Numerical Analysis of the Mechanical Behaviour of Light Embankment Piling

Analyse numérique du comportement mécanique des remblais sur pieux

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ABSTRACT: 2D and 3D Finite element simulations were performed to investigate the mechanical behaviour of the light embankment piling method as a pre-study to further develop a new Swedish design guideline. The light embankment piling method is used for sulphide soils and utilises timber piles as its key feature. The Swedish Transport Administration (Trafikverket) recently changed the national standard of the light embankment piling method from the use of a square to a triangular pile arrangement, based on a theory that a triangular arrangement creates more stable arches in between the piles. The objective with the present study is to evaluate the current standard by modelling setups with square and triangular pile arrangements with varying centre-to-centre distance. Both, completely floating and semi-floating pile groups were modelled here. The evaluation mainly focused on comparing embankment settlements as well as axial forces in the piles. No evident difference in the mechanical behaviour between the triangular and the square piling pattern was found. The maximum allowed centre-to-centre distance can potentially be increased from 1.2 to 1.5m; resulting in approximately 30% fewer piles used.

RESUMÉ: Des simulations 2D et 3D aux éléments finis ont été réalisées pour étudier le comportement mécanique des fondations sur pieux pour remblais routiers ou ferroviaires, en vue d'améliorer les recommandations suédoises de dimensionnement. La méthode est employée dans les sols sulphidiques et consiste à utiliser des pieux en bois. L'administration suédoise des transports a récemment changé la norme concernant cette méthode de fondation en passant d'un agencement en carré à un agencement en triangle des pieux. Cette modification est basée sur l'hypothèse qu'un agencement en triangle génère des arches plus stables entre les pieux. L'objectif de cette étude est d'évaluer la norme actuelle en modélisant des cas d'agencement en triangles et en carrés tout en variant l'espacement des pieux. Les cas de pieux flottants et travaillants en pointe ont été modélisés. Les différents cas étaient principalement comparés en termes de tassements et de forces axiales dans les pieux. L'étude n'a pas mis en évidence de différences évidentes de comportement mécanique entre les agencements en carrés et en triangles des pieux. La distance maximum autorisée entre centres de pieux peut potentiellement être augmentée de 1.2 à 1.5m, ce qui se traduirait par une réduction de 30% du nombre de pieux à utiliser.

KEYWORDS: piled embankment, timber piles, triangular arrangement, sulphide soil, finite element method, PLAXIS 3D.

1 INTRODUCTION

Piled embankments with a basal reinforcement are widely used as a foundation method for road and railways on soft soils. The foundation method, known as geogrid-reinforced pile-supported embankments (GRPS), has a short construction time and creates efficient reduction of both vertical and horizontal displacements. The load transformation onto the piles (through arching in between the piles) and subsoil is complex and many studies have discussed the load transfer mechanism and how it could be optimised in design.

Currently there is an uncertainty in the Swedish industry concerning the optimum design of GRPS with timber piles, also called the light embankment piling method. The method is currently used for mainly sulphide soils with timber piles as its key feature and is classified purely in reducing settlement while stability increase is not taken into account. Theoretically any foundation can be constructed in such a way that the settlements are reduced to zero. The question is how the foundation should be constructed to yield the highest resource efficiency, whilst maintaining serviceability. The pile groups contain numerous piles and a main concern is whether they should be installed in a square or a triangular arrangement. The current Swedish standard for light embankment piling (Trafikverket 2014) states that a triangular pattern should be used due to higher efficiency. There is however a lack of research supporting this claim, and the question also involves the optimum centre-to-centre distance (s) of the piles. The maximum allowed s of 1.2m is by the Swedish Transport Adminstration thought to be too narrow for the geogrid reinforcement (GR) to have any cost efficiency.

The model by Hewlett and Randolph (1988), the Zaeske (2001) model and the Concentric Arches (CA) model by Van Eekelen (2015) are analytical methods for determining the 3D arching in a piled embankment, focusing on a square pile arrangement. Zhang et al. (2016) developed a 3D arch model for equilateral triangular arrangements on the basis of the Hewlett and Randolph (1988) model. In the thesis by Van Eekelen (2015) the load components are divided into the load transferred directly onto the piles through the arches (A), and the load beneath the arches acting on the GR and subsoil (B+C). B is transferred through the GR onto the piles, whilst C is transferred onto the subsoil.

