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NUMERICAL INVESTIGATION OF RIGID INCLUSION-REINFORCED SOILS UNDER SHALLOW FOUNDATIONS

F. MEZIANI[1],A. KAHIL[2], and L. IDDIR[3]

[1]Assistant professor at the Mouloud Mammeri University of Tizi-Ouzou, Algeria
[2]Professor at the Mouloud Mammeri University of Tizi-Ouzou, Algeria
[3]Master student at the Mouloud Mammeri University of Tizi-Ouzou, Algeria

ABSTRACT

This study presents a numerical investigation into the behaviorof a compressible soil reinforced with a load-transfer platform (LTP) and rigid inclusions beneath shallow foundations. The primary objective is to quantify the effectiveness of these reinforcement techniques by analysing settlement evolution both directly under the footing and within the LTP. The numerical model was developed for three scenarios: natural ground, ground reinforced only with an LTP, and ground reinforced by the combined LTP and rigid-inclusion system. The results indicate that the LTP efficiently redistributes stresses and mitigates settlements, while the rigid inclusions facilitate a more direct load transfer to deeper strata, thereby markedly enhancing foundation stability and overall performance. These findings underscore the merit of integrating both techniques in shallow-foundation designs on weak bearing soils.

KEYWORDS:shallow foundations; ground improvement; rigid inclusions; load transfer platform; settlements; Plaxis

Author Correspondence, e-mail: faroudja.meziani@ummto.dz
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1. INTRODUCTION

The construction of shallow foundations on compressible or low-bearing-capacity soils remains a major geotechnical challenge because excessive, time-dependent settlements can compromise structural stability. If not properly controlled, such settlements may trigger severe damage and lead to costly remedial works. To overcome these difficulties, a variety of ground-improvement techniques has been developed. Among them, the combined use of rigid inclusions [1, 2] for example, stone columnsand a load-transfer platform (LTP) has become an increasingly widespread solution for shallow foundations on weak soils [3–5]. This hybrid approach simultaneously harnesses the load-spreading capacity of the LTP and the high bearing resistance of the inclusions, offering a cost-effective alternative to deep foundations or extensive surface treatments [6, 7].

The load transfer platform (LTP), typically composed of compacted granular materials, serves to redistribute foundation loads toward the rigid inclusions, thereby ensuring improved load distribution and a significant reduction in settlements [8]. Composite LTP–inclusion systems are increasingly employed to enhance the stability of structures founded on compressible clay soils [9]. This configuration takes advantage of the high load-bearing capacity of the inclusions in conjunction with the stress-diffusion role of the platform, resulting in a highly efficient composite system whose effectiveness has been demonstrated across various geotechnical contexts [10].

However, understanding the overall behaviorof such systems remains complex, particularly regarding the interactions among the various componentssoil, load transfer platform (LTP), and rigid inclusions (RI)as well as the distribution of settlements within the reinforced zone. Numerical modelling has proven to be an essential tool for simulating these interactions and predicting the performance of reinforced soils under various loading conditions [11]. Recent studies have employed numerical tools such as Plaxis to investigate the foundation–LTP–inclusion interaction, confirming their potential to optimise design practices [12].

The objective of this study is to assess, through a numerical approach, the influence of the load transfer platform (LTP) and rigid inclusions on the settlement behaviorbeneath shallow foundations. Three configurations are compared: natural soil, soil reinforced solely with an LTP, and soil reinforced with the combined LTP and rigid inclusions.

2. CASE STUDY DESCRIPTION

The case study concerns shallow foundations resting on a compressible soil characterized by low bearing capacity and high settlement susceptibilitytypical of alluvial zones or saturated fine-grained soils such as soft clays.

The modelled foundation is a rigid rectangular footing with a width of 2.00 m and a height of 0.45 m, placed directly on the natural ground surface. It is subjected to a vertical load simulating the effect of a conventional structure (Figure 1).

