Study of the load transfer mechanisms in reinforced pile-supported embankments

Briançon L. & Delmas Ph.
Cnam, 2 rue Conté, 75141 Paris cedex 03, France

Villard P.
3S-R, Grenoble University, UJF, INP, CNRS, BP 53, 38041 Grenoble Cedex 09, France

Keywords: piled embankment, load transfer, geotextile, geogrid, Discrete Element Method

ABSTRACT: Soft soil improvement by geosynthetics and rigid piles is an interesting technique to provide an economic and effective solution, which reduces settlements, construction time and cost. The geosynthetics could be placed under the embankment or introduced in the granular earth platform. The load transfer mechanisms developed in geosynthetics, earth platform, along the piles and in the underlying soft soil between the piles remain incompletely understood. This paper presents results of a full-scale experiment, which is conducted within the French national research project A.S.I.RI and developed to provide a new design method. This experiment shows the great influence of granular platform reinforced with geosynthetics in this load transfer mechanisms. The measures of geosynthetic strain highlight that the maximum strain takes place at the vicinity of pile heads during the construction of embankment. Measures also highlight that the load transfer behavior of platform reinforced by a single geotextile is different from that of a platform reinforced by two geogrids, although the final settlement is the same in both sections. To a better understanding of the load transfer behavior, a numerical analysis based on the use of a three-dimensional discrete-element model (DEM) was performed. From theses results a load transfer mechanism was proposed and compared to the experimental data.

1 INTRODUCTION

Soft soil improvement by geosynthetics and rigid piles is usual. However, some of the existing design methods do not take into account the complex behaviour developed in these reinforced structures (Briançon et al., 2004[a]). From that, a French national research project (A.S.I.RI) was launched to improve the knowledge in this field and to draft a document constituting the Guidelines relating to the set up and the design of embankments and pavements on ground reinforced by rigid piles.

In this connection, a full-scale experiment of embankment reinforced by geosynthetics and rigid piles over soft soil was carried out. The observations of settlement and stress in the reinforced structure and strain in geosynthetic sheets highlight the mechanisms of load transfer. The experimental measures obtained on full-scale experiments give interesting results about the global behaviour of the structure but it remains difficult to understand the role of each component on the reinforcement process. For a better understanding, a parametric study based on the Distinct Element Method was carried out. The numerical analysis shows that the load transfer mechanisms act in a specific area located over the piles.

2 FULL-SCALE EXPERIMENT

Full-scale test sections (Briançon et al., 2008) are constructed on a 52 m by 23 m surface of ground level divided in four instrumented sections (1R, 2R, 3R and 4R).

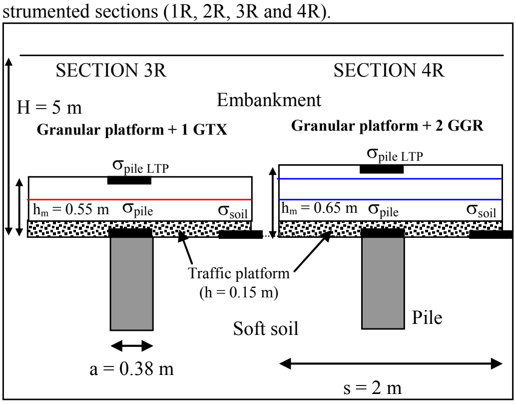

Figure 1. Typical cross-section of reinforced sections

Three sections (2R, 3R and 4R) are reinforced by a rigid piles network and loaded by a uniform embankment, 5 m in high, of density γ =19 kN/m^3. The section 1R is unreinforced and included for the reference. Every reinforced section has a surface of 8 m by 8 m square under the embankment, which is set out of 4 by 4 square rigid pile grids spaced at 2 m.

A load transfer platform (LTP) formed by compacted granular fill reinforced by geosynthetics is installed above sections 3R and 4R (Figure 1) while section 2R is setting up without LTP. For section 3R, reinforcement is constituted by one geotextile (75 kN/m) layer and for section 4R, by two geogrid layers (55 kN/m). Instrumentations are installed for monitoring the evolution of the differential settlements between the pile and its surrounding soil, the geosynthetics strain, the stress applied on the piles (S1), and the soft soil (S2) and over the granular platform (S3) (Briançon et al., 2004[a]).

3 RESULTS FROM EXPERIMENTS

For the three reinforced sections, the shape of the subsoil settlement is very flat. The differential settlement between soil and pile is generated during the embankment construction. Note that in section 2R (Figure 2), the settlement of piles, in agreement with the level of load applied on pile heads, is very slight (8 mm); in sections 3R and 4R, the settlement of piles reaches 30 mm.

