Prediction of Load Transfers in Granular Layers Used in Rigid Inclusions Technique - Experimental and Discrete Element Method Analysis.

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ABSTRACT

The rigid inclusions technique is based on the use of a network of piles covered by a load transfer granular layer which allows the construction of roads, railways and buildings on very poor subsoil. Today, there are no relevant design methods able to predict the behavior of such structures due to the lack of knowledge about the load transfer mechanisms in the granular layer. Consequently, experimental works and numerical studies based on the Discrete Element Method were carried out. Both experimental and numerical results show that the granular layer can reduce greatly the surface settlement and the load applied to the soft soil. The numerical analysis shows that the load transfer mechanisms take place in a specific area located over the piles and is highly influenced by the rigidity of the soft soil. Thanks to the good agreement obtained with the numerical analysis, a prediction of the load transfer amplitude close to the description of Carlsson was proposed.

INTRODUCTION

Soil improvement by rigid inclusions (network of piles covered by load transfer granular layer) is commonly used to limit the surface settlement in soft soil areas; in this technique, concrete piles are referred to as rigid piles because of their low relative deformability comparatively to the soft soil. However, the majority of the existing analytical design methods do not consider the complex behavior involved in these structures (Briançon, 2002; Briançon et al., 2004): some of these methods make restricting assumptions for the load transfer mechanisms occurring in the granular layer, others simply ignore the interaction with the underlying soft soil. Load transfer mechanisms may be approached either by arching theory or negative skin friction concept. Settlements are estimated with some homogenization methods implying various assumptions.

A large amount of small scale experiments of soft soil reinforcements was performed. Though only few true scale experiments were developed to study the load transfer mechanisms taking place in the granular layer. In addition, little attention was paid to phenomenon occurring in the soft soil layers. In light of those observations, a French national research project A.S.I.RI was set up to improve the understanding about this foundation technique and to draft a standard defining design and construction guidelines related to embankments and pavements on ground reinforced by rigid piles. The experimental measures obtained on true scale experiments gave interesting results about the global behavior of the structure but it remained difficult to separate the role of each component in the reinforcement process. In order to focus specially on the load transfer mechanisms occurring in the granular layer, a numerical parametric study using three-dimensional Discrete Element Method was performed.

EXPERIMENTAL RESULTS

True-scale experiments using different reinforcement solutions were tested under an embankment built on soft soil. The vertical stress on piles and the differential settlements (between a pile and its surrounding soil) were monitored. The monitoring was performed during and after the phase of construction of a 5m high embankment. This embankment represented the load acting on the reinforcement structure which could be assumed uniform on the centered elementary cell. For all the reinforced sections, each pile, 0.38m in diameter, had its tip slightly embedded in the bearing layer and its head cut off level with the traffic layer base. A total of four different sections were tested:

- Section 1R: non-reinforced and included as reference case,
- Section 2R: reinforced by a regular square network of piles (Fig.1).
- Section 3R: reinforced by piles, load transfer layer and a geotextile sheet,
- Section 4R: reinforced by piles, load transfer layer and two geogrids.

The load transfer platform was composed of dry industrial gravel and the ground water level was found to be 2 m deep.

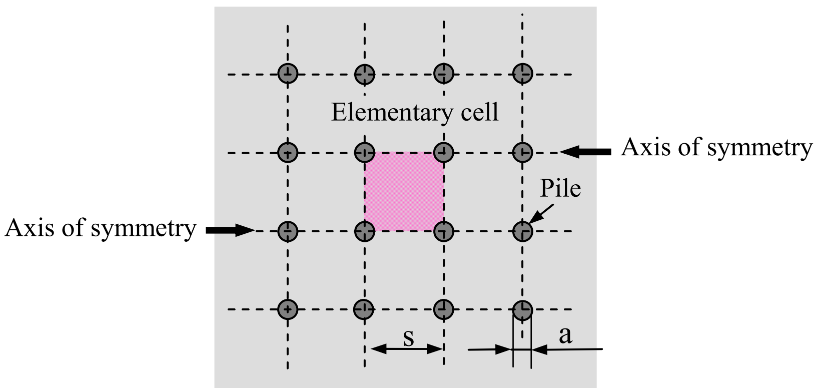

Figure 1. Geometry of the network of piles.