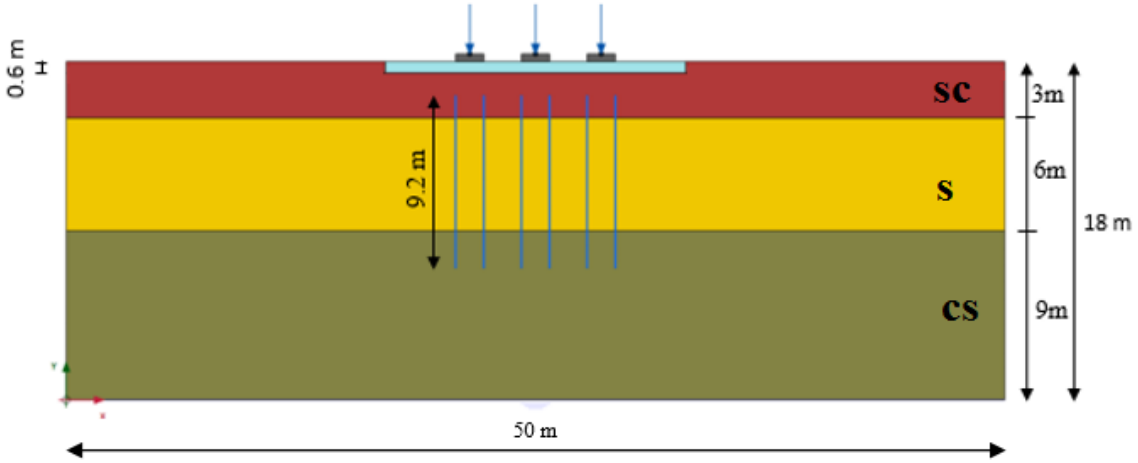


Fig.1. Geometrical model of the case study

The geological profile under investigation consists of three main soil layers. The upper layer is composed of compressible silty with a variable thickness of 3 metres. It is underlain by a compressible silt layer of constant thickness, measuring 6 metres. Finally, a rigid lower layer composed of coarse sand extends over a depth of 9metres. Within this context, three ground reinforcement configurations (Table 1) were analysed to evaluate their impact on the overall mechanical behaviorof the soil mass, with a particular focus on settlement performance beneath shallow foundations.

Table 1. Ground reinforcement configurations

Configuration	Reinforcement description	Constituent elements
Case 1	Natural, unreinforcedsoil**(US)**	No additionalreinforcement
Case 2	Soil reinforced with a load transfer platform **(US +LTP)**	0.60 m thick LTP made of compacted granular material placed beneath the footing
Case 3	Soil reinforced with LTP and rigid inclusions **(US +LTP+RI)**	0.60 m thick LTP and vertical rigid inclusions and embedded into the rigid stratum

3. Material parameters

3.1 Natural soil

The compressible soil, represented in this study by a silty clay layer and a silt layer, is modelled using the Mohr–Coulomb failure criterion, which is commonly applied to cohesive soils exhibiting plastic behavior. The properties adopted for the numerical modelling are summarised in the table 2.

Table 2. Mechanical properties of the modelled soil layers

Parameter	Silty Clay (SC)	Silt (S)	Coarse Sand (CS)
Model	MohrCoulomb		
Behaviortype	Drained		
Dry weight [kN/m³]	19	17	20
Saturated weight [kN/m³]	23	20	22
Young'smodulus [kN/m²]	15600	5200	84000
Poisson's ratio	0.30	0.30	0.30
Cohesion [kN/m²]	40	30	0
Friction angle (°)	16	6	32

3.2Loadtransferplatform(LTP)

In the numerical model, the load transfer platform (LTP) is represented as a compacted granular material exhibiting elasto-plastic behaviour. This modelling approach captures both the initial elastic response under low stress levels and the plastic behaviorthat develops under higher loads. The thickness of the LTP layer is uniformly set at 0.60 metres in all configurations where the LTP is applied, in accordance with the recommendations of the ASIRI design guide (2012) [13], which considers this value representative of common practice in ground reinforcement systems involving rigid inclusions.The mechanical properties of the LTP used in the modelling are summarised in table 3.

Table 3. Mechanical properties of the LTP used in the numerical modelling

Parameter	LTP
Model	Linearelastic
Behaviortype	Drained
Dry weight [kN/m³]	20
Saturated weight [kN/m³]	22
Young'smodulus [kN/m²]	50000
Poisson's ratio	0.30

3.3 Rigidinclusions

The rigid inclusions are modelled as vertical columns, representing either reinforced or unreinforced concrete elements, embedded within the compressible soil and extending down to the rigid substratum. Theirbehavioris assumed elastic (Table 4), effectively capturing their high load-bearing capacity and low deformability relative to the surrounding soil. These inclusions are considered to be perfectly anchored in the underlying rigid layer, ensuring a direct and efficient transfer of vertical loads from the foundation to the substratum while bypassing the compressible layers. This assumption of perfect anchorage also serves to minimise potential slippage or failure at the soil–inclusion interface within the numerical modelling.

