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Physical Modelling in Geotechnics

Development of a test setup for piled embankment modelling

P. Gunnvard, Q. Jia, J. Laue & H. Mattsson
Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden

ABSTRACT: This paper outlines the design and development of a trapdoor test setup used to simulate the effect of a geosynthetic reinforcement on the load distribution in a timber piled embankment. Geosynthetic-reinforced pile-supported embankment (GRPSE) is a common foundation method for both roads and railways on soft subsoil. Timber piling allows for a solution with lower carbon footprint than concrete or steel piling. The removal of concrete pile caps further reduces the footprint but increases the requirements of the geosynthetic reinforcement. The purpose of the trapdoor test setup is to find the best suited number, placement, stiffness, and strength of the layers of geosynthetic reinforcement for different embankment heights and pile spacings. The tested embankment model consists of a vertical cross section of the embankment between two adjacent piles, assuming plane strain. The test is performed under Earth's gravity. A hydraulically controlled trapdoor mechanism in between the two pile heads acts as the deformed subsoil. The trapdoor is composed of several segments to model a non-horizontal top surface of the displaced subsoil. Displacements are captured using optical measurement techniques to confirm and study the arch formation. The arching efficacy is quantified by pressure cells on each of the two pile heads. Though the primary application is timber piled embankments, the test results can be extrapolated to GRPSE designs in general.

Keywords: physical modelling, piled embankment, geosynthetic reinforcement, arching, timber piles.

1 INTRODUCTION

This paper describes part of a study with the aim of optimising the use of geosynthetic reinforcement (GR) in the method of geosynthetic reinforced pile-supported embankments (GRPSE) with timber piles, referred to here as light embankment piling (Gunnvard et al., 2022b). GRPSE is an effective foundation method, which utilises arching effect (Terzaghi, 1943) and membrane effect (Villard et al. 2000) to transfer the embankment weight and traffic load onto the piles instead of the soft subsoil. Light embankment piling is a low-cost alternative to GRPSE with steel or concrete piles, as the material and transport cost of timber often is far less. More importantly, the use of timber piles results in a reduced carbon footprint in comparison to concrete or steel piling. Although timber piles are widely used for infrastructure in the United States, Canada, Australia, and the Netherlands, Sweden is the only country with an explicit standard or recommendation for GRPSE with untreated timber piles. Untreated timber is cheaper and can last almost indefinitely if kept in anaerobe conditions.

In accordance with Swedish standards TRVINFRA (STA, 2022), pile caps are excluded in lightly piled embankments. Thus, the pile coverage ratio is very low, which could lead to punching failure and unwanted settlements. To counter this, the embankment base is reinforced with two layers of GR (usually geogrids) and the centre-to-centre pile spacing (s) is limited to $0.8 \leq s \leq 1.2$ m. See Fig. 1 for a cross section.

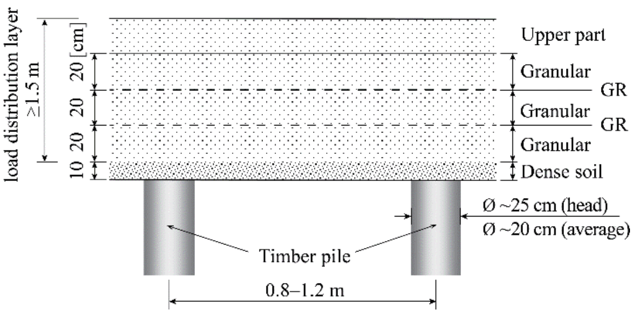

Fig. 1. The design criteria by TRVINFRA (STA, 2022) for geosynthetic-reinforced timber pile-supported embankments (lightly piled embankments).

The two common tree types used for piling in Sweden are Norway Spruce (*picea abies*) and Baltic pine (*pinus sylvetris*). The granular material is crushed rock, 0-90 mm in fraction size. A layer of dense fine-grained soil with high capillarity is added on top of the pile heads to keep the soil around the timber piles fully capillary saturated, as the timber will otherwise rot over time.

