

Numerical study of treated load transfer platforms on rigid inclusions

Julien Mannah, Caroline Chalak, Hassan Farhat, Alia Quirin-Hatem
Arcadis ESG, Lyon, France, julien.mannah@arcadis.com

Laurent Brianchon
INSA, Lyon, France

Daniel Dias
Université Grenoble Alpes, Grenoble, France

Thomas Lenoir
Université Gustave Eiffel, Nantes, France

ABSTRACT: Rigid inclusion is a ground improvement method significantly developed in recent years. Granular load transfer platforms (LTP) are commonly used in this technique leading to an increase in the use of natural resources. In this context, soil treatment can be considered as an alternative solution to use the in-situ soil, improve its characteristics and limit the pressure on the granular material resources. As part of the French ASIRI+ project, a full-scale test was carried out to test the efficiency of treated LTP on rigid inclusions. An experimental program was conducted to fully characterize the soil and find the best treatment for the LTP with consideration for the environmental and the economic effects. Then, the test was performed in an 8 m x 8 m pit with a network of 16 rigid inclusions of 30 cm diameter and 1 m height, where an experimental set-up was installed to represent the compressible soil, the loads and simulate the site conditions. Settlement and stress sensors were installed to monitor the load transfer mechanism within the treated platform. Numerical simulation tests were also performed using Plaxis 2D software. A parametric study is carried out to assess the effect of different parameters on the efficiency and the behavior of the treated LTP. Calibration of the numerical model on experimental measurements gave consistent results, with an average uncertainty of 1% for stress and 7% for settlement. Stress diffusion within the treated LTP was assimilated to a truncated cone of the vertical axis, originating from the head of the RI and forming an angle ϕ (friction angle of the treated LTP) with respect to the vertical. The cohesion of the treated LTP had the greatest impact on stress and settlement efficiencies compared to the other parameters.

KEYWORDS: Rigid inclusion, Soil treatment, Load transfer platform, Numerical modeling.

1 INTRODUCTION

The technique of soil reinforcement using rigid inclusions has been developed rapidly in recent years. This technique combines vertical rigid inclusions passing through a compressible soil layer and a load transfer platform (LTP) installed between the structure and the inclusions. These elements transfer the load to a substratum at the base of the inclusions without overloading the compressible soil layer. The national ASIRI project was carried out in France between 2005 and 2012 to propose rules for the implementation and dimensioning of soil reinforcement using rigid inclusions. 39 companies and academic partners took part in this project resulting after 6 years' work in the drafting of the (ASIRI, 2012) recommendations. In 2019, a new national project (ASIRI+, 2019) has been initiated to complement these recommendations on insufficiently addressed topics such as treated load transfer platforms.

Soil reinforcement projects using rigid inclusions are generally modeled using 2D models: plane strain or axisymmetric, to represent an elementary mesh or 3D models. However, these approaches have their limitations. In the case of a plane strain model, the inclusion is represented unrealistically, while in the axisymmetric model, load transfers are imperfectly modeled. It is only the 3D models that offer the best advantages since they consider all interactions, complex loads, and more diverse behavior models. Their limitation is essentially based on calculation and preparation time.

There are a few examples of numerical modeling of treated load transfer platforms with rigid inclusions. Okyay (2010), Okyay & Dias (2012) and Okyay et al. (2014) carried out reduced-scale centrifuge tests with the mobile tray device on granular and treated LTP as part of the ASIRI project. They modeled the tests using a two-dimensional axisymmetric model

centered around an inclusion. They used a linear elastic-perfectly plastic model with the Mohr-Coulomb failure criterion for the treated LTP, which was sufficient to reproduce the load transfer mechanisms in the treated platform. Anggraini et al. (2015) studied the behavior of a treated LTP on rigid inclusions. A simplified planar numerical model was built with ABAQUS CAE 6.11. A linear elastic model was used for the rigid inclusion while Mohr Coulomb's model was used for the RI-soil interfaces. A linear elastic-perfectly plastic model with the Mohr-Coulomb failure criterion was also used to simulate the treated LTP. The literature review shows that these models are sufficient to simulate the treated LTP and obtain results consistent with the experimental measurements.

