; Fonseca and Palmeira, 2019; Palmeira et al., 2022; Rui et al., 2024; Guo et al., 2023; Chen et al., 2024; Liu et al., 2025). However, further investigation is needed to understand how stress distribution occurs throughout the soil mass, as different approaches consider the design based on distinct assumptions.

This investigation aims to compare the accuracy of three design methods for piled embankments: the British Standard (BSI BS 8006, 2010), EBGEO (2011), and the Concentric Arches method (Van Eekelen et al., 2013), based on Finite Element Analysis and a series of laboratory instrumented tests. The results indicate that the accuracy of the design method depends on the analyzed parameter.

2 Design methods and standards for piled embankments

Various design approaches and standards for geosynthetic reinforced piled embankments are available (Filz and Smith, 2006; BSI BS 8006, 2010; EBGEO, 2011; van Eekelen, 2015; van Eekelen et al., 2011; 2015; Zhuang et al., 2014; CUR 226, 2016; Fonseca and Palmeira, 2019; among others). The most commonly used standards or guidelines for the routine design and construction of geosynthetic reinforced piled embankments are BSI BS 8006 (2010) and EBGEO (2011). Recently, CUR 226 (2016) has also gained increasing acceptance for the design of such structures.

Different soil arching theories are employed by various authors and standards, including those proposed by Terzaghi (1943), Hewlett and Randolph (1988), van Eekelen (2015), and Heitz (2006). These theories, along with the methods used to calculate mobilized tensile loads in the geosynthetic reinforcement, can lead to significant differences in the prediction of displacement, stresses, reinforcement tensile loads, and vertical loads transferred to the piles. Fonseca and Palmeira (2019) compared predictions from different design approaches with results from large-scale laboratory tests on reinforced piled embankments. The accuracy of a given method depended on the parameter considered (displacement or force). In terms of pile efficacy predictions, the best results came from the method utilizing the concentric arches concept (van Eekelen et al., 2015), followed by EBGEO (2011), BSI BS 8006 (2010) (employing the Hewlett and Randolph (1988) arching theory), and Zhuang et al. (2014). For fill settlements, the BSI BS 8006 (2010) method, modified by van Eekelen et al. (2011), the concentric arches method (van Eekelen, 2015), and Zhuang et al. (2014) showed the best accuracy. Regarding reinforcement tensile strains, the most accurate predictions were those from van Eekelen (2015) and BSI BS 8006 (2010) [modified by van Eekelen et al. (2011)]. The deviations in predictions of relevant parameters across different methods underscore the need for further research and the importance of sound engineering judgment when designing reinforced piled embankments using analytical methods. Consequently, the use of more sophisticated design tools, such as finite element and finite difference methods, is highly recommended for important engineering projects.

Careful construction practices must also be implemented to minimize issues related to improper fill behavior and reinforcement damage. Standards such as BSI BS 8006 (2010), EBGEO (2011), and CUR 226 (2016) provide recommendations to mitigate or avoid construction-related problems. A critical aspect is the potential for mechanical damage to the reinforcement due to poor construction practices and improper placement of the reinforcement layer, as illustrated in Figure 1 (Palmeira et al., 2022). In this case, direct contact with the pile cap the geogrid may tear? along the perimeter of the cap, leading to significant settlements at the embankment surface. In this regard, EBGEO (2011) recommends maintaining minimum elevations of the reinforcements above the pile cap to prevent or minimize such issues.

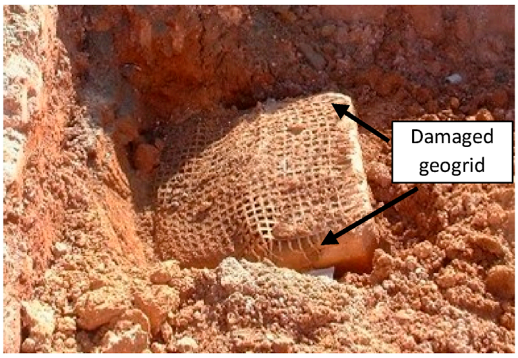

FIGURE 1
Geogrid reinforcement damage caused by direct contact with the pile cap (Palmeira et al., 2022).