Numerical analyses of GRPS have been performed increasingly in last years. Van Eekelen (2015) used finite element (FE) simulations to verify the shape of the arches assumed in the CA model. Lai et al. (2014) evaluated the effects of geosynthetic reinforcement in pile-supported embankments through discrete element simulations. Both studies proved that it is possible to clearly visualise the formation of the arches with numerical simulations. Lai et al. (2014) also found that the GR greatly improves the efficiency of load transfer and enhances the stability of soil arching.

Bhasi and Rajagopal (2015) observed that the arching effect is not instantaneous and that the arches are fully developed during the consolidation process after final construction. The arches formed were distinctly visible by analysing the vectors of the major principal stresses; as was also noticed in the work by Van Eekelen (2015).

Esmaeili and Khajehei (2016) evaluated the use of triangular pile arrangements as a viable option to square pile arrangements, studying deep mixed columns in loose subsoils. The results from their small-scale experiment indicate that the two patterns give similar embankment support in terms of tolerated vertical load and settlement reduction. However, this study is to the authors' knowledge the only study in which square and triangular pile arrangements are studied in comparison and no studies had been found with focus on the use of wooden piles with their particular natural conical shape in soft soils.

The aim of the main project following this pre study is to clarify the behaviour of lightly piled embankments, and create a guide for optimal design for different conditions that involves road or railway embankments on soft subsoil. The main focus is on Swedish conditions with soft clay or silt layers on glacial till. A theoretical analysis of the construction based on 2D and 3D FE modelling, verified by field and laboratory experiments, is to be performed. The optimisation is based on the formation of the arches, load transfer onto the piles, differential and total settlements, but also resource efficiency. The number of timber piles can range between 9 000 and 20 000 per kilometre two-lane road for s according to the current standard of 0.8-1.2m (Trafikverket 2014), so there is an interest in reducing the material usage.

The aim in this paper is to (1) find the key mechanisms of the load transfer in GRPS and (2) make a first evaluation of the efficiency of a triangular pile arrangement in comparison to a square pile arrangement and (3) evaluate which s in the x and y plane the piles should be placed in. FE simulation with the FE Code PLAXIS was used in this study while the results were compared with analytical analysis.

2 LIGHT EMBANKMENT PILING

Sulphide soil, more commonly known as acid sulphate soil, is an alluvial soil type formed during the last 10 000 years through sedimentation in anaerobe environments and a supply of sulphates. The soil type most ranges from clay to silt and can be found worldwide in coastal floodplains and inter-tidal swamps (Dent 1986). It is characterised by its high content of pyrite and iron sulphides, which results in a black colour. When oxidised, iron ion solutions and sulphuric acid are leached, lowering the pH of nearby water bodies.

In Sweden, sulphide soil can be found all along the northern coastal area as a result of the land rise following the withdrawal of the ice cap formed during the last ice age. Embankment piling with timber piles has proven to be the most sustainable foundation method for roads and railways in the area; the sulphide soil is environmentally hazardous to excavate and the large coastal woodlands provides a renewable resource of timber.

Timber need to be kept in an anaerobe environment to avoid rotting. An anaerobe zone is created around the pile group by the saturated subsoil and a 10 cm layer of high capillarity soil placed on top of the pile heads, following the Swedish design criteria (Trafikverket 2014). Further, the embankment is reinforced with two layers of GR spaced 20cm apart, with the lower layer 20cm above the fine grained soil. The layers of GR cause the lower part of the embankment to act like a beam, resting on top of the timber piles. This beam effect is thought to maintain the arches in between the piles without the need of pile caps, whilst keeping the risk of punching failure low.

To avoid breaking the timber piles during installation, they are either driven with a low practical refusal blow count limit or simply pushed down to a known firmer soil layer (most often glacial till), as stated by SGI (2015). Thus the pile toe more or less rests on top of the firm soil layer, yielding relatively low toe resistance.