For the three reinforced sections, the shape of the subsoil settlement is very flat from 0.2m of the pile circumference (Fig.2). The settlement profiles at the vicinity of piles could not be precisely determined because of the use of only one sensor (located at 0.1 m from pile circumference) but showed nevertheless a mechanism of hanging up of the soft soil on the pile during the embankment construction phase. In the reinforced sections, differential settlements between soft soil and piles were generated during the embankment construction only. Afterwards, the piles sank in the soft soil and consequently settled homogeneously with the soft soil. It can be noticed that, according to the intensity of loads on piles, the pile settlement is very small for the Section 2R (0.008m) and greater in Sections 3R and 4R (0.030m).

Load transfer mechanisms in the granular layer can be estimated from the measurements of vertical stresses in several points of the structure (Fig.3). In Section 2R, the measured stress in the pile (= 590kPa) is lower than the stress corresponding to a total load transfer (= 3350kPa). In this case, the small load transfer toward piles could be explained by the lack of load transfer platform and the small covering rate. The covering rate (equal to 2.2% in our case) is defined as the ratio of the piles heads areas and the total embankment area.

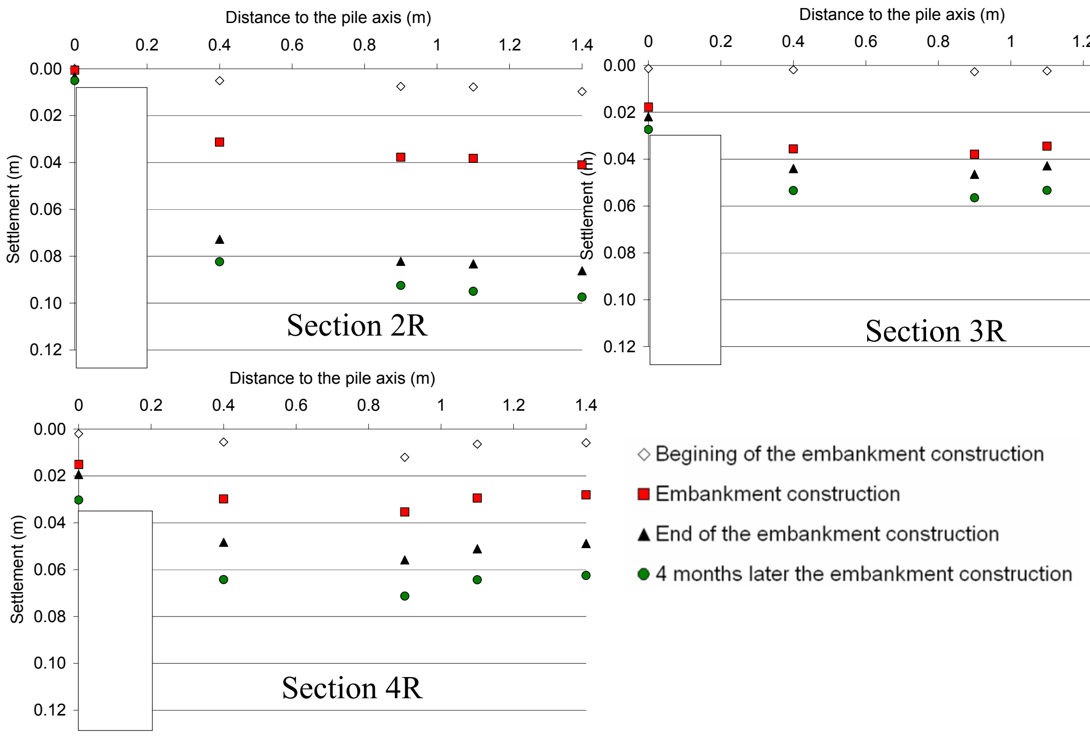

Figure 2. Settlement at the pile level for sections 2R, 3R and 4R.

In Sections 3R and 4R, the measured stress on piles heads showed that the reinforcement system transferred efficiently the load toward piles head. Above the piles, the vertical stress at the top of the granular layer in section 3R (= 500 kPa) differed from that in section 4R (= 125 kPa) while the stress on pile head was rather the same. These very different values of stresses showed the great influence of the reinforcement type on the load transfer mechanisms in the granular layer.