3 Laboratory tests and numerical analysis

In the present study, laboratory tests were conducted at a scale of 1:5 to simulate a reinforced piled embankment under axisymmetric conditions (Figures 2A,B) in a controlled environment (Melchior Filho, 2022). The filling material consisted of a 0.45 m gravel layer over square caps measuring 0.2 m on each side, spaced 0.5 m apart (center to center). The instrumentation included: (i) five total pressure cells placed at various locations in the soil mass, (ii) a load cell positioned over the central pile, and (iii) four displacement transducers (Figure 2C).

To better understand the stress distribution, numerical analyses were also performed alongside the laboratory tests, utilizing the geometry depicted in Figure 2D under axisymmetric conditions. These analyses were conducted using PLAXIS 2D Finite Element software (Brinkgreve and Vermeer, 2012). The medium was discretized using a mesh composed of 815 triangular elements, formed by 15 nodes and 12 stress points (Gauss integration points), each. In the soil-geogrid-pile contact, interface elements were incorporated, consisting of 5 pairs of nodes and 5 stress points. The soil behavior was modeled using the hardening soil model (Schanz et al., 1999), while the geosynthetic was represented by a geogrid-type element, consisting of 5 nodes and 5 stress points. This type of element only allows for the development of tension forces. Although the pile caps had a square cross-section, they were modeled as circular shapes using the equivalent area concept, as suggested by Han and Gabr (2002). The gravel properties were obtained from large direct shear tests, and the properly scaled tensile strength and stiffness of the geosynthetics were obtained through wide strip tensile tests (ASTM D6637, 2015), as summarized in Table 1.

The embankment construction was simulated in three phases, each consisting of lifts of 0.15 m in height, followed by three

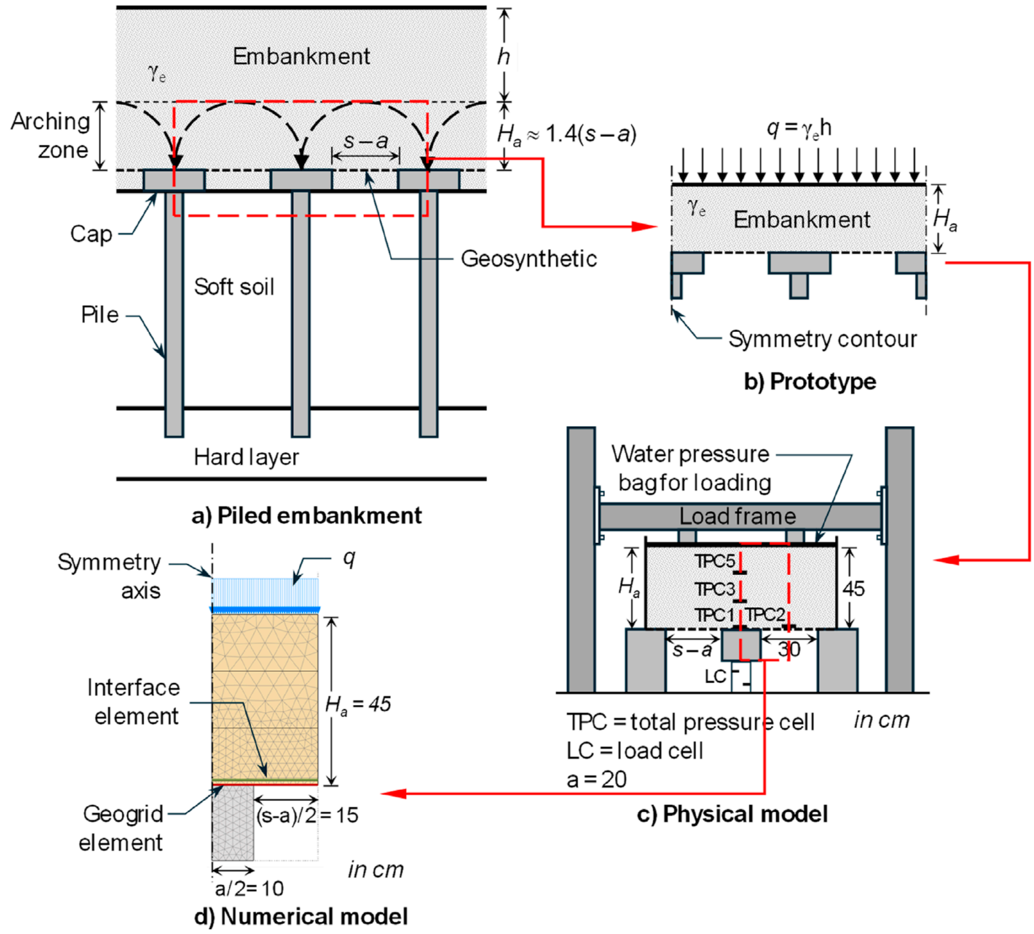

FIGURE 2
(a) Piled embankment, **(b)** Prototype, **(c)** Physical model and **(d)** Numerical model.

