Different approaches to predict the ground settlements reinforced by rigid inclusions

Farbod Yarmohammadi[1], Ondrej Synac[2], Kostas Lontzetidis[3]

[1]CMW Geosciences, A3/63 Apollo Drive, Rosedale, Auckland 0632; PH (+64) 09 4144 632; email: FarbodY@cmwgeo.com
[2]CMW Geosciences, Level 3.17, 55 Miller Street, Pyrmont, NSW 2009; PH (+61) 02 9054 1243; email: OndrejS@cmwgeo.com
[3]CMW Geosciences, A3/63 Apollo Drive, Rosedale, Auckland 0632; PH (+64) 09 4144 632; email: KostasL@cmwgeo.com

ABSTRACT

Excessive ground settlements associated with building loads in highly compressible soils are among the most challenging geotechnical engineering problems, which can adversely affect the performance of the structures. Improving the performance of the soil using rigid inclusions is one of the most innovative methods to reduce the differential and overall settlements under the buildings. Rigid inclusions are not connected to the structures but are separated by a load transfer platform, usually consisting of a dense-graded aggregate layer with or without geogrids. Due to the complex nature of the load transfer mechanism and the interaction between the soil and the rigid element, there are still significant challenges to predict the settlements of the rigid inclusions. This paper draws a comparison between the possible methods including finite element modelling and analytical approaches for predicting the settlement of the ground improved by rigid inclusions. The results of the analyses are compared against the field measurements from a static load test in a site located in Auckland, New Zealand. This comparison between the predicted and measured settlements aims to assist the engineers to choose the appropriate approach for designing rigid inclusions.

Keywords: Numerical Modelling, Ground Improvement, Rigid Inclusions, PLAXIS, RATZ, RSPile

1 INTRODUCTION

Soft compressible soils can undergo significant settlements under an external surcharge. A classical solution to this problem is to use deep foundations under structures to transfer loads to the competent layers (Das & Sivakugan, 2018). However, due to the significant cost and time required for deep foundations, researchers and engineers have proposed different techniques to improve the performance of existing ground to support structural loads. Han (2015) classified the soil ground improvement methods into six main categories: 1) densification, 2) replacement, 3) drainage and consolidation, 4) chemical stabilisation, 5) reinforcement, and 6) thermal and biological treatment. Rigid inclusion is one of the recent techniques of soil reinforcement to increase the bearing capacity of the shallow soft soil and decrease the building settlements (Cirión et al., 2013). Early applications of rigid inclusion consisted of wooden piles pushed into the ground to increase the overall soil stiffness under the foundations (Auvinet & Rodríguez, 2006). However, with the recent advancements in technology, engineers have started to use concrete inclusions, which showed significant improvement compared to the timber columns (Cirión et al., 2013). These columns are not connected to the superstructure as their purpose is to improve the bearing capacity of the soft ground and reduce the anticipated settlements. A load transfer platform (LTP) consisting of a sandy or gravelly layer, is usually placed on top of the reinforced soil to help the efficient transfer of the load from the superstructure to the rigid inclusions (Auvinet & Rodríguez, 2006; Han & Gabr, 2002; Russell & Pierpoint, 1997; van Eekelen et al., 2013).

Several researchers have proposed different methods for rigid inclusions modelling (Bhasi & Rajagopal, 2015; Blanc et al., 2014; Combarieu, 1990; Mánica Malcom et al., 2016; Pérez & Melentijevic, 2015; Raithel et al., 2008). However, due to the complex interaction between the concrete columns, the soil, the LTP and the superstructure, there is still considerable uncertainty about the most efficient way to model the inclusions, especially for typical commercial solution such as warehouses. This paper draws a comparison between five possible approaches including finite element (FE) modelling and analytical approaches for predicting the settlements of the ground improved by rigid inclusions. The results of the analyses are compared against the field measurements from a static load test in a site located in Auckland, New Zealand, to assess the accuracy of the predictions. Furthermore, the ability of the different approaches to capture the ultimate capacity of the rigid inclusions will be analysed. This study aims to assist the designers in choosing the most efficient approach for designing the rigid inclusions.

2 SUMMARY OF THE PROJECT

CMW Geosciences undertook the detailed design of a ground improvement system in July 2021 to provide permanent support to a proposed single storey commercial development located at Papakura, Auckland, New Zealand. The ground improvement system comprises concrete rigid inclusions installed beneath the proposed footings and slab to limit the ground settlements. Post-construction load tests were performed on a test pile by putting a steel plate on top of the rigid inclusion and applying the pressure on it using a jack. Additionally, the piling rig was placed directly above the jack to apply the counterbalancing force. Three gauges were placed on different sides of the plate to monitor the vertical displacement of the rigid inclusions. The results of these tests are used in this paper to assess the predictions of different modelling approaches.

