Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

Centrifuge modelling for the investigation of the load-transfer mechanism of rigid inclusions foundation

Modélisation en centrifugeuse pour l'étude des mécanismes de transfert de charge des fondations renforcés par inclusions rigides

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ABSTRACT: The Rigid inclusions are cylindrical or prismatic elements used to transfer loads to deeper and more resistant strata. Rigid inclusions are not structurally connected to the foundation, are separated by a load transfer platform commonly formed by granular material reinforced with geosynthetics placed above the inclusions. This technique has been used mainly in embankment projects for settlement control in soft soils. In recent decades the technique has been used more frequently as a foundation method for different structures. This paper investigates the load transfer mechanism developed in the earth platform conformed by fine-grained soil (with and without cement) characteristic of the Central Brazilian plateau, considering the load applied through a rigid slab. Part of the results obtained from 11 physical models developed in a geotechnical centrifuge was presented. The main parameters studied were: the diameter of the inclusion and the thickness of the load transfer platform. The axial load developed in the center and border inclusions and the vertical displacements in the foundation slab were measured. Likewise, for each of the materials used, it was possible to obtain the shape of the load transfer column developed between the head of the inclusion and the foundation slab.

RÉSUMÉ : Les inclusions rigides sont des éléments cylindriques ou prismatiques utilisés pour transférer des charges vers des strates plus profondes et plus résistantes. Les inclusions rigides ne sont pas structurellement connectées à la fondation, sont séparées par une couche de transfert de charge généralement formée par un matériau granulaire renforcé avec des géosynthétiques placés au-dessus des inclusions. Cette technique a été principalement utilisée dans les projets de remblais pour le contrôle des tassements dans les sols tendres. Au cours des dernières décennies, la technique a été utilisée plus fréquemment comme méthode de fondation pour différentes structures. Cet article étudie le mécanisme de transfert de charge développé dans la couche de transfert de charge conformée par un sol à grain fin (avec et sans ciment) caractéristique du plateau central du Brésil, en considérant la charge appliquée à travers une radier de fondation. Une partie des résultats obtenus à partir de 11 modèles physiques développés dans une centrifugeuse géotechnique a été présentée. Les principaux paramètres étudiés étaient: le diamètre de l'inclusion et l'épaisseur de la couche de transfert de charge. La charge axiale développée dans les inclusions de centre et de bordure et les déplacements verticaux dans la radier de fondation ont été mesurés. De même, pour chacun des matériaux utilisés, il a été possible d'obtenir la forme de la colonne de transfert de charge développée entre la tête de l'inclusion et le radier de fondation.

KEYWORDS: centrifuge modelling, foundations, rigid inclusions, soft soils, cohesive load transfer platform, ground improvement.

1 INTRODUCTION.

Rigid inclusions are vertical elements that transmit the load of the structure to deeper and less compressible layers. Load transfer occurs through a compacted material known as a load distribution platform (LTP), Figure 1. The earth platform can be composed of gravel, ballast, lime-cement-soil, cement, or another type of cemented soil (Okyay et al., 2014).

According to Okyay et al. (2014), the technique is used to design different types of structures, e.g., embankments, slabs, industrial buildings, wastewater treatment plants, wind turbines, among others. In most of the studies found in the literature, the LTP is formed by granular material reinforced with geosynthetics, and this technique is primarily applied to embankment projects (Briançon et al., 2015). According to Chevalier et al. (2011), when the load is transferred to the LTP through a rigid slab or footing, the load transfer mechanism obtained is very different from that observed in the case of an embankment.

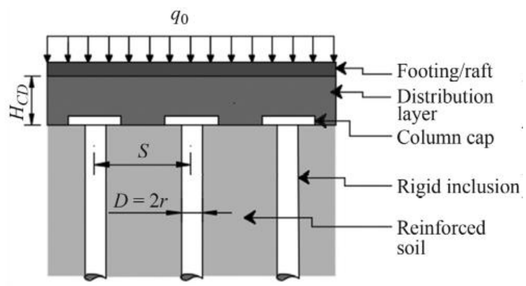


Figure 1. General scheme of a rigid inclusion foundation (Rodriguez-Rebolledo et al., 2019)

The rigid inclusions technique has been studied through: field and laboratory tests, full-scale physical models, small-scale models using a geotechnical centrifuge and numerical models (Auvinet and Rodríguez-Rebolledo, 2006; Rodríguez-Rebolledo and Auvinet, 2006; Garnier et al., 2007; Ellis & Aslam, 2009a, 2009b; Baudouin, 2010; Baudouin et al., 2010; ASIRI, 2011;

Blanc et al., 2013; Okyay et al., 2014; Girout et al., 2014 , 2016, 2018; Pérez, 2017; Rodríguez-Rebolledo, et al., 2019; Pérez et al., 2020).