Table 4. Mechanical properties of the modelled rigid inclusions

Parameter	Inclusion
Material model	Elastic
Axial stiffness [kN/m]	$9.329\ 10^{6}$
Flexural stiffness [kN·m²/m]	$2.099\ 10^{3}$
Poisson's ratio	0.20

4. Numerical model

4.1 General parameters

The simulation is conducted using a staged construction procedure, with the progressive activation of structural components (LTP and inclusions) prior to the application of a uniform vertical load of approximately 100 kPa on the foundation. The convergence criterion is set at 10^{-3}, with automatic load-step adjustment enabled [14].

The geometrical model has a minimum width of five times the foundation width to eliminate boundary effects, and a total depth of 28 m, including a safety margin beneath the tips of the rigid inclusions.

4.2 Mesh and boundary conditions

A very fine two-dimensional mesh composed of 15-node triangular finite elements was adopted [14]. In sensitive zones, the mesh element size ranges from 0.05 m to 0.15 m. The applied boundary conditions are as follows:

- Lateral boundaries: horizontally restrained and vertically free (2D symmetry);
- Bottom boundary: fully fixed, preventing both vertical and horizontal displacements;
- Ground surface: stress-free (no constraints);
- Loading: applied exclusively on the foundation.

5. Results and interpretation

5.1Settlement evolution with depth and at the surface

In this study, settlements are assessed along several analysis sections, as illustrated in figure 2. Due to their symmetric configuration and the similarity of their results, vertical sections 1 and 3 are represented by a single curve. In contrast, vertical section 2 is analysed separately owing to its distinct configuration.

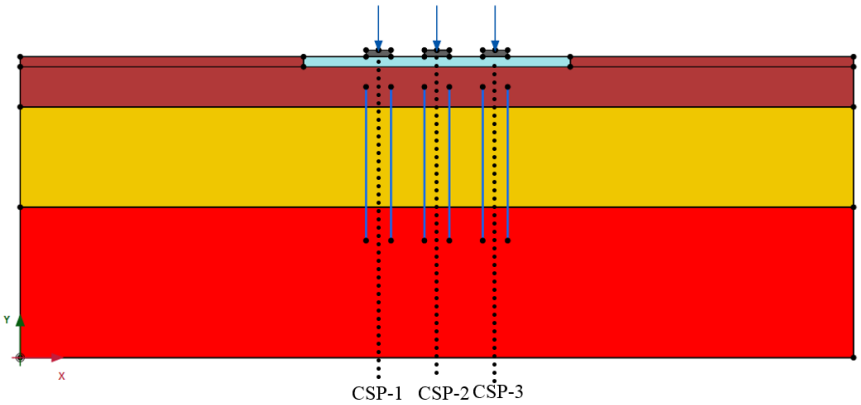


Fig.2. Location of cross section profile (CSP-1, CSP-2, CSP-3)

5.1.1 Case 1: Untreated soil (US)

The comparative analysis of profiles CSP-1 and CSP-2 reveals distinct settlement behaviors:

- Gross section CSP-1 shows a gradual reduction in settlement, decreasing from 94.88 mm at the surface to 3.89 mm at a depth of 9 m (Figure 3). This trend reflects the response of a relatively homogeneous but compressible soil, with significant deformation concentrated within the top 3 metres.
- In contrast, gross section CSP-2 exhibits a slightly higher initial settlement (105.04 mm at the surface), followed by a sharp decrease starting at a depth of 0.6 m, and subsequent stabilisation phases around depth of 1.56 m and of 3m (Figure 3). This behaviorindicates a heterogeneous stratigraphy, characterised by successive layers with varying stiffnesses.

This comparison highlights the importance of designing foundation solutions that consider not only the magnitude of settlements but also their depth-dependent distribution, which is strongly influenced by the soil's stratigraphic profile.