2.1 Ground model

Figure 1 and Table 1 present the ground model and the material properties used in the numerical modelling, respectively. 11m long unreinforced rigid inclusions with 450mm diameter and variable centre to centre spacings (i.e. from 2.5m to 6m) were designed to mitigate the large settlements in the soft material due to the bearing pressure of the proposed building (around 125mm under a 10kPa load).

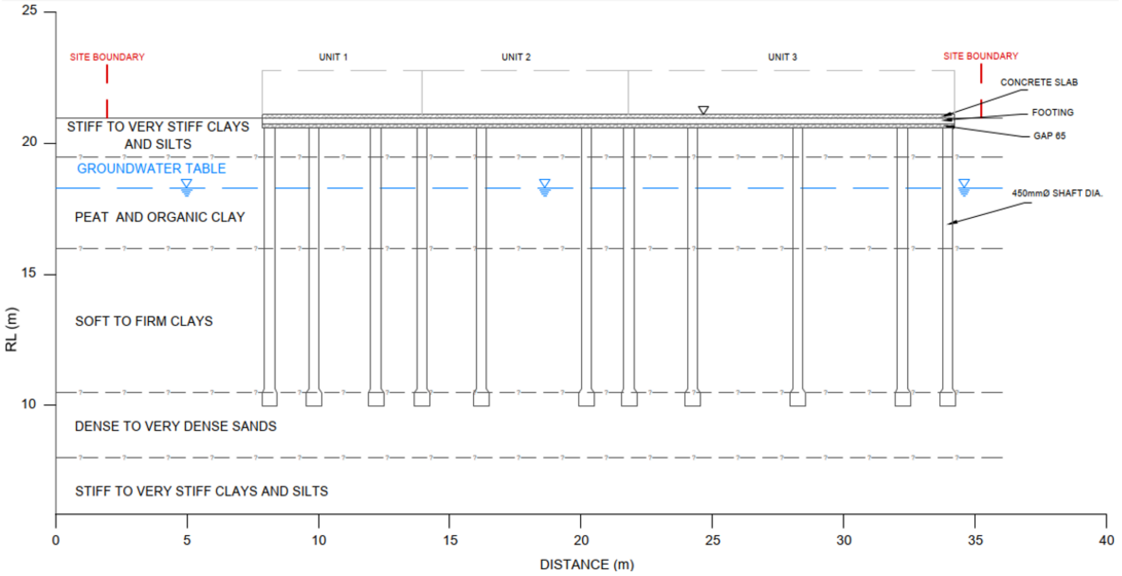

Figure 1 – The proposed ground model for the site

Table 1 –Material properties

Soil Layer	Thickness (m)	γ (kN/m)	S_u (kPa)	E (MPa)	Mohr-coulomb		HS/HS Small				HS Small	
					c' (kPa)	ϕ' (°)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur} (MPa)	m	γ0.7	G_0^{ref} (MPa)
Stiff to Very Stiff Clays and Silts	1.50	18	80	28	5	28	22.4	17.92	67.2	1	8×10^{-4}	25
Organic Clays and Peat	3.50	17	10	1.5	1	25	1.2	0.96	3.6	1	5×10^{-5}	5
Soft to Firm Clays	5.50	17	20	3	1	25	2.4	1.92	7.2	0.8	7.5×10^{-5}	11
Dense to Very Dense Sands	3.50	18	-	40	1	35	32	25.60	96.0	0.5	1.5×10^{-4}	100
GAP65	0.15	20	-	100	0	40	-	-	-	-	-	-
Rigid Inclusion	-	22	-	16.67×10^{3}	-	-	-	-	-	-	-	-
Concrete Slab	0.18	23	-	25.70×10^{3}	-	-	-	-	-	-	-	-

Five different numerical modelling approaches are used in this study: 1) FE modelling using Mohr-Coulomb model in PLAXIS 2D (Brinkgreve et al., 2017), 2) FE modelling using the Hardening Soil model (Schanz et al., 2019), 3) FE modelling using Hardening Soil model with small strain stiffness-HS-small (Benz, 2007; Schanz et al., 2019) in PLAXIS, 4) analytical analyses using RATZ software (Randolph, 2003), and 5) analytical analyses using t-z/Q-z curves (API, 2000) in RSPile software (Rocscience Inc., n.d.).