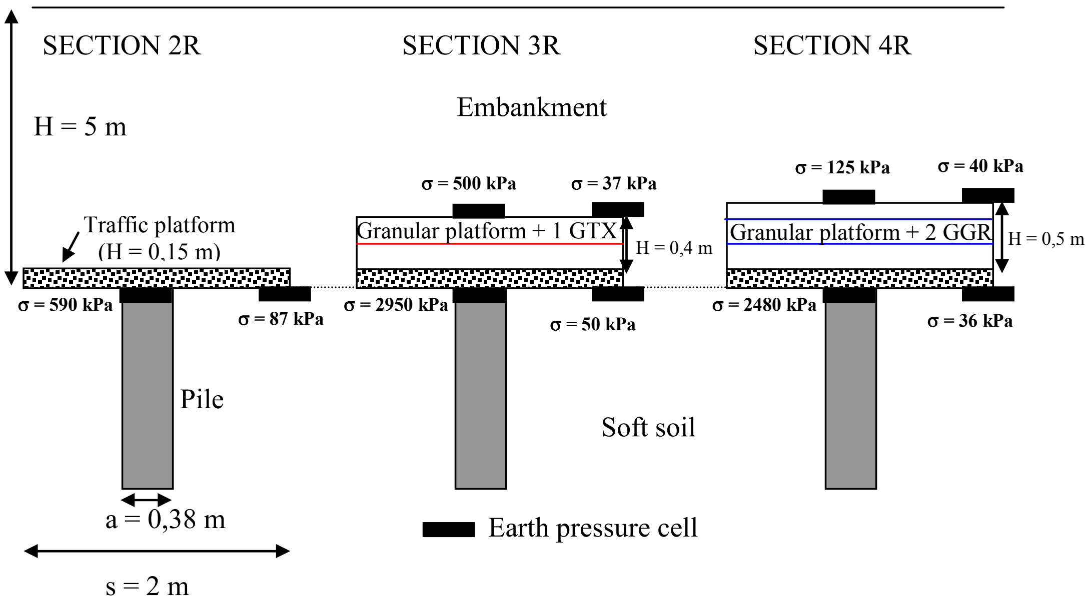

Figure 3. Load transfer – 4 months later the end of the embankment construction.

In conclusion, the load transfer is the result of several mechanisms depending on the complexity of the reinforcement. When no granular platform is involved, a low part of the vertical load is transferred to the piles heads consecutively to load transfer mechanisms that take place in the upper embankment. The efficiency of this mechanism is not great (for Section 2R, only 17% of the load was transferred to pile head and 83% to the soft soil). Reinforcement with granular layers improves greatly the efficiencies (for Sections 3R and 4R respectively, 90% and 75% of the vertical load were transferred to piles). However, in order to clarify the mechanisms involved in the granular layer, a numerical analysis is needed.

NUMERICAL MODEL

The numerical analysis of the behavior of the granular material presented here was carried out with three-dimensional Discrete Element Method (DEM). The numerical model (Villard et al., 2009) is based on the molecular dynamic (Cundall and Strack, 1979) and is well adapted for the modeling of load transfer in granular material in dry conditions (in particular with the non dependency to elastic properties of the material). The analysis involves clump particles made of two inseparable imbricate spheres of same diameter d spaced of 0.95 d. The maximal lengths of the clumps ranged between 18mm and 70mm. These clumps interact with linear contact laws. A Coulomb friction criterion bounded the tangential contact force to the normal contact force. The micro mechanical parameters (stiffness of the contact laws and friction coefficient) were determined so that the macro mechanical characteristics (elastic modulus and peak friction angle) of a representative sample of 8000 particles under triaxial tests were similar to the characteristics of the material of the load transfer layer used in the experimental tests. The tangent initial Young modulus of the numerical sample was 257MPa for a Poisson ratio of 0.08, the peak friction angle φ_p = 43.7° and the residual friction angle φ_r = 30.1°.

A square mesh piles network was considered in the analysis like in the experimental tests. The pile's horizontal cross section was a 375x375mm² square. The piles heads are taken into account by horizontal frictional wall allowing no vertical displacements of the granular particles in contact with the cap pile. A friction angle of 30° was considered between the granular layer and the piles. Due to symmetry, only an 2.50x 2.50m² elementary cell was modeled. The height h_m of the load transfer layer was either 0.5m (16000 particles for the granular layer) or 1.0m (32000 particles for the granular layer). The vertical boundary conditions for the granular layer consisted in vertical frictionless walls (frictionless because of the symmetry condition).