2 EXPERIMENTAL STUDY

A full-scale test was carried out in Cerema's experimental pit in Rouen, France (Figure 1). The test aims to study the behavior of a treated load transfer platform on rigid inclusions.

An experimental campaign was held to characterize the soil used for the LTP and evaluate the effect of different treatment formulas on its mechanical resistance. The experimental set-up that was installed to assess the efficiency of the treated load transfer platform was characterized by Brianchon et al. (2024) through laboratory standardized tests. It consists of several soil layers modeling soft soil, rigid inclusions, a treated LTP, a 1.5 m high backfill and surcharges.

The soft soil is modelled by a 10 cm thick layer of honeycomb cardboard planks (called Biocofra) installed on wooden gratings, a 50 cm thick layer of tire aggregates (called Deltagom) and a 37.5 cm thick layer of sand. The load transfer platform is 40 cm thick. It consists of a low-plasticity silt treated with 1% lime and 4% cement. A 1.5 m high backfill was then

installed on the treated LTP to simulate real loading. It was then left for a month to allow sufficient time for the system to reach equilibrium (settlement and stress stability). Finally, surcharges were added to the backfill. The aim was to study the behavior of the treated LTP under heavy loads.

Mannah (2025) gave a detailed description of the characterization of the treated soil, the installation of the experimental set-up, the instrumentation of the central mesh (force, stress and settlement sensors) and the main results of the test.



Figure 1. Experimental pit, Cerema.

3 NUMERICAL STUDY

A numerical model is developed using Plaxis 2D software to represent the full-scale test. The comparison between the numerical model and the full-scale test provides a better understanding and visualization of the load transfer mechanisms and the system operation. The model adopted is in 2D axisymmetric configuration. It is centered around a rigid inclusion. A radius equivalent to the square mesh is used for the axisymmetric elementary cell.

3.1 Overview

Figure 2 shows a cross-sectional view of the experimental set-up and the corresponding numerical model. The overload applied in the Plaxis model is equal to 7.65 kPa. It is calculated from the real overload, considering that the latter diffuses into the backfill and becomes uniformly distributed at the top of the treated LTP.

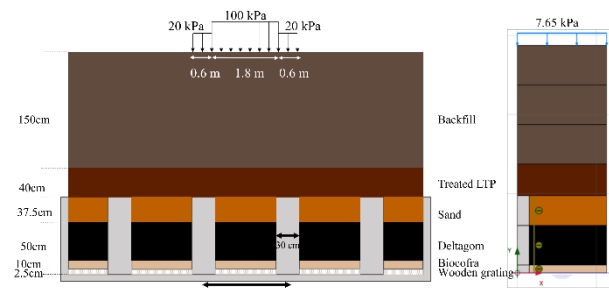


Figure 2. Cross section and numerical model of the test.

3.2 Calibration

The numerical model adopts the same phasing as the full-scale test. An initial state is considered after the installation of the treated LTP. Thus, the calibration of the numerical model is done for two construction phases: backfill and surcharges. It is based on several criteria (Table 1). The initial and the final parameters (after calibration) are presented in Table 2.

Table 1. Experimental results.

	Backfill	Surcharges
Stress at the base of the RI (kPa)	998	1216
Stress at the head of the RI (kPa)	816	1022
Settlement of Deltagom (mm)	26	37
Settlement of sand (mm)	31	43
Settlement of treated LTP (mm)	28	43

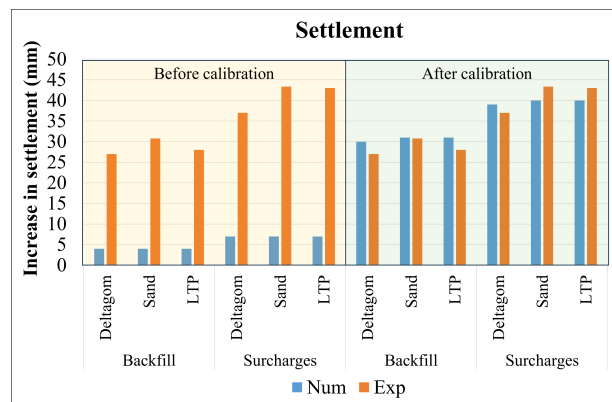
Table 2. Initial and final parameters.