The case studied in this paper is a newly constructed lightly piled embankment northwest of Luleå in northern Sweden. The road was reinforced with timber piles and GR after it suffered from large settlements without reinforcement. The subsoil consists of 13m of soft sulphide soil on top of a silty till. The groundwater is situated at a level of 0.5m below the surface.

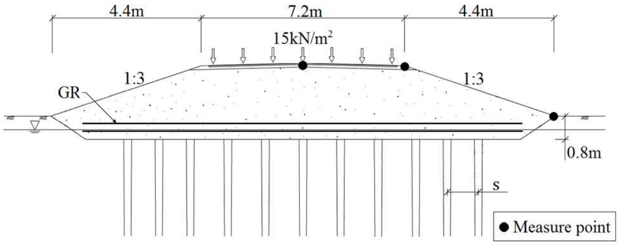

Figure 1. Cross section of the modelled road embankment.

3 NUMERICAL MODELLING

The numerical analysis was performed using the FE program PLAXIS. Figure 1 shows a cross section of the modelled piled embankment and is based on the blueprints of the constructed embankment. The simulation of the piled embankment was divided into several stages of construction, followed by a final consolidation simulation until the excess pore pressures reached 1kPa (assumed as full consolidation). The traffic load of 15kN/m^2 was added as a static load after 45 days of consolidation.

A road embankment resting on a pile group with square arrangement can be modelled with plane strain condition and the out-of-plane pile columns as a wall with equivalent thickness. In the case of a triangular arrangement the in-plane arrangement is repeated, but in cycles, in the out-of-plane direction as shown in Figure 2. Triangular arrangements are therefore a 3D problem. The square arrangement was primarily modelled in 3D, with verification in 2D, in order to compare the two arrangements under the same conditions.

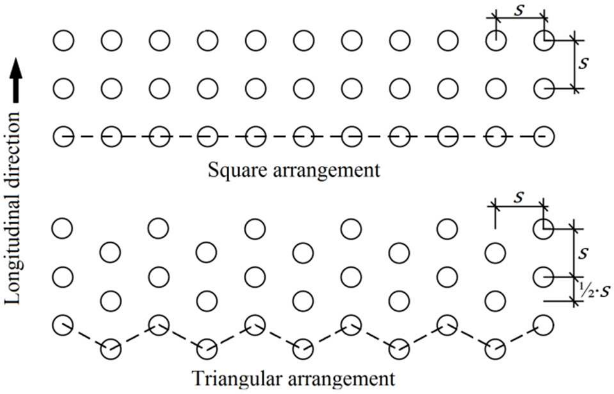

Figure 2. Square (previous standard) and triangular (current standard) pile arrangements. Pile row marked with dashed line.

The modelled square and triangular pile arrangements in Figure 2 were based on the previous (Trafikverket 2011) respectively the current Swedish standard (Trafikverket 2014). The pile groups were modelled as both end bearing (semi-floating with a small toe resistance) and frictional (floating pile group) to model a normal and the worst case scenario, respectively. In order to allow formation of arches in between a centred pile and any adjacent pile, creating a group of domes in two directions, three pile rows were chosen as the minimum required pile group length. The embankment width was constant, leading to a decreasing number of piles in each row as s increases, as shown in Table 1. The number of piles per meter road will thus decrease with increasing s.

Table 1. Number of piles per row for each s.

s (m)	1.2	1.3	1.4	1.5	1.6	1.8	2.0
Number of piles	11	10	9	9	8	7	7

Field and laboratory results from the site showed three main soil layers: a top layer of sulphide-bearing silt (*Su_{top}*) at 0-5m depth, a middle layer of silty sulphide clay (Su_{bottom}) at 5-13m depth and a bottom layer of silty glacial till (*siTi*) from 13m depth downwards. The end bearing pile group was driven 30cm into the $siTi$. For the friction pile group, the same pile length was used whilst the layer of Su_{bottom} was extended to 25m depth.