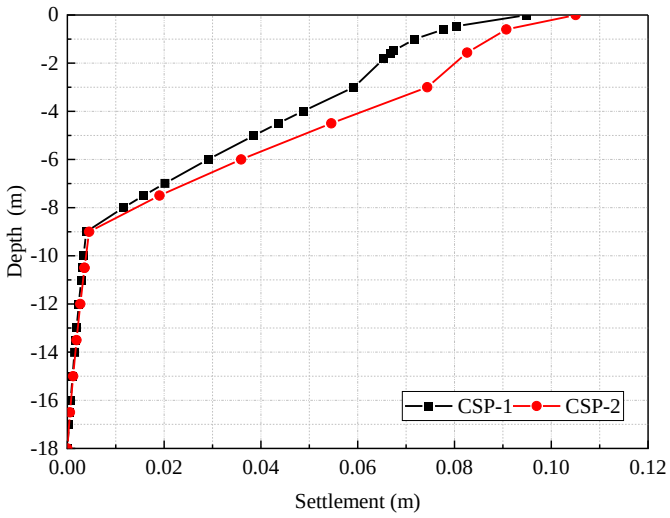


Fig.3. Settlement evolution with depth – Profiles CSP-1 and CSP-2 (Case 1: US)

5.1.2Case 2: USreinforced with LTP

The evolution of settlement with depth for gross section CSP-1 and CSP-2, corresponding to Case 2: Soil reinforced with a load transfer platform (LTP), is presented in figure 4.

Gross section CSP-1 shows a significant improvement compared to the untreated natural soil, with the maximum surface settlement reduced to 76.11 mm (Figure 4). Settlement decreases progressively to 3.88 mm at a depth of 9 m, indicating the overall effectiveness of the LTP in uniformly improving the treated soil mass. However, the 16.68 mm reduction between the surface and a depth of 3m suggests that, despite its general efficiency, the LTP does not entirely eliminate compressibility in the upper layers.

In comparison, gross sectionCSP-2 exhibits a higher initial settlement (90.05 mm), followed by a sharp increase in stiffness starting at a depth of 0.6 m. Pronounced settlement plateaus at a depth of 1.56 m and of 3 m indicate a more heterogeneous mechanical response, likely

reflecting variability in the quality or effectiveness of the LTP installation. Although the final settlement is similar to that of gross sectionCSP-1 (3.52 mm at a depth of 9 m), this variability underscores the need for strict quality control during LTP implementation to ensure uniform mechanical properties throughout the reinforced zone.

These observations confirm that the LTP's influence is most pronounced at greater depths. Consequently, additional reinforcement in the upper layers could be considered to further optimise the overall performance of the foundation system.

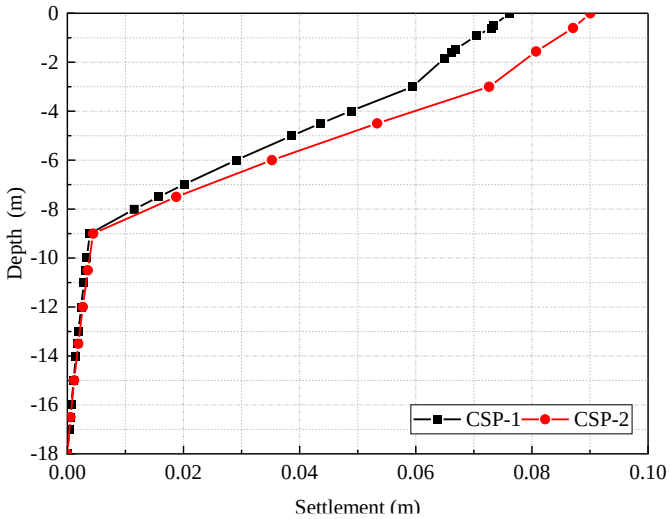


Fig.4. Settlement evolution with depth – Profiles CSP-1 and CSP-2 (Case 2: Soil reinforced with LTP)

5.1.3Case 3: US + LTP + rigid inclusions

Figure 5 illustrates the evolution of settlement with depth for gross section CSP-1 and CSP-2, corresponding to Case 3: Soil reinforced with both a load transfer platform (LTP) and rigid inclusions.

The comparative analysis of CSP-1 and CSP-2 reveals generally similar settlement behaviour, albeit with some notable differences. Gross sectionCSP-1 records a maximum surface settlement of 31.4 mm, slightly lower than that of gross section CSP-2 (32.35 mm). Both curves exhibit a sharp decrease in settlement within the first few metres, followed by a gradual stabilisation beyond a depth of 3 m.

However, gross sectionCSP-2 displays slightly more pronounced fluctuations between 1.3 m and 2.7 m of depth, which may reflect localised heterogeneities in the implementation of the reinforcement. The results confirm the effectiveness of the combined treatment, with settlements below 15 mm from −3 m downward. Moreover, the convergence of both profiles beyond 6 m of depth, with a maximum deviation of only 0.5 mm, attests to the high quality of deep reinforcement.