	RI	Bio.	Delt.	Sand	Back.	LTP
Model	LE	LE	LE	MC	MC	MC
γ (kN/m ³)	24	0	5.2	19	18	20.8
Ey (MPa)	11500	50	0.652 (0.19)	35	35	93
ν (-)	0.2	0	0.25	0.3	0.3	0.2
c (kPa)	-	-	-	0	8 (4)	193 (25)
ϕ (°)	-	-	-	32 (30)	33 (27)	29
Ψ (°)	-	-	-	2 (0)	3 (0)	0
R_{inter}	-	(0.9)	(0.2)	(0.7)	-	-

() : The values in brackets are the degraded parameters after calibration.

The calibration was done by degrading the Young's modulus of the Deltagom and the shear properties (friction angle and cohesion) of the backfill, the sand and the treated LTP. For the RI-Deltagom interface, typically, new material must be created and assigned to the interface using a Mohr-Coulomb model, with a friction angle set to 0 and a cohesion equal to the limit skin friction q_s . However, due to the difficulties of characterizing the parameters of this interface using laboratory soil mechanics standard tests and considering that a linear elastic model was used for the Deltagom, the properties of this interface are considered identical to those of the Deltagom with a reduction factor R_{inter} applied to degrade its properties. A parametric study will be presented later on to assess the effect of this interface on stress and settlement efficiencies. As for the sand, a linear elastic-perfectly plastic model with the Mohr-Coulomb failure criterion was used, allowing us to use the reduction factor R_{inter} to determine the properties of the interface.

The comparison between the numerical model and the full-scale test is presented in Figure 3. The results obtained before calibration show settlement and stress values with an average uncertainty of 551% and 60%, respectively, compared with experimental results. After calibration, the new numerical model gave results consistent with experimental measurements, with an average uncertainty of 7% for settlement and 1% for stress.



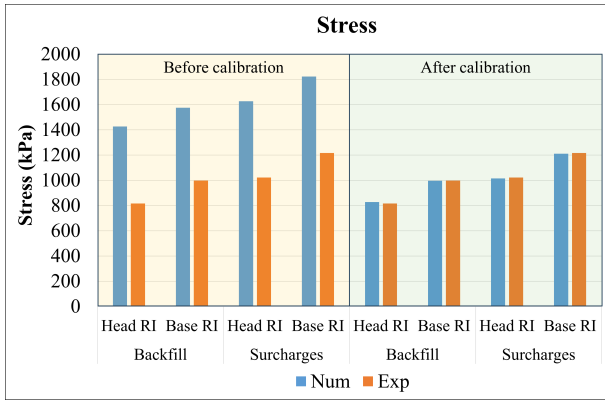


Figure 3. Calibration of the numerical model.

3.3 Load transfer mechanisms

3.3.1 Shear effects

Horizontal cut sections at different levels are shown in Figure 4. It presents the vertical stress for the backfill installation phase. The results show an increase in vertical stress as we go through the different layers of the backfill towards the treated LTP. The concentration of the vertical stress at the head of the rigid inclusions highlights the load transfer mechanisms due to shear effects (inside the backfill and the LTP) and the importance of modeling the backfill as a soil layer and not as a load. The same evolution is observed for the loading phase but with higher vertical stress values.