surcharge applications of 10 kPa (phase 4), 25 kPa (phase 5), and 40 kPa (phase 6). For boundary conditions, the bottom of the geometry was fixed, while the vertical boundaries were allowed to move freely in that direction. Preliminary analyses were conducted to determine the maximum horizontal distance necessary to avoid boundary influences. Additionally, a mesh refinement analysis was performed (Cunha, 2025).

4 Results

Results were obtained from the physical model, including the variation of total pressure at different points within the embankment, measured by total pressure cells (TPC, Figure 1C), as well as the load applied at the central pile head (LC). Simultaneously, the numerical model calculated total pressures at integration points located at the same positions as those of the TPCs in the physical model, enabling a direct comparison between predicted and measured values.

Figures 3a,b present graphs showing the variation of vertical stress (σ) recorded at TPC-1 and TPC-2 cells, respectively, as a function of the dimensionless ratio between the embankment thickness (H) and the distance between caps (s-a). These results are shown for both models: physical (PM) and numerical (NM). The first graph (Figure 3a) represents the vertical stress acting on the pile cap, while the second (Figure 3B) corresponds to the vertical stress on the geogrid reinforcement. A vertical stress of up to 350 kPa on the pile cap for an $H/(s\text{-}a)$ ratio of 10 was observed (Figure 3a). In contrast, the vertical stress on the geogrid is significantly lower, with maximum values around 12 kPa (Figure 3b), showing the effect of soil arching. Moreover, the numerical model accurately reproduces the behavior observed at TPC-1, showing only minor discrepancies for $H/(s\text{-}a)$ values above 6. On the other hand, regarding the geogrid, although the numerical model results follow the same general trend as the physical model, notable differences in stress magnitudes exist. This discrepancy is attributed to limitations of the numerical model in simulating embankment soil arching and soil-reinforcement interaction and/or limitations of the total stress cell.

It is clearly observed that most of the embankment load is transferred directly to the pile head, with a system efficacy (E, defined as the ratio between the pile load and the embankment load on the pile tributary area) greater than 90% (Figure 3c). All the analyzed methods (British, German and Dutch methods) investigated in the present study showed similar predictions, with

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TABLE 1 Embankment and reinforcement properties for numerical analysis.

Soil properties (gravel)				
Strength	Dry specific unit weight	γ_d	kN/m^3	16.0
	Cohesion	c	kPa	0.1
	Friction angle	ϕ	°	43
	Dilatancy angle	ψ	°	10
Stiffness	Secant stiffness in standard drained triaxial test	E_{50}^{ref}	MPa	10.0
	Secant stiffness for primary oedometer loading	E_{eod}^{ref}	MPa	8.0
	Unloaging/reloading stiffness from drained triaxial test	E_{ur}^{ref}	MPa	30.0
	Power of stress-level dependency of stiffness	m	-	0.5
Advanced	Poisson's ratio for loading/unloading	ν_{ur}	-	0.2
	Reference stress for stiffness	p'_{ref}	kPa	100
	K0 value for normal consolidation	K_0^{nc}	-	0.32
	Failure ratio, q_f/q_a	R_f	-	0.9
Geosynthetic properties				
	Stiffness at 5% strain	$J_{5\%}$	kN/m	80