3.1 PLAXIS models

Unit cell axisymmetric models were developed in PLAXIS 2D to predict the settlement of the reinforced ground during the load tests. Undrained soil properties were used to model the load tests as they are done in short-term. Ballam and Booker (1981) recommendations were used to determine the dimensions of the unit cell. Mohr-Coulomb, Hardening Soil (HS) and HS-Small models were considered in the analyses to investigate the importance of the change in soil stiffness with strain in studying rigid inclusions. 15-node triangular elements with "very fine" global coarseness were chosen for the model (Figure 3). Furthermore, solid elements were used to model the soil, rigid inclusion and the overlying slab. Finally, an interface strength reduction factor of $R_{inter} = 0.6$ was chosen for the interface between the soil and the rigid inclusion. To properly model the testing condition, the loads from the tests were applied as point loads on top of the inclusions consecutively to calculate the corresponding displacements at the top of the piles for each soil model.

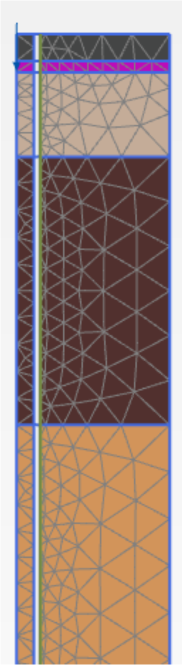

Figure 2 – Generated mesh for the FE model

3.2 Other models

Additional analyses were performed to estimate the rigid inclusion settlements using two different approaches including modelling of the rigid inclusion as a pile in RSPile and RATZ computer programs. RSPile uses the t-z/Q-z curves to take into account the skin friction and end bearing acting on the rigid inclusion and calculate its settlement under different loads. This is consistent with the approach recommended by the American Petroleum Institute (API, 2000) to model embedded piles.

RATZ is a software developed for non-linear 1-dimensional multi-segment modelling of piles. It considers the interaction between the soil and the rigid inclusion using the modified t-z/Q-z curves according to the soil properties. RATZ is also able to consider the group effects, cyclic load effects and thermal effects on the pile, which are beyond the scope of this paper.

4 RESULTS

4.1 Comparison with the load test

Figure 3 presents the settlement predictions of different modelling approaches compared to the experimental results from the load tests. Moreover, Table 2 summarises the root mean square (RMSE) values of the numerical modelling approaches with respect to the experimental data. From Figure 3 and

Table 2 it can be concluded that the HS Small model is the best model for predicting the settlement of the rigid inclusions during the loading and unloading events. Additionally, although the RATZ software decently captures the rigid inclusion settlements during the loading period, the unloading process was not modelled in this software, which led to a higher RMSE value compared to the HS Small model. Figure 3 also shows an example of the improved performance of the HS Small model in capturing the soil response, especially in small strains compared to the HS model. Finally, Figure 3 demonstrates that all the non-linear models performed better than Mohr-Coulomb, which significantly overestimates the rigid inclusion settlements, especially in larger loads that lead to more non-linearity in soil behaviour.