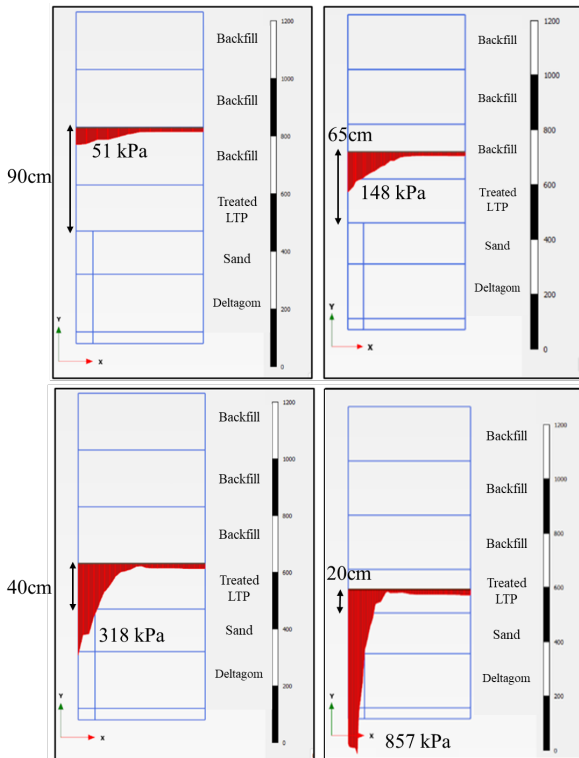


Figure 4. Vertical stress evolution.

3.3.2 Phasing influence

Two numerical models are tested in this section to further investigate the influence of phasing on settlement and stress states for the backfill and the surcharge installation phases. Both models are based on the parameters chosen after calibration (Table 2), with just one difference: in the first model, the backfill is placed as experimentally (3 layers of 50 cm), whereas in the second model, it is placed in a single layer.

Figure 5 shows the settlements and the stresses of the two models. Placing the backfill in a single layer results in a 67% and 10% increase in settlement and stress respectively. This comparison highlights the importance of taking phasing into account in numerical modeling.

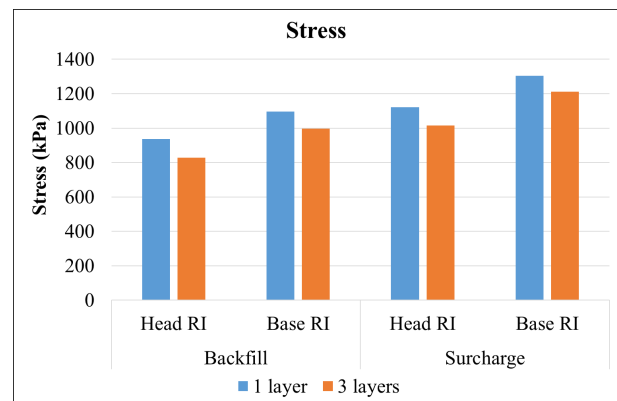
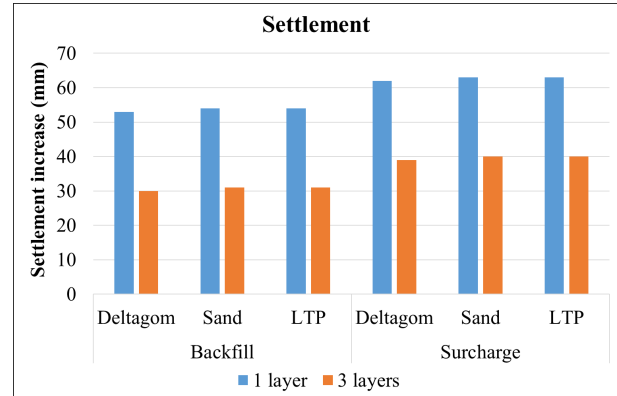


Figure 5. Phasing influence of settlement and stress states.

3.3.3 Stress diffusion

The failure mechanisms were visualized on the treated platform during the dismantling of the test. The fracture surface at the LTP was larger than the inclusion surface, with a failure mode that can be likened to a truncated cone with a vertical axis, originating from the head of the RI.

The stress diffusion diagrams are shown in Figure 6 according to three methods:

- Numerical: based on the calibrated Plaxis model.
- Analytical: based on the shear cone diagram presented in (ASIRI, 2012), where the load transfer is assimilated to a truncated cone forming an angle ϕ concerning the vertical.
- Experimental: based on observations and measurements after disassembly of the test.