The sulphide soil was modelled using the Soft Soil (SS) model (Brinkgreve et al. 2015) since the model is developed for soft soils under large compression. The majority of the deformations were expected to take place within the soft soil layers, thus both the $siTi$ and the granular embankment material (*Granular*) were modelled with the simpler Mohr-Coulomb (M-C) model. The soil material parameter values, evaluated from soil tests from the site and experience, are shown in Table 2. Su_{top}, Su_{bottom} and $siTi$ were modelled as Undrained A and *Granular* as Drained. For the definitions of each symbol, see the PLAXIS 3D AE manual (Plaxis 2015).

Table 2. Soil material parameter values.

Parameter	Su_{top}	Su_{bottom}	$siTi$	*Granular*
Material model	SS	SS	M-C	M-C
γ_{unsat} (kN/m^3)	15	13.4	20	20
γ_{sat} (kN/m^3)	15	13.4	20	23
λ^*	0.117	0.136	-	-
κ^*	0.035	0.05	-	-
E (MPa)	-	-	10	50
ν	-	-	0.25	0.25
ν_{ur}	0.15	0.15	-	-
φ (°)	36	35	40	45
c' (kPa)	3	3	0	0
e_0	2.18	2.18	0.5	0.5
POP (kPa)	38	41	0	0
k (m/day)	$2.16\cdot10^{-4}$	$3.12\cdot10^{-4}$	$2.27\cdot10^{-4}$	0.6

The embankment in the case study was reinforced with two layers of biaxial geogrids, with the lower being stronger in the transversal direction and the upper being stronger in the longitudinal direction. The two geogrids were combined in the numerical model to a single layer of geogrid and placed in between the existing layers, with an equivalent stiffness of 2200 kN/m based on the values used for design.

The timber piles were modelled with a stiffness of 2200MPa, a unit weight of 12kN/m^3, a length of 13m and a diameter of 20cm. They were modelled as embedded beams, which consist of line elements with a stiffness equivalent to the timber piles. The line element interacts with the surrounding soil with a linear elastic interface. The toe resistance is modelled in the same manner, but with a linear elastic perfectly plastic interface element. The maximum geotechnical bearing capacity, $N_{pile,max}$, in PLAXIS (Plaxis 2015) is calculated as

$$N_{pile,max} = F_{max} + \frac{1}{2} L_{pile}(T_{head,max} + T_{toe,max}) \qquad (1)$$

where F_{max} is the toe resistance of 14kN, $T_{head,max}$ is the shaft resistance at the pile head set to 14.4kN/m and $T_{toe,max}$ is the shaft resistance in level with the pile toe set to 15.6kN/m, calculated using Pålkommissionen (2004). L_{pile} is the pile length of 13m. Based on the values used for design each pile was given a maximum structural bearing capacity of 106kN.

The model size was 100m wide, 40m deep and three pile rows long (Figure 2). The groundwater was allowed to flow through the upper horizontal boundary of the model as well as through the vertical outer model boundaries on either side of the road. All vertical boundaries were normally fixed, with the ground surface boundary fully free and bottom horizontal boundary fully fixed. A 10-noded tetrahedral element mesh was refined in steps until there were no significant differences in the results. The final general mesh size was 5.2m with 0.3 and 0.5m large elements in the embankment and pile group, respectively.

4 RESULTS

4.1 *Settlements*

The settlements were extracted at the top of the embankment, on the roadside and in the embankment toe (see measure points in Figure 1). No increase in differential settlements was observed when increasing s. The plot in Figure 3 shows the reduced settlements in percentage, comparing the average measured settlements with a control embankment without piles. The average settlement for an embankment with no pile group support was 18cm for Su_{bottom} reaching down to 25m (case of friction piles) and 14cm for the case of Su_{bottom} reaching down to 13m (end bearing piles). In both the friction and end bearing pile group, the settlement reduction is more or less maintained when increasing s from 1.4 to 1.5m.

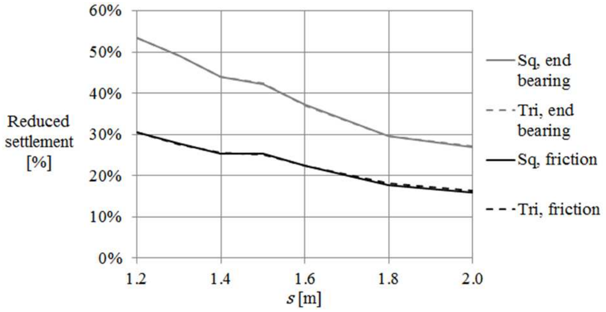

Figure 3. Percentage of the displacement reduction compared to an embankment without a piled foundation.