The soft soil settlement was reproduced with vertical springs (Winckler model): different values of the soft soil stiffness K_c were considered in order to study the influence of the soil compressibility. The linear springs modeling the soft soil were used here only to reproduce the increase of settlement with the load and not for a precise description of how the soft soil layer behaves.

In a first step, the granular layer was generated (without friction and without gravity). After applying gravity, the soft soil springs were released (phase 0) and an uniform overload was applied by increment at the top of the soil layer (phase 1 to 4: 12.8kPa, 25.5kPa, 46.8kPa and 68kPa). An equilibrium state was reached between each phase of the overloading process. The case of a uniform load only was considered (case of a centered elementary cell).

LOAD TRANSFER MECHANISMS AND PREDICTION

The results of the numerical model are the displacements of the granular layer and the loads acting on the piles and on the soft subsoil. In order to predict the load transfer mechanisms, the kinematics of the granular mass was check between two piles in a vertical cross section for both values of the layer height (Fig.4).Two different areas of the granular mass can be defined: areas over piles were particles displacements are very small and areas over the soft soil were particles displacements are heigher (equal to settlement of the soft soil). We notice (Fig.4) that the shape of the area over the piles is an inverted pyramidal shape. This shape is very closed to the mechanism of load transfer proposed by Carlsson (Rogbeck et al., 1998) (Fig.5). Following the assumption of Carlsson, the load transfer was supposed to concentrate in these areas: the self-weight of the "over piles" areas is transmitted directly to the pile, as the overload carried by this area. However, the numerical value of the angle θ defining the pyramid shape is very different from Carlsson solution. Indeed, Carlsson proposed a value of θ = 15° while the value of θ obtained in the numerical analysis is around 45°.

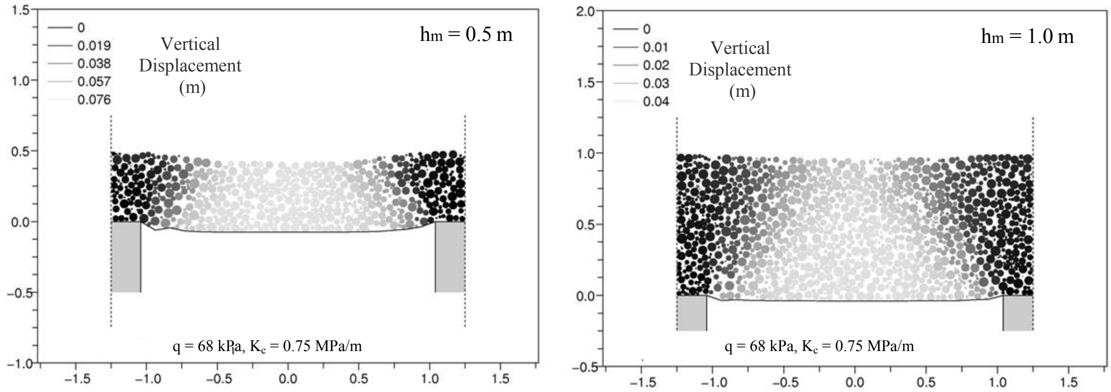

Figure 4. Particles displacements for the maximal load applied (soft soil stiffness K_c equal to 0.75MPa.m^{-1}): h_m=0.5m (left) and h_m=1.0m (right).

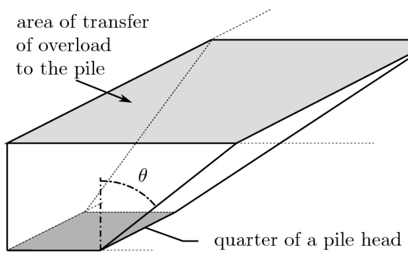

Figure 5. Shape of the granular layer area where load transfers are developed.

The load transfers in the granular layer are quantified by the efficiency E defined as the percentage of embankment weight (self weight and overload) carried by the pile head. The Fig.6 shows the relation between efficiency E and total load q_t for a soft soil stiffness K_c equal to 0.75MPa.m^{-1} (i.e. an uniform load equal to 0.75MPa applied on the soft soil induces an uniform settlement equal to 1 meter). The efficiency E increases with the total load. In the case of h_m = 0.5m, E reaches a threshold around 30%. For h_m = 1.0m, the maximal efficiency is around 60%.