Table 3 shows the length of the cone bases x (cm) according to the three methods, where similar values are obtained, indicating that the shear cone method provides a good representation of the load transfer mechanisms within the treated LTP.

Table 3. Cone base length

Method	Calculation	x (cm)
Numerical	x (cm) = $2 \cdot 38$	76
Analytical	x (cm) = $\Phi_{RI} + 2 \cdot H_M \cdot \tan(\phi_{LTP})$ $= 30 + 2 \cdot 40 \cdot \tan(29)$	74
Experimental	measurements	80

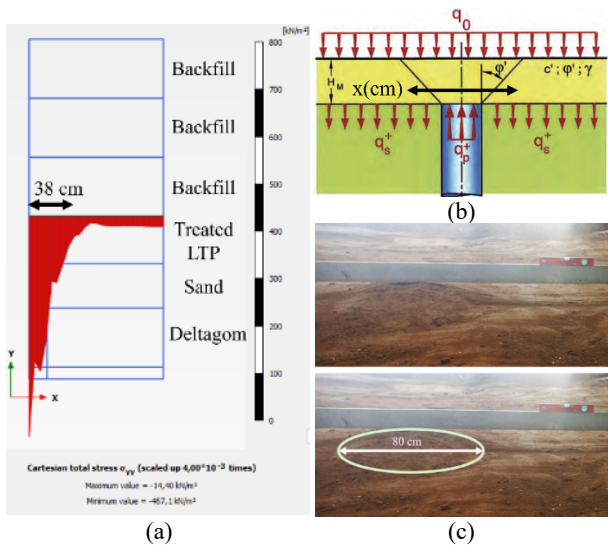


Figure 6. Stress diffusion based on (a) numerical, (b) analytical and (c) experimental methods.

3.4 Parametric study

The sensitivity study focuses on assessing the effect of different parameters on the system's stress and settlement efficiency. As a reminder, the stress efficiency is defined by (ASIRI, 2012) as the percentage of the load taken by a rigid inclusion concerning the total load applied on the elementary mesh. As for the settlement efficiency, it consists of calculating the reduction in settlement by comparing a reinforced and a non-reinforced soil, according to Equation (1):

$$\text{Efficiency}_{\text{Settlement}} = 1 - \frac{\text{Settlement (reinforced soil)}}{\text{Settlement (non-reinforced soil)}} \quad (1)$$

3.4.1 Interface

This section aims to evaluate the influence of a new interface on settlement and stress efficiencies. As mentioned earlier, the properties of the RI-Deltagom interface in the calibrated model are considered identical to those of the Deltagom with a reduction factor R_{inter} applied to degrade its properties. Therefore, a new material is created and assigned to the interface with a Mohr-Coulomb model, a cohesion equivalent to the limit skin friction q_s varying from 1 to 20 kPa, and a friction angle of 0. The results show that the new interface does not affect the stress at the head of the rigid inclusion and hence, the stress efficiency with a little impact on the settlement efficiency (Figure 7). The results also show close efficiencies for backfill and surcharge installation phases with similar evolution.

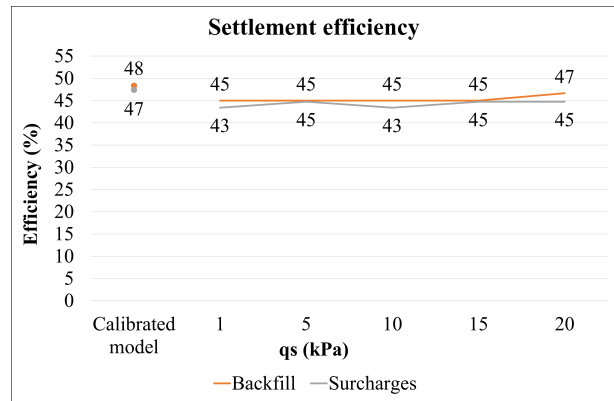
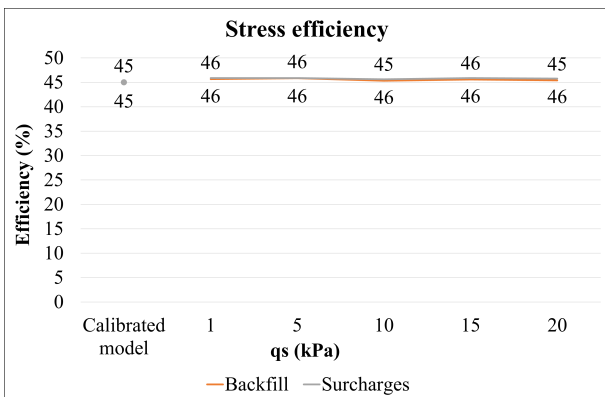