In section 2R, the stress (S1) measured on the pile ($\sigma_{pile\ 2R}$ = 590 kPa) is lower than that corresponding to a complete load transfer ($\gamma Hs^2/\pi(a/2)^2$ = 3350 kPa). In this case, the small load transfer toward piles could be explained by the lack of load transfer platform and the little area ratio, defined as the percent coverage of the pile head over the total embankment area, equalled to 2.8%.

In sections 3R and 4R, the stress measured on the pile head (S1) shows that for both sections, the reinforcement system transfers the load toward the piles head ($\sigma_{pile\ 3R}$ = 2950 kPa, $\sigma_{pile\ 4R}$ = 2480 kPa). This difference shows that the load transfer mechanisms acting on the granular platform are complex and affected by the use of one or two layers of reinforcement.

4 BEHAVIOUR OF PILES

The figure 2 shows, for the three reinforced sections, the pile settlement versus the stress measure directly on the pile (σ_{pile}). Theses curves could be compared to the curve deduced from the static loading of a single pile (established for several steps of loading), showing the pile head settlement versus the stress at the pile base.

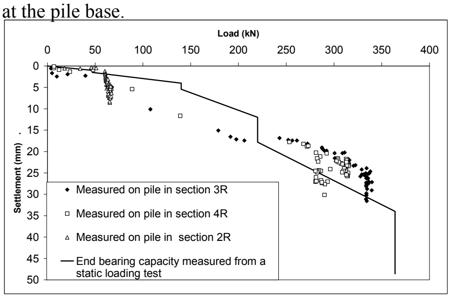

Figure 2. Comparison between the loads measured on pile head and the end bearing capacity of the static loading test

We observe a good agreement between measures of the full-scale experiment and those of the static loading test and deduce that the piles of full-scale experiment mobilize essentially end-bearing capacity. This behaviour is in accordance with the slight anchorage of the pile.

5 LTP BEHAVIOUR

Measure of soft soil settlement versus the stress (σ_{soil}) applied on soft soil measured under the LTP (Figure 3) highlights the different behavior of load transfer in the four sections. In the unreinforced section (1R), the stress increases during the embankment construction and remains constant after that; settlement continues to increase after the embankment construction. In section 2R (without LTP), stress and settlement increase slightly after the embankment construction. For reinforced-sections with LTP (3R & 4R), we notice a decrease of stress applied on soil after the embankment construction.

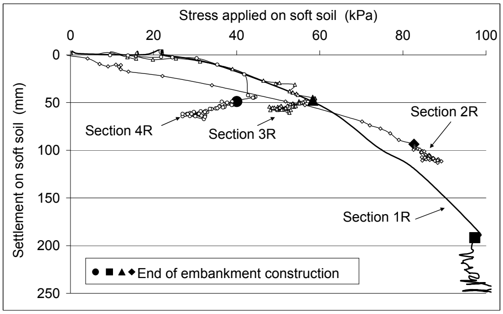

Figure 3. Settlement of soft soil versus stress applied (measured under the LTP)

Over the load transfer platform, the stress above the pile in section 3R ($\sigma_{pile\ LTP}$ = 500 kPa) differs from that in section 4R ($\sigma_{pile\ LTP}$ = 125 kPa) although the settlement of the pile is the same at the end of the embankment construction for both the sections. This difference shows that the load transfer mechanisms obtained during the construction process in the upper embankment depend on the rigidity of the granular layer (height and reinforcement used).

6 MEASUREMENT VALIDATION

To validate the measurement, the load Q_{calc1} applied on a grid is calculated from the stress measured on the pile σ_{Pile} and the stress measured on the soil σ_{Soil} ($Q_{calc1} = \sigma_{Pile}\,\pi(a/2)^2 + \sigma_{Soil}\,(s^2-\pi(a/2)^2)$) and compared (Table 1) with the load Q_{calc2} calculated from the heights of the embankment and of the granular platform and from their bulk unit weights ($Q_{calc2} = (\gamma_m h_m+\gamma(H-h_m))/s^2$).

Table 1. Measurement validation

Section	Measurement			Q_{calc2} (kN)
	σ_{Pile} (kPa)	σ_{Soil} (kPa)	Q_{calc1} (kN)	
2R	590	87	405	400
3R	2950	50	529	404
4R	2480	36	404	421

We observe that there is a good agreement for sections 2R and 4R; but for section 3R, the load calculated from the stress measured is too large. There is probably, for this section, a mistake with the measure of the stress on the pile σ_{Pile} or on the soil σ_{Soil}. The soil pressure cell reading installed on soil has to be analysed carefully because it is less accurate than that installed on pile head.

7 NUMERICAL MODEL

To highlight the load transfer mechanisms, a numerical analysis was carried out with the three-dimensional discrete element code SDEC (Donzé and Magnier, 1995) based on the molecular dynamics (Cundall and Strack, 1979). In this scheme, the granular layer is split in an assembly of particles that interact with each other at contact points. Contact laws defined locally allow restoring the macroscopic behavior of a natural granular soil.