The efficiency defined by the Carlsson mechanisms can be obtained according to the scheme describes on Fig.5. The weight of the area "over piles" W_p can be written from the unit weight of the granular layer γ, its height h_m, the width of the pile a, and the angle θ:

$$W_p = \frac{\gamma}{6\tan\theta}\left((a + 2h_m \tan\theta)^3 - a^3\right) \text{ for } h_m \le h^* = \frac{s-a}{2\tan\theta} \qquad (1)$$

where h* is the height of the granular layer for which the areas over piles joint in the granular mass. The part of the overload carried by the area "over pile" Q_p can be estimated from the value of the uniform load q, the height of granular layer h_m and the angle θ by:

$$Q_p = q(a + 2h_m \tan\theta)^2 \tag{2}$$

Consequently, a value of efficiency E' can be estimated from (1) and (2):

$$E' = \frac{W_p + Q_p}{s^2(\gamma h_m + q)} \tag{3}$$

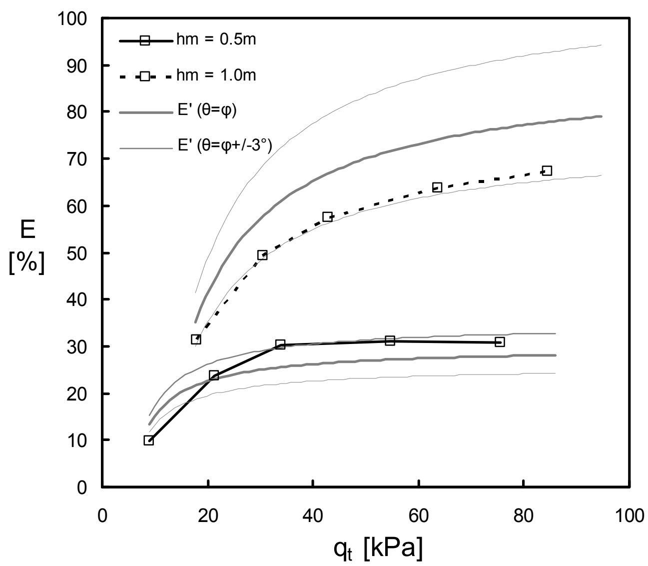

Figure 6. Numerical efficiency E and predicted efficiency E' versus total load q_t (K_c= 0.75MPa.m^{-1}) for a granular layer height of 0.5m (left) and 1.0m (right).

The predictions of the efficiency E' are compared to numerical values of the efficiency E on Fig.6 for several values of θ (45°, 45°-3° and 45°+3°). In spite of the great influence of θ, the predicted efficiencies E' are close to the values obtained with numerical analysis E for h_m = 0.5m and also h_m = 1.0m. For soft soil stiffness K_c equal to 0.75MPa.m^{-1}, a value of θ around 45° is closed to the peak friction angle of the granular material. In addition, a value of θ equal to the friction angle of the material induces that the interactions between areas "over piles" and the other areas are horizontal only. This consideration confirms the assumption stating that the load applied on the pile head comes from the self-weight of the area "over piles" and the part of the overload which is applied to it.

In order to understand the role of the soft soil compressibility on the efficiency, numerical simulations were performed for several values of the compressibility K_c: 0.25; 0.50; 0.75; 1.00 (MPa.m^{-1}). The evolution of the efficiency E versus total load q_t is given on Fig.7. For very soft soils (K_c=0.25MPa.m^{-1} and 0.50MPa.m^{-1}), the efficiency increases with the total load, then decreases for greater values of load. For soft soils with a greater compressibility (K_c=0.75MPa.m^{-1} and 1.00MPa.m^{-1}), the load transfers are similar has those described on Fig.6: increasing with the total load and then reaching a threshold. These results are similar to those obtained in plane strain conditions in the case of the trap-door problem (Chevalier et al., 2009).