Figure 7. Evolution of efficiencies as a function of q_s .

However, the limit skin friction q_s affects the stress at the base of the rigid inclusion (Figure 8). The results show that for a q_s value close to 20 kPa, the stress values at the base of the RI are close to those measured experimentally and that the influence of the q_s remains relatively acceptable, with an 11% variation in stress when going from 1 to 20 kPa.

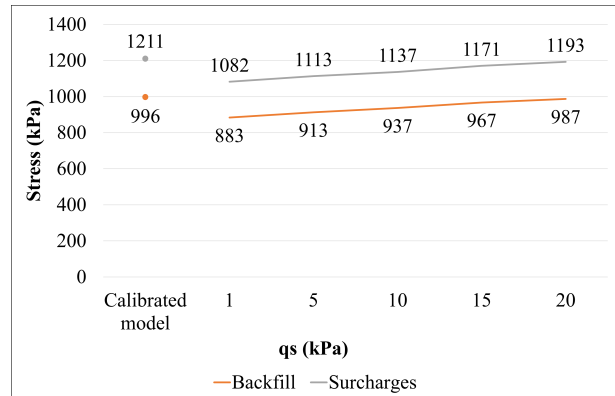


Figure 8. Stress evolution at the base of the rigid inclusion as a function of q_s .

3.4.2 Other parameters

Other parameters are tested to evaluate their influence on stress and settlement efficiencies. For the different parameters, very close efficiencies were observed for the backfill and surcharge phases with similar evolution.

- Cohesion of the LTP:** After the calibration of the numerical model, a cohesion value of 25 kPa was assigned for the treated LTP. Different values of cohesion were tested: 15, 25, 50, 100, 150, and 193 kPa (measured in laboratory tests), and the results show an average increase in the efficiencies of the order of 44% when going from 15 to 193 kPa. This evolution is not uniform where a significant increase is observed (33%) when going from 15 to 100 kPa followed by a smaller increase when moving from 100 to 193 kPa (11%), which indicates that a compromise can be found between the cohesion and the efficiencies to take into account the economic and environmental effects.
- Backfill characteristics:** The backfill parameters chosen after calibration were a cohesion value of 4 kPa and a friction angle of 27°. This section aims to assess the role of the backfill in the load transfer mechanisms. Different combinations (cohesion-angle of friction) were tested: (4-27), (8-33), (12-35), (20-35) and (20-40). The results highlight the influence of the backfill on the system's efficiency, showing that improving backfill quality can

increase settlement and stress efficiencies by 19.5% and 16.5%, respectively.