To a better understanding, the numerical simulations were carried out in a simple configuration (Chevalier et al. 2010). In this way, the soft soil behavior was reproduced with vertical springs (Winckler model), the piles had a square section and the upper embankment was assumed to act as a uniform vertical overload (q).

The numerical results presented are the displacements of the particles of the granular layer at the end of the simulation (Figure 4) and the efficiency of the load transfer during the overloading process (Figure 5). The efficiency E is defined as the proportion of the total q_t (self weight granular layer and overload) transmitted to the pile by load transfer.

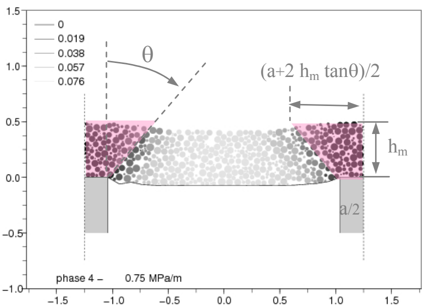

Figure 4. Particles displacements after the overloading process (Maximal vertical displacement around 0.08 m)

As it can be seen in figure 4 the load transfer mechanisms act in a specific area located over the piles. We notice that the shape of the area over the piles is an inverted pyramidal shape closed to the mechanism of load transfer proposed by Rogbeck et al., 1998. The value of θ obtained with the numerical model deals with the peak friction angle of the granular material.

Analytical value of the efficiency E' can be found on the base of the previous mechanism considering the weight of the pyramidal volume of soil over the piles (W_p) and the overload Q_p acting on a surface square area of edge ($a+2h_m\tan\theta$):

$$E' = \frac{W_p + Q_p}{s^2(\gamma h_m + q)} \quad (1)$$

With:

$$W_p = \frac{\gamma}{6\tan\theta}\left((a + 2h_m \tan\theta)^3 - a^3\right) \quad (2)$$

$$Q_p = q(a + 2h_m \tan\theta)^2 \quad (3)$$

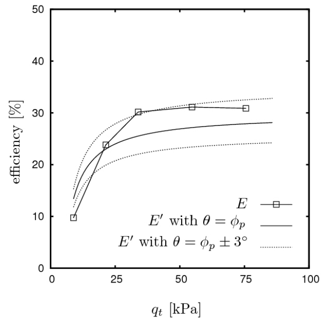

Figure 5. Comparison between numerical and analytical values of the efficiency for several values of θ.

The predictions of the efficiency E' are compared to numerical values of the efficiency E on figure 5 for several values of θ: ϕ_p, ϕ_p - 3° and ϕ_p +3°. In spite of the great influence of θ, the predicted efficiency E' is very close to the values obtained with the numerical model. Other simulations performed with several granular layer thicknesses showed that this mechanism remain valid so long as the maximal vertical displacements of soil particles are not too high regardless of the value of the granular layer height.

8 LOAD TRANSFER ANALYSIS

When there is no granular platform (section 2R), we can note, due to an arching effect occurring during the construction of the upper embankment, an increase of the load applied on the pile head (Figure 6). The efficiency of this mechanism is not great, only 17 % of the load is transferred toward the pile head and the soft soil is strongly loaded. The difference of stress measurements at several cross sections of the pile head shows that a second mechanism of load transfer takes place in the soft soil by friction between soil and piles. The efficiency of this transfer depends on the quality of the superficial soil layer.

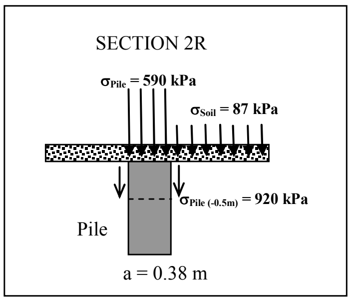

Figure 6. Load transfer in section 2R

For section 4R, there is a load transfer inside the granular platform. Its rigidity homogenizes the stress at the embankment base and decreases the differential settlement. It is not easy to determine the shape of the area over the piles in the LTP because the pile is cylindrical and the grid is rectangular. For inverted pyramidal shape (Figure 7a) and inverted conical shape (Figure 7b) and for several values of θ (ϕ_p, ϕ_p - 3° and ϕ_p +3°), we calculate the stress applied on the pile (σ_{pile}) from the stress measured on the LPT above the pile ($\sigma_{pile\ LTP}$).

For this simplified analysis, the case of inverted pyramidal shape and for θ = ϕ_p +3° is in good agreement with the measured stress applied on the pile.