The narrow allowable pile spacing results in a lot of timber piles. The results of the study Gunnvard et al. (2022b) shows a potential of increasing the upper limit of s to 1.4 m. Additionally, from the field test results in Gunnvard et al. (2022a) it can be concluded that the GR layers are subjected to small strains (<1%).

The thicknesses of the granular and dense fine-grained soils are the minimum possible from a practical point of view, but the resulting height of the arch above the top GR is potentially less than half the arch height if $s \leq$ 1.2 m. Satibi (2009) showed using numerical modelling that the GR layers need to be placed within the lower half of the arch height to efficiently reduce subsoil settlements. Thus, it needs in this study to be evaluated whether increasing s or adjusting the placement and stiffness of the two GR layers (Fig. 1) is the most resource efficient alternative for lightly piled embankments. Other options are to adopt a single GR layer, or exclude GR entirely to yield a more resource efficient (and sustainable) design. Physical and numerical modelling will be performed to help optimise the use of the GR. The analyses also include finding a minimum embankment height for a given s and testing the hypothesis by Gunnvard et al. (2022a) of increasing the upper limit in TRVINFRA of the s above 1.2 m, decreasing the number of timber piles needed in the design. Though the aim focuses on timber piling, the results will be general to GRPSE design.

2 TEST SETUP

2.1 Physical modelling

A physical experiment is being developed at Luleå University of Technology to study the load distribution between two adjacent piles while simulating the cross section of an embankment and load transfer platform. The tests will be performed under Earth's gravity (1g). As shown in Fig. 2, the test setup corresponds to a section of the pile-supported embankment between two adjacent piles. For practical reasons, the modelled road section will be in half-scale, i.e. all dimensions and grain sizes of a regular road embankment will be reduced to 50%. The presented test setup shall be reconstructible for later physical modelling in full-scale.

The test setup approximates a 2D plane-strain case. Plane-strain is chosen to enable ocular observation of the arch formation and development of voids below the GRs (or the dense fine-grained soil). A depth of at least 200 mm is set to mitigate arching in the out-of-plane direction. The traffic load, reduced by 50%, will be added as a surcharge load by a hydraulic cylinder from the top.

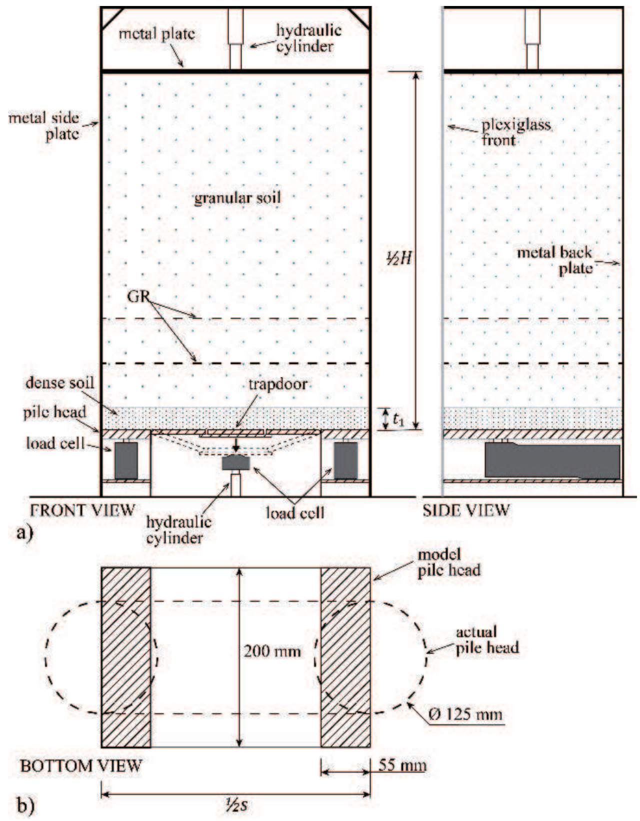

Fig. 2. Sketch of the test setup showing (a) front view as seen through the plexiglass window and cross-sectional side view, as well as (b) bottom view of the setup in respect to the actual piles.