- **Thickness of the LTP:** The thickness of the treated LTP in our case is 0.4 m. Different thickness values were tested: 0.3, 0.35, 0.4, 0.45 and 0.5 m. The results show that the effect of thickness is less significant than that of cohesion, where better efficiencies were observed when going from a cohesion value of 25 to 50 kPa than when going from a thickness of 0.4 to 0.5 m. The results also show an average increase in settlement and stress efficiencies of 7% and 13%, respectively, when going from 0.3 to 0.5 m.
- **Surcharges:** The surcharge applied for our test is 7.65 kPa. For this section, a cohesion value of 150 kPa is considered for the treated LTP to evaluate the influence of surcharge values on stress and settlement efficiencies. Different surcharge values were tested: 7.65, 11.48, 15.3, 19.13 and 22.95 kPa. The results show that surcharge has little influence on efficiencies, with a 6% and a 5% decrease in settlement and stress efficiencies, respectively, when going from 7.65 to 22.95 kPa.
- **Young's modulus:** The Young's modulus measured in the laboratory tests for the treated LTP is 93 MPa. Experience has shown that in the majority of real projects involving treated platforms with rigid inclusions, the Young's modulus used is estimated and a general value is considered. Different Young's modulus values were tested: 30, 60, 93, 120 and 150 MPa. The results show that Young's modulus has little influence on the system's efficiency. An average increase of 2.5% in settlement and stress efficiencies is observed when going from 30 to 150 MPa.
- **Mesh size:** a very fine mesh was used for the calibrated model. Three mesh sizes were evaluated: very fine, fine and medium with a corresponding calculation time of 17.5, 5.5 and 1.5 minutes respectively. The results indicate that mesh size does not impact stress and settlement efficiencies. However, having a very fine mesh enables us to simulate more accurately the load transfer mechanisms and the load distribution at the head of the rigid inclusion and the top of the treated LTP and the compressible soil.

4 CONCLUSIONS

As part of the national project ASIRI+, a full-scale test was carried out to test the efficiency of the treated load transfer platform with rigid inclusions. An experimental campaign was carried out in the laboratory to evaluate different treatments and find the best with regard to environmental and economic effects. An experimental set-up was also developed and characterized as part of ASIRI+ to simulate real site conditions and best represent the actual behavior of a treated load transfer platform with rigid inclusions under uniform vertical loads.

A finite element numerical model with 2D axisymmetric configuration centered around a rigid inclusion was developed to represent the full-scale test. The calibration of the numerical model on experimental measurements is based on the stress levels at the head and the base of the RI and the settlement at the top of the Deltagom, the sand and the treated LTP. The calibration of the numerical model gave consistent results with an average uncertainty of 7% for settlement and 1% for stress. It was done by degrading the mechanical strengths of the treated LTP, indicating that the strengths obtained in reality are significantly lower than those of the laboratory tests and thus, a safety factor is required.

The numerical model highlights the importance of modeling the backfill as a soil layer and not as a surcharge, which allows us to observe the load transfer mechanisms through shear effects. Furthermore, considering a phasing similar to reality (backfill installation by 3 layers instead of a single layer) proved to be crucial for the load transfer mechanisms and the behavior of the system. The shear cone diagram (ASIRI, 2012) best represents the load transfer mechanisms in the treated LTP where stress diffusion is assimilated to a truncated cone with a vertical axis, originating from the head of the rigid inclusion and forming an angle φ (friction angle of the treated LTP) with respect to the vertical. This was verified analytically (shear cone diagram), numerically (Plaxis 2D) and experimentally (measurements and observations).

A parametrical study was carried out to assess the influence of various parameters on the system's stress and settlement efficiencies. It shows that the backfill and the surcharges installation phases have close efficiencies with similar evolution. Different parameters were tested and showed different impacts on the system's efficiency. The cohesion of the treated LTP shows the highest impact on stress and settlement efficiencies (44%), followed by the backfill quality (cohesion and angle of friction) that affects the load transfer mechanisms through shear effects inside the backfill, resulting in an average increase of 18% in stress and settlement efficiencies. The thickness of the treated LTP, the surcharges and the Young's modulus have a smaller influence (of the order of 10%, 6% and 2.5% respectively). Finally, the mesh size and the interface properties show no influence on stress and settlement efficiencies, however, the interface properties can affect the stress levels at the base of the rigid inclusion and a very fine mesh allows us to simulate more accurately the load transfer mechanisms within the treated LTP.

The tested parameters have different effects on settlement and stress efficiencies; however, it is very important to study the influence of each scenario on the economic and environmental effects. This sensitivity study allows us to determine which of the parameters is most important to characterize in comparison to others, where a general value can be considered.

5 ACKNOWLEDGEMENTS

This work was carried out as part of the national ASIRI+ project. The authors would like to thank all the members of this project for their support.

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