4.2 *Pile load*

The distribution of the mobilized total axial load, $N_{pile,mob}$, along a pile row for the friction and end bearing pile groups were summarised to evaluate the load transfer along the pile row (see Figure 4). The results were the same for square and triangular pile arrangements. The distribution was irregular with larger force acting on the outer most piles, up to s equal to 1.4 for friction pile groups and 1.5m for end bearing pile groups. Friction pile groups with s equal to 1.5 and 1.6m showed an almost uniform distribution of the pile load. The difference in axial load between the friction and end bearing pile groups was interpreted as the difference in toe resistance. The maximum structural capacity was not exceeded.

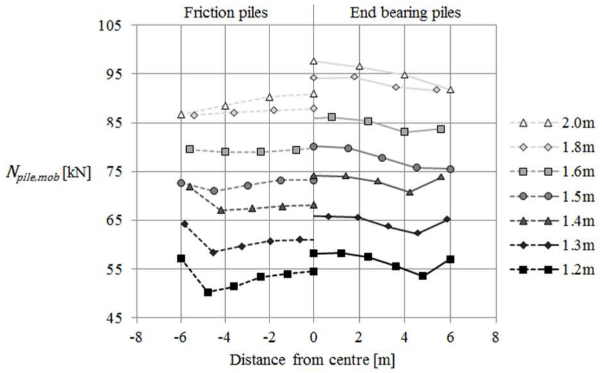

Figure 4. Load distribution across the middle pile row in the friction and end bearing pile groups.

4 .3 *Comparison with analytical methods*

For the case studied in the pre-study, no field measurements were available to verify the numerical results. Instead the results were compared using the CA model proposed by Van Eekelen (2015), applicable for square arrangement of piles. The model assumes the formation of concentric arches and an inversed triangular load distribution in between the piles. Van Eekelen (2015) found that the CA model was more suited for load distribution calculations in GRPS in the case of low subsoil support than the commonly used methods by Hewlett and Randolph (1988) and Zaeske (2001).

Figure 5 shows a comparison of the average load per pile, P, for the numerical simulations and the CA model. The increases in load are similar for the two calculation methods, but with the analytical results being consistently lower. The CA calculations of P only included the axial pile load that was transferred directly through the arches (load part A) giving a lower value than $N_{pile,mob}$. The GR in the CA model is assumed to be directly on the pile heads for the calculation of load part A, whilst the geogrid was above the pile heads in the numerical model, which gives different results.

In Figure 6 the percentage of load transferred to the piles is shown, calculated as

$$P\% = \frac{P}{(\gamma H + p) \cdot s} \qquad (2)$$

where γ is the unit weight of the embankment, H is the height of the embankment and p is the surcharge (traffic load). Consequently with P being lower for CA, $P\%$ is also lower but follows the same overall trend.

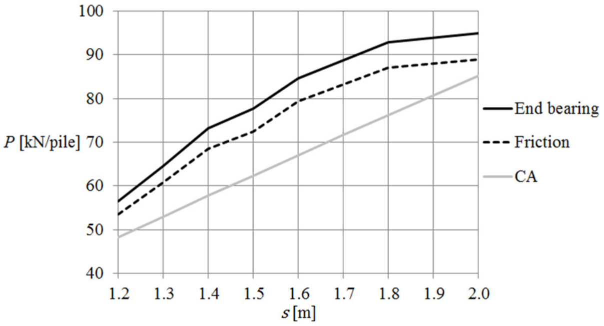

Figure 5. Average load per pile.

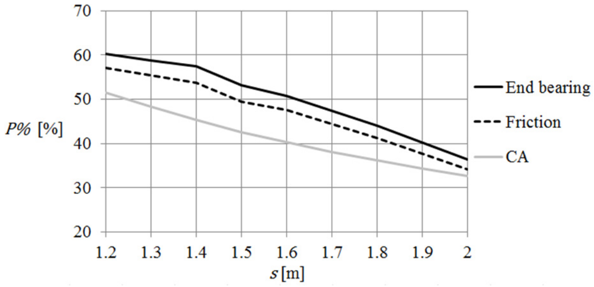

Figure 6. Percentage of total load transferred to the piles.