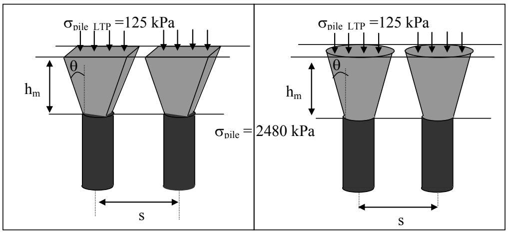

Figure 7. Inverted pyramidal and conical shapes in LTP

Table 2. Measured and calculated stress on pile in section 4R for different cases of load transfer

	Conical shape	Pyramidal shape	Measured
ϕ_p - 3°	1448 kPa	1785 kPa	2480 kPa
ϕ_p	1678 kPa	2091 kPa	
ϕ_p +3°	1936 kPa	2442 kPa	

9 VALIDATION WITH GEOSYNTHETIC STRAIN

Geosynthetic strain was monitored with optical fibres using the technique of Bragg grating. This optical device, called Geodetect, measures the local strain with high accuracy without any disturbance (Briançon et al., 2004[b]).

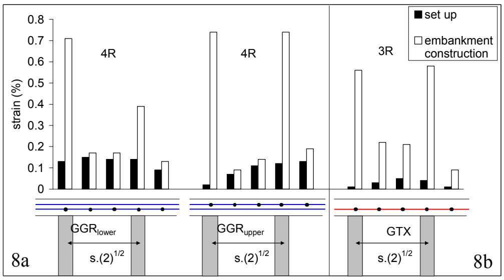

Figure 8. Geosynthetics strain

Measures of sheet strain (Figure 8) in sections 3R and 4R confirm that the behaviour of platform reinforced by a single geotextile is different from that of a platform reinforced by two geogrids, although the final settlement is the same in both sections. For section 3R, the tensile force of geotextile sheet increases during the embankment construction and especially near the pile head (Figure 8b). A small part of vertical load is transferred during the embankment construction to the geotextile. In the case of section 4R, the geogrids are stretched during the compaction of granular platform (Figure 8a). The tension induced in the reinforcement by compaction tends to make the granular platform rigid. Hence, we notice similar values of stress measurements on the top of the platform above the soft soil and above the pile (a uniform stress repartition will be obtained with a perfect rigid platform). During the embankment construction, the tensile force of the geogrids increases near the pile head.

10 CONCLUSION

A full-scale experiment of embankment reinforced by geosynthetics and rigid piles over soft soil was carried out in the frame of a French research project A.S.I.RI. The experiments carried out and the numerical results obtained show similar trend about load transfer mechanisms in the granular layer. Without granular platform, an increase of the load applied on the pile head occurs due to an arching effect in the embankment, a second mechanism of load transfer takes place in the soft soil by friction between soil and piles. Measurement of stress on soil and on piles highlights a significant improvement of load transfer toward piles when there is a reinforced granular platform. The rigidity of the platform homogenates the stress repartition at the base of the embankment and decreases the differential settlement.

In addition, for a better understanding, new numerical models were developed with discrete element method to take into account all the reinforced components participating to the load transfer in reinforced pile-supported embankment.

11 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the French national project A.S.I.RI which has been funding this research within the partnership of Fondasol, IREX, Keller, LCPC, EGIS, Socotec, Tencate Geosynthetics. This work was possible thanks to the financial support of Drast and RGCU and to the loan of experimental zone by the “Conseil Général de Seine et Marne”.

12 REFERENCES

Briançon, L., Kastner, R., Simon, B., and Dias, D. 2004[a]. Etat des connaissances - Amélioration des sols par inclusions rigides. *Proceedings International Symposium on Ground Improvement* (ASEP-GI 2004), Paris, France, 15-43.

Briançon, L., Nancey, A., Caquel, F. & Villard, P. 2004[b]. New technology for strain measurements in soil and the survey of reinforced earth constructions. *Proceedings EUROGEO 3*, Munich, Germany, 471-476.

Briançon, L., Faucheux, G. & Andromeda, J. 2008. Full-scale experimental study of an embankment reinforced by geosynthetics and rigid piles over soft soil. *Proc. of Eurogeo 4*, 07-10 September 2008, Edinburgh, UK.

Chevalier, B., Briançon L., Villard, P. & Combe, G. 2010. Prediction of Load Transfers in Granular Layers Used in Rigid Inclusions Technique - Experimental and Discrete Element Method Analysis. *Proc. of GeoFlorida,* 20-24 February 2010, West Palm Beach, Florida, USA.

Cundall, P.A., and Strack, O.D.L. (1979). A discrete numerical model for granular assemblies. *Geotechnique*, 29(1), 47-65.

Donzé, F., Magnier, S.A. (1995). Formulation of a three-dimensional numerical model of brittle behavior. *Geophysical Journal International*, 122, 790–802.

Rogbeck, Y., Gustavson, S., Södergren, I., and Lindquist, D. (1998). Reinforced pile embankments in Sweden – Design aspects. *Proceedings 6th International Conference of Geosynthetics*, Atlanta, USA, 755-762.