Nevertheless, the discrepancies observed between 1.5 m and 3 m of depth suggest that additional quality control targeting this depth range could be beneficial. These results indicate

that the settlement-reduction objectives were largely achieved, while also revealing potential for further optimisationparticularly in the upper soil layers.

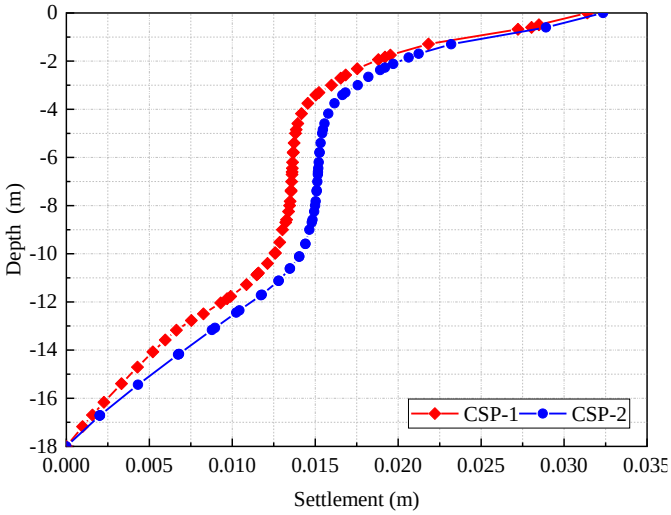


Fig.5. Settlement evolution with depth – Profiles CSP-1 and CSP-2 (Case 3: US + LTP + RI)

5.2 Comparative analysis of results

The comparative analysis of the three settlement cases reveals a progressive and significant improvement in soil behavior due to the successive reinforcement treatments. In its initial state, the untreated soil exhibits a maximum surface settlement of 94.88 mm, with a gradual decrease reaching 3.89 mm at a depth of 9 ma typical response of a highly compressible material, justifying the need for ground improvement strategies such as preloading with vertical drains or the use of deep foundations.

The introduction of a load transfer platform (LTP) in the first reinforcement scenario already yields a notable reduction in surface settlements, ranging from 20% to 30% (Figure 6). However, the discrepancies between the two profiles suggest heterogeneity in treatment effectiveness, likely attributable to construction variability or local soil conditions.

In contrast, the optimised configuration with both LTP and RI leads to a marked improvement, with maximum settlements reduced to 31.4 mm and 32.35 mmrepresenting a 65% to 70% reduction compared to the untreated soil (Figure 6). Furthermore, the consistency of the results across both profiles indicates the robustness of the implementation protocol. This treatment is characterised by prompt settlement stabilisation within the first few metres and negligible residual deformations beyond 6 m depth, making it a reliable and high-performance solution for structures requiring strict deformation control.

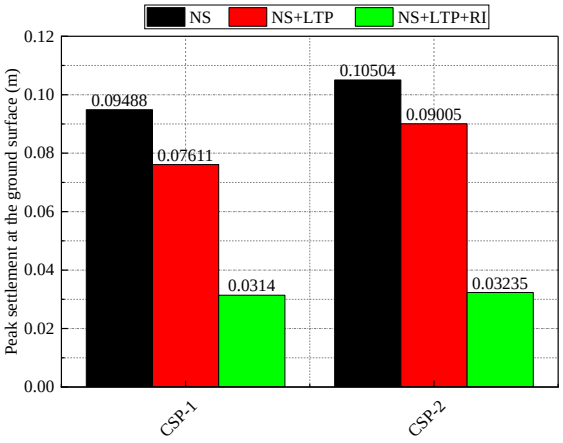


Fig.6. Effect of reinforcement method on the magnitude of final settlements

6. CONCLUSION

This study assessed, through numerical modelling, the behaviorof a compressible soil under shallow foundations, reinforced successively with a load transfer platform (LTP) alone, and then with a combination of LTP and rigid inclusions. The analysis focused on the evolution of settlements and the distribution of stresses.

The results indicate that:

- The natural soil exhibits significant settlements, heterogeneous stress distribution, and a high risk of localised plastic deformation;
- The load transfer platform significantly reduces settlements and improves stress distribution, although its effectiveness is limited at greater depths;
- The addition of rigid inclusions leads to a substantial reduction in settlements and provides an almost uniform bearing layer, though stress redistribution at depth may result in localised deformation increases.

These findings highlight the relevance of combining LTP and rigid inclusions in foundation projects on weak soils. However, a detailed analysis of deep-soil behavioris recommended to prevent unfavourable stress redistribution effects.

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