2.2 Model piles

The width of the test setup will be equal to $½s$ for half-scale conditions. Only the upper-most part of the two piles is to be included as boxes on either side in the base of the setup. Each box shall be made from steel for overall durability and to exclude the stiffness of the timber. To approximate plane-strain conditions, the circular pile heads are modelled as rectangular pile heads, as shown in Fig. 2b. The total in-plane width of the two pile heads is equal to the side length of a square with the same cross-sectional area as a circular pile head. In full-scale, the total in-plane width a is defined as

$$a = \sqrt{\frac{1}{4}(d^2\pi)} \tag{1}$$

where d is the pile head diameter. Since the presented test setup is at half-scale, the total in-plane width of the two pile heads is equal to $½a$. The average timber pile head diameter is about 25 cm (Fig. 1). Thus, the width of each modelled pile head ($¼a$) is 55 mm (Fig. 2b).

2.3 Model soil

The main embankment material will consist of granular unsaturated soil, fraction size 0–45 mm, i.e. half-scale of the 0–90 mm crushed fill material used in practice. The dense soil on top of the trapdoor and pile heads will be a silty sand. Compaction will be performed with the test setup lying horizontally, back plate facing down, to avoid scratching the front plexiglass. The soil density is increased to compensate for a lowered dilatancy in half scale in comparison to full scale.

Settlement of the subsoil in between the piles is implemented with a trapdoor, a common tool in centrifuge modelling of GRPSE (Rui et al., 2016; da Silva Burke and Elshafie, 2021; Rui et al., 2022). The trapdoor will be divided into segments, as shown in Fig. 2, to approximate the non-uniform subsoil displacement that develops between the piles. To further approach natural subsoil behaviour, the trapdoor system can be replaced with a cushion filled with water, where the subsoil settlements are controlled via drainage during the test through a tap. Van Eekelen (2012) successfully used a water-filled foam-cushion system to approximate the natural subsoil surface shape.

2.4 Monitoring

Soil and GR displacements will be monitored using Particle Image Velocimetry (PIV), captured through sheets of plexiglass on the front of the test setup, drawing inspiration from the trapdoor geotechnical centrifuge tests by da Silva Burke and Elshafie (2021) and Rui et al. (2016). This enables formation of arches to be observed in real time while simultaneously measuring load distribution and deformations. Trapdoor displacement (subsoil settlement) and settlements at the top of the modelled embankment is going to be monitored by linear variable differential transformers (LVDTs). The GR strain will be measured by PIV analysis or fibre optics (Briançon and Simon, 2012).

Load cells will be placed in the two piles and under the trapdoor to measure the total load on the two pile heads (Q_{head}) and the load on the trapdoor (W_{sub}). The load distribution is evaluated based on pile efficacy E and soil arching ratio ρ, defined as (Van Eekelen and Han, 2020):

$$E = \frac{Q_{head}}{\sigma'_{v0} \cdot s^2} \tag{2}$$

$$\rho = \frac{W_{sub}}{\sigma'_{v0} \cdot s^2} \tag{3}$$

where σ'_{v0} is the initial effective vertical stress. σ'_{v0} is determined from Q_{head} and W_{sub} at the start of the test. Rui et al. (2016) and King (2017) observed maximum values of E and ρ for small subsoil settlements and a residual or decreasing arching effect for larger subsoil settlements.

3 MODELLING

3.1 Cases to be modelled

Three cases are to be modelled, shown in Fig. 3. For Case 1, the geometry is based on the current design criteria in TRVINFRA (Fig. 1) with two uniaxial geogrids (stronger in the machine direction). Following practice, the top geogrid will be placed with its machine direction perpendicular to the machine direction of the bottom geogrid. For Case 2, one biaxial geogrid is placed at the base of the modelled embankment. An unreinforced embankment is to be modelled as Case 3.