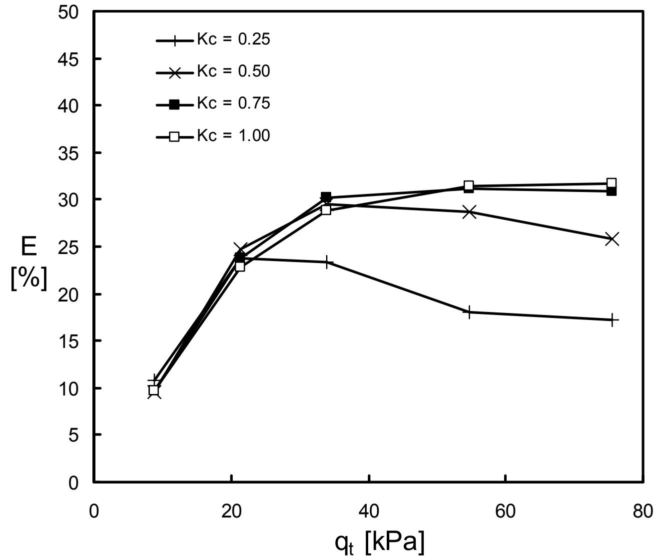

Figure 7. Numerical efficiency E versus total load q_t for a granular layer height of 0.5m.

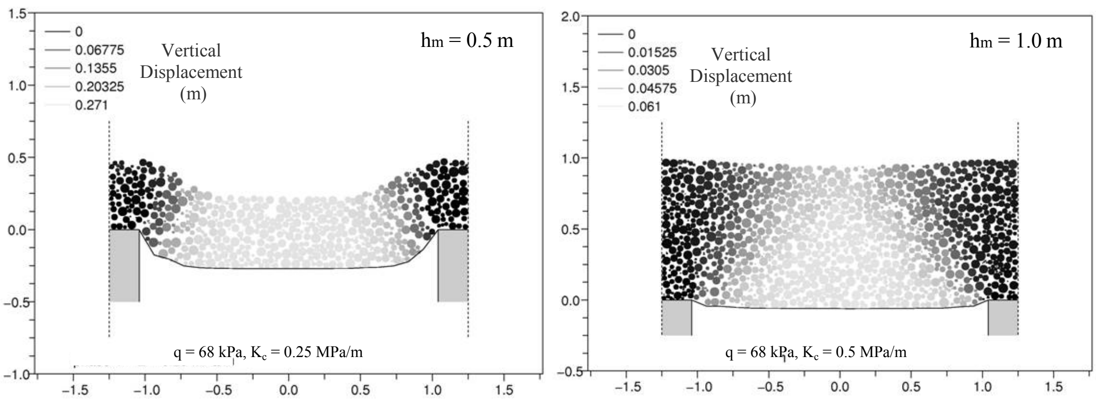

Figure 8. Distributions of particles displacements in a vertical cross section for soft soil compressibility K_c of 0.25MPa.m^{-1} (left) and 1.00MPa.m^{-1} (right).

To underline this difference of behavior between cases of small and high basis settlements, the distributions of particles displacements in a vertical cross section between two piles were represented on Fig.8 for two different values of soft soil compressibility. We observe on this figure that the shape of the soft soil settlements is closed to the one obtained for the experiment (Fig.2).

It also can be noticed that the angle θ existing between the areas "over piles" (characterized by direct load transfer) and the other part of the granular layer, decreases as the settlement at the basis of the granular layer increases. Consequently, the prediction of the load transfers with Eq.3 should be calculated using an adjusted angle θ varying between the peak and the residual friction angles values, depending on the amplitude of settlement at the base of the load transfer layer. Indeed, the predicted value for the efficiency E' for h_m = 0.5m and $\theta=\varphi_r$=30.1°, which can be compared to the value of the efficiency E on Fig.6, is E' = 13.7%. This effect of the compressibility makes the prediction of efficiency delicate because of the uncertainties existing on the settlement of the soft soil under the load transfer layer.

Consequently, the application of the Carlsson method gives good prediction results as long as the angle defining the direct load transfer area is considered with realistic value. The value of 15° proposed by Carlsson is indeed not sufficient to give satisfactory prediction. A value close to the current friction angle of the granular material (peak or residual, depending on deformations in the material) was found to be a good evaluation for θ.

CONCLUSION

The experiments carried out and the numerical results obtained show similar trend about the shape settlements and load transfer mechanisms in the granular layer. Due to the difficulty to dissociate the influence of each component from the experiment performed, a parametric study was carried out. From it, a new method for the prediction of the load transfer in reinforcements of soft soils with rigid piles is proposed. Based on the description of Carlsson, and verified from a numerical study, this method assumed the existence – in the granular layer – of zones of direct load transfer located over the piles. The prediction of the efficiency of the load transfer can be easily calculated as soon as the value of the angle θ is known. This angle varies between the peak and the residual friction angle values due to an effect of the compressibility level of the soft soil.

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