5 CONCLUDING REMARKS

Based on the methodology used in this paper, there is no evident difference in settlement distribution and magnitude or pile axial load distribution between square and triangular arrangements of piles for the light embankment piling method.

Based on the results in the present study, the maximum value of s according to the Swedish standard (Trafikverket 2014) could potentially be increased from 1.2 to 1.5m. The axial load is increased by approximately 20%, whilst in remarkable distance to capacity. An increase of 30cm in s results in approximately 35% less piles used in total (6000 instead of 9200 piles per kilometre), 7-8% less load directly transferred through the arches onto the piles and a decreased settlement reduction of 11% (1.5cm) for end bearing piles and 6% (1.1cm) for friction piles.

In this study the presumed arch formation between the piles were not measured. The line element and interface of the embedded beams did not generate a visible arching effect, possibly due to the line elements not having an actual cross section for the arch bases to rest on. In the PLAXIS 3D simulations by Van Eekelen (2015), where the arching effect was observed, volume piles were used.

Key mechanisms of the light embankment piling method lays within the load transfer onto the piles through arching, but also indirectly through the GR. The effect of the pile shape and the effects on the load transfer for different embankment heights and locations of the geogrid are to be evaluated. Creep deformation is planned to be simulated in the FE model to see its effect on the load transfer. Field tests or scale model experiments will be used for verification.

6 ACKNOWLEDGEMENT

This study has been supported by the Swedish transport administration (Trafikverket), the Swedish joint research program for road and railway geotechnology Bransch-samverkan i grunden (BIG) and Luleå University of Technology. The authors would like to express their gratitude for the financial support.

7 REFERENCES

Bhasi A. and Rajagopal K. 2015. Numerical study of basal reinforced embankments supported on floating/end bearing piles considering pile-soil interaction. *Geotextiles and Geomembranes* 43, 524-536.

Dent D. 1986. *Acid sulphate soils: a baseline for research and development*. International Institute for Land Reclamation and Improvement (ILRI, Wageningen.

Esmaeili M. and Khajehei H. (2016). Mechanical behavior of embankments overlying on loose subgrade stabilized by deep mixed columns. *Journal of Rock Mechanics and Geotechnical Engineering* 8, 651-659.

Hewlett W.J. and Randolph M.F. (1988) Analysis of piled embankments. *Ground Engineering* 21 (3), 12-18.

Lai H.-J., Zheng J.-J., Zhang J., Zhang R.-J. and Cui L. 2014. DEM analysis of « soil »-arching within geogrid-reinforced and unreinforced pile-supported embankments. *Computers and Geotechnics* 61, 13-23.

Plaxis 2015. *PLAXIS 3D AE Manual*. Plaxis bv, Delft.

Pålkommissionen (2004). *Kohesionspålar*. Commission on Pile Research, Linköping (in Swedish).

SGI 2015. *BIG Förstudie: Jordarmering över olika typer av bankpålning*. Swedish Geotechnical Institute (SGI), Linköping (in Swedish).

Trafikverket 2011. *Trafikverkets tekniska krav för geokonstruktioner TK Geo 11*. Swedish Transport Administration, Borlänge (in Swedish).

Trafikverket 2014. *Trafikverkets tekniska krav för geokonstruktioner TK Geo 13*. Swedish Transport Administration, Borlänge (in Swedish).

Van Eekelen S.J.M. 2015. *Basal reinforced piled embankment*. Delft University of Technology, Delft.

Zaeske, D. 2001. Zur Wirkungsweise von unbewehrten und bewehrten mineralischen Tragschichten über pfahlartigen Gründungs-elementen. *Schfritenreihe Geotechnik* Heft 10, University of Kassel, Kassel (in German).

Zhang C., Jiang G., Liu X. and Buzzi O. 2016. Arching in geogrid-reinforced pile-supported embankments over silty clay of medium compressibility: Field data and analytical solution. *Computers and Geotechnics* 77, 11-25.