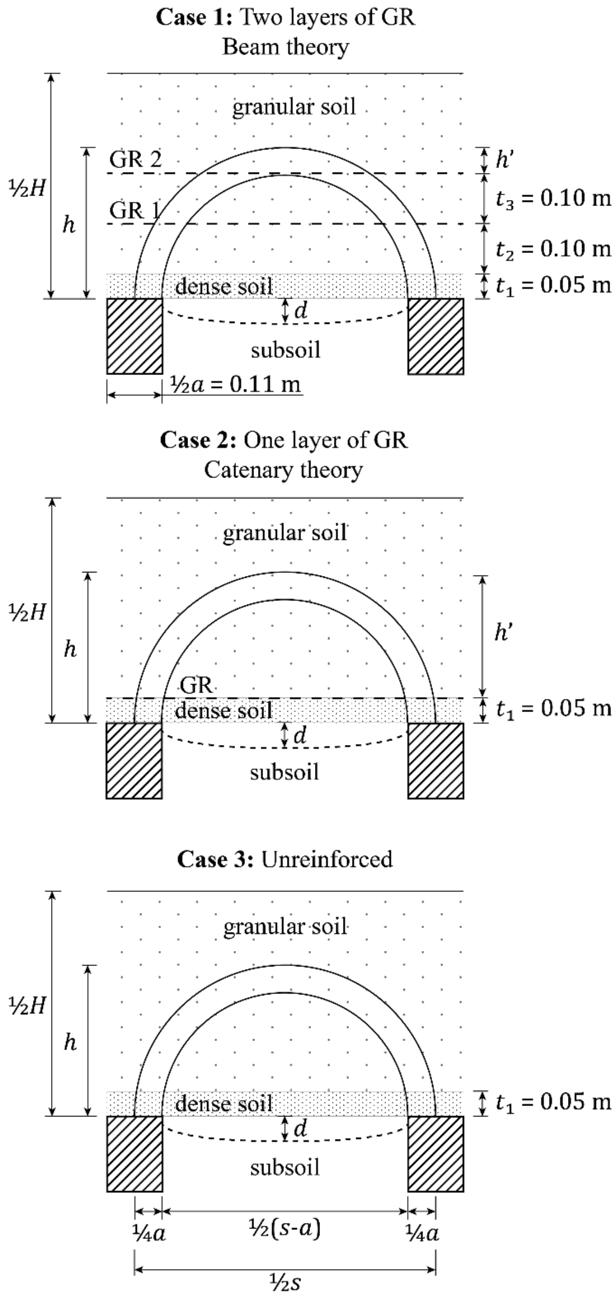

Fig. 3. Illustration of a semi-circular arch formation between two piles for three different cases of GR placement.

Several studies like Rui et al. (2016) and Rui et al. (2022) have proposed recommended values for the ratio $H/(s-a)$ to allow optimal arch formation, primarily for cases like Case 2 and 3. As illustrated in Fig. 3, the conditions for an optimal value of $H/(s-a)$ are different for Case 1–3. The hypothesis in this study is that for a range of H and s, there exists values of $H/(s-a)$ for which one of the cases is preferrable to the other two in terms of arch formation and resource efficiency.

3.2 Calibration

The data used for calibration of the physical model is from a monitoring project of lightly piled road embankment in northern Sweden, near Luleå. The road was reconstructed due to settlements above the serviceability limit. For the reconstructed piled embankment, $H = 1.8$ m and $s = 1.1$ m. The load distribution layer was designed according to the criteria shown in Fig. 1. More project details and results of the first year of monitoring is presented in Gunnvard et al. (2022b). For calibration, H and s will be set to match the field test conditions, i.e. Case 1 in Fig. 3 with ½H = 0.90 m and ½s = 0.55 m. E and ρ were in the range of 0.29–0.48 and 0.31–0.48, respectively. The GR strain was $\leq$0.03%. Settlement measurements in field suggested maximum 2–4 cm of subsoil settlement relative to the pile heads.

A parametric study using a finite element model of the lightly piled road embankment is being conducted ahead of the physical modelling to estimate the test results and the impact of reduced scale.

4 OUTLOOK

The analyses of the physical modelling and complementary numerical modelling will potentially allow for a revision of the design criteria in TRVINFRA for lightly piled embankments. Values for the ratio $H/(s-a)$ are to be recommended for different GR placement and stiffness, to allow for more flexible design than previously with TRVINFRA. The analysis should improve timber piling as an environmental and cost-efficient alternative for GRPSE design. However, the results of the physical modelling are applicable for GRPSE design in general.

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