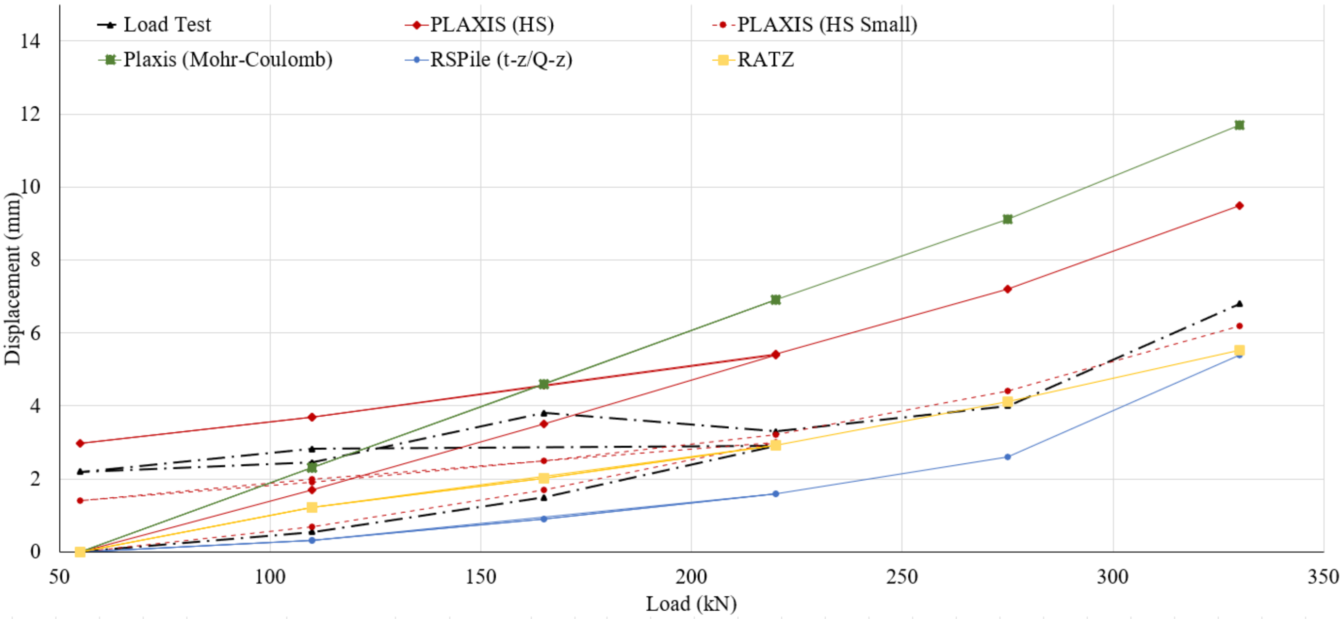

Figure 3 – The results of different modelling approaches compared to the load test

Table 2 – Comparison between the RSME values of different approaches

Modelling approach	PLAXIS (Mohr-coulomb)	PLAXIS (HS)	PLAXIS (HS Small)	RSPile	RATZ
RMSE (mm)	3	1.8	0.6	1.7	1.2

After validating the developed models against the experimental data from the load tests, additional analyses were performed to compare the ability of the models in estimating the ultimate capacity of the inclusions. The results of these analyses are presented in the next section.

4.2 Ultimate capacity of the piles

API recommends the point where the pile settles more than 10% of its diameter as its failure point and the load corresponding to this point as the ultimate capacity of the pile (API, 2000). Therefore, for the rigid inclusion considered in this study, the ultimate capacity is the load that leads to 45mm settlement in the column. However, due to the lack of experimental data and the ability of the PLAXIS HS Small model to accurately capture the pile displacements, this model was chosen as a reference to assess the other models' predictions. It should be noted that the load tests were done to a maximum displacement of around 6mm (≈ 13% of the ultimate load) and therefore are not included in this section. According to Table 3, most modelling approaches significantly underestimate the ultimate capacity of the rigid inclusions mainly due to the overestimation of the displacements. On the other hand, RATZ has the closest prediction to the PLAXIS-HS Small model while slightly overestimating (i.e. around 5%) the ultimate capacity.

Table 3 – Predicted ultimate capacity of the piles using different numerical approaches

Modelling approach	PLAXIS (HS Small)	PLAXIS (Mohr-coulomb)	PLAXIS (HS)	RSPile	RATZ
Ultimate capacity (kN)	892	430	635	405	935

5 CONCLUSIONS

This paper drew a comparison between five numerical modelling approaches to estimate the settlement and ultimate bearing capacity (based on the measured settlement) of rigid inclusions: 1) FE modelling using Mohr-Coulomb model in PLAXIS 2D, 2) FE modelling using the Hardening Soil model, 3) FE modelling using Hardening Soil model with small strain stiffness-HS-small in PLAXIS, 4) analytical analyses using RATZ software, and 5) analytical analyses using t-z/Q-z curves in RSPile software.

The results of the analyses were compared to the experimental data from a load test performed for a project in Auckland, New Zealand to validate the developed models and assess the quality of the predicted settlements. The results of these analyses showed that although most of the models could decently predict the rigid inclusion settlements during the loading period, only a proper non-linear model (i.e. HS Small) could predict the pile performance during the unloading event. Moreover, a comparison between the RSME values of the predicted settlements showed that the PLAXIS HS Small models could estimate the results of the load test better than other models (i.e RSME value of 0.6mm). The analyses performed in the RATZ software also showed a decent performance with an RMSE value of 1.2mm. On the other hand, the results showed that an elastic-plastic model like PM4Sand cannot consider the complex behaviour of the reinforced soil during the load tests.

Further analyses were performed to assess the ultimate capacity of the inclusions using the aforementioned approaches. Since the HS Small model produced the most accurate results in the previous section, the results of this model were chosen as reference to assess the performance of the other models in capturing ultimate capacity of the piles. These analyses showed that similar to the settlements, RATZ has the closest prediction to the PLAXIS-HS Small model with around 5% difference. All other models significantly underestimated the ultimate capacity of the rigid inclusions mainly due to the overestimation of their settlements.

This paper can help the engineers to choose the most efficient approach when modelling the rigid inclusions for real world applications. It also shows the importance of choosing the proper soil model for analysing the complex behaviour of rigid inclusions. It should be noted that the results of this study are limited to the soil type and the piles included in these analyses. Further studies are required to generalize the findings of this paper.

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