This work focuses on using an alternative material for the LTP, which is a compacted fine-grained tropical soil with or without cement. The material is abundant in the Central Brazilian Plateau. The behavior and the transfer mechanism developed for both center and border inclusions are studied. Results obtained from 11 physical models developed in a geotechnical centrifuge are presented. The main parameters studied are the diameter of the inclusion and the thickness of the LTP. The forces in the heads of the inclusions and the vertical displacements of the foundation slab were measured. Likewise, for each of the materials used, it was possible to obtain the shape of the load transfer column developed between the head of the inclusion and the foundation slab.

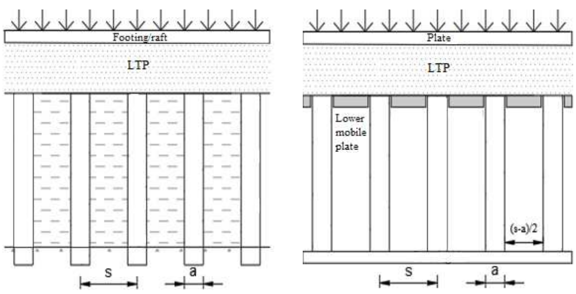
2 CENTRIFUGE MODELING

The geotechnical centrifuge used belongs to the geotechnical modeling laboratory of the Universidad de los Andes in Bogotá, Colombia. The centrifuge has a 1.9 m radius, which supports models up to 400 kg at a maximum radial acceleration field of 200g and 50 channels for Instrumentation. Figure 2 shows the main parts of the centrifuge: 1) data acquisition system, 2) arm, 3) model containers, 4) counterweight box, 5) drive motor.

Figure 2. *Universidad de los Andes* geotechnical centrifuge

2.1 *Principles and geometry of the test*

The prototype represented consists of a group of 14 rigid inclusions with diameters of 38.1 cm and 76.2 cm, with axis spacing of 180 cm, thicknesses of the load transfer platform (LTP) of 100 and 166 cm, rigid slab of 750 cm diameter, and formed by compacted natural soil (NS) and natural soil improved with cement (CS). The reinforced soil contribution was not included in the model and was replaced by using a mobile plate at the bottom of the LTP. The plate had 14 holes to allow the inclusions to pass freely through it. Figure 3 shows the cross-section of the prototype and the physical model.



(a) (b)

Figure 3. Comparison of the represented phenomenon: a) prototype and b) physical model.

2.1.1 *Model description*

Figure 4 shows the small-scale centrifuged device made of aluminum inside the centrifuge basket.

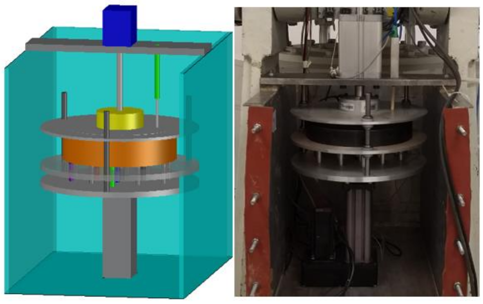


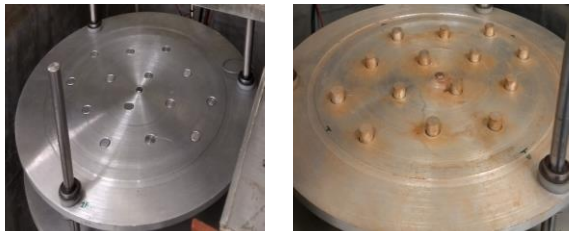
Figure 4. *Schematic view of the model and manufactured equipment*

The physical model was supported on an aluminum plate (plate 1) where the inclusions were embedded employing a rigid connection. On the first plate, the linear bearings were set. Linear bearings prevent tilting of the other plates during the test.

The central plate (plate 2), which simulates the subsoil settlement, can move downward using