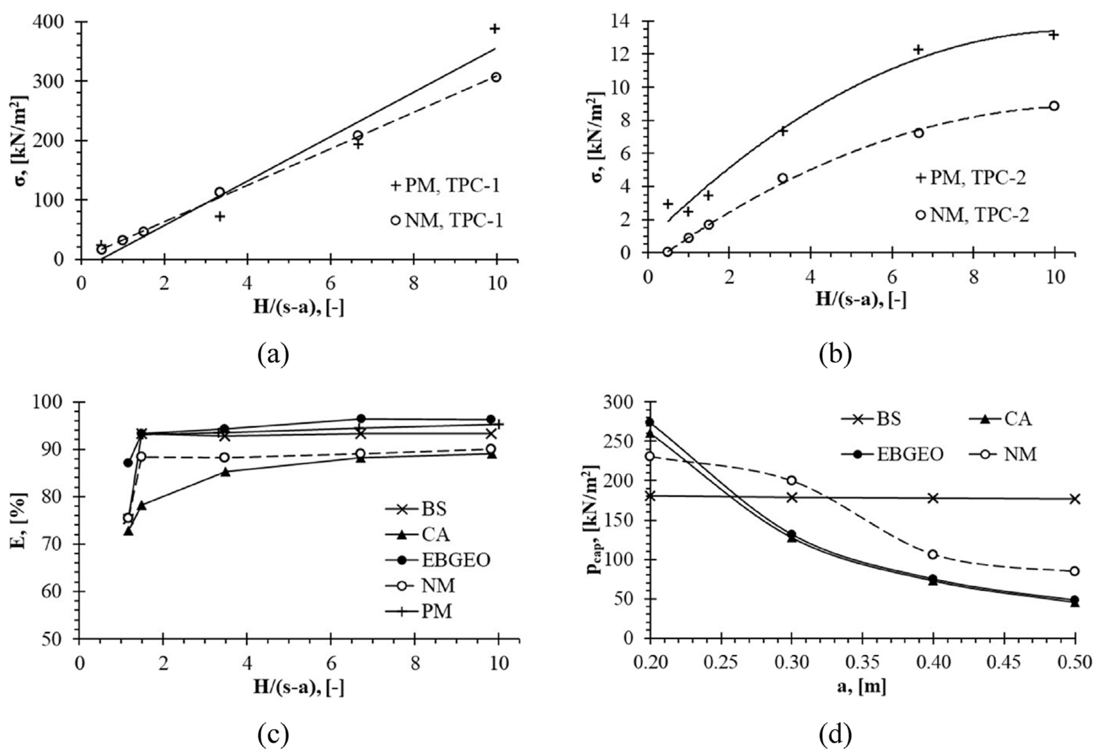

FIGURE 3
Obtained results: **(a)** σ recorded at TPC-1 *versus* $H/(s\text{-}a)$, **(b)** σ recorded at TPC-2 *versus* $H/(s\text{-}a)$, **(c)** *Efficacy (E) versus* $H/(s\text{-}a)$ and **(d)** p_{cap} *versus* a.

E values ranging between 85% and 95% for $H/(s\text{-}a)$ ratios greater than 2. For values below 2, the arching phenomenon is not fully developed, which explains the differences among predictions by the methods, as each is based on distinct hypotheses and simplifications. The Dutch method (based on the concentric arches theory) compared best with the results from the numerical model.

With the successful validation of vertical stress magnitude at the pile cap in the numerical model, parametric analyses were conducted to evaluate the vertical stress on the pile cap (p_{cap}) for different cap diameters (a). These results were compared with predictions from the British (BS), German (EBGEO), and Dutch (CA) methods, and the results are presented in Figure 3d. Satisfactory agreement is observed both in trend and magnitude between the numerical model and the Dutch and German methods for values of a of 0.2 m and greater than 0.4 m. Larger deviations between predictions can be observed for the British method (BS), which maintained a practically constant p_{cap} value regardless of the cap size.

5 Conclusion

In this paper, the predictions from three design methods for piled embankments were compared to results from laboratory and finite element analysis. Based on the results obtained, the following conclusions can be drawn:

- $H/(s\text{-}a)$ ratios directly influence the arching effect and the stress on the reinforcement, as well as the agreement between predicted and measured values. Additionally, larger discrepancies between predictions and measurements were observed for the vertical stresses on the reinforcement layer.
- Regarding the stress on the pile cap, the numerical model predictions compared well with laboratory results and, in general, satisfactorily with the Dutch and German methods. In contrast, the British Standard (BS) method showed values that remained practically constant regardless of pile geometry.
- System efficacy was consistently high for embankment thickness-to-pile spacing ratios above 2, emphasizing the importance of the arching effect in load distribution.
- The validation of design methods under laboratory and numerical conditions highlights the importance of considering the interaction between system components in real-world projects, suggesting that future investigations should explore the influence of different soil types and environmental conditions on the performance of reinforced piled embankments.

Author contributions

JR: Methodology, Writing – original draft, Writing – review and editing. EP: Formal Analysis, Methodology, Validation, Writing – review and editing. GA: Formal Analysis, Validation, Writing – review and editing. JC: Methodology, Writing – review and editing. JF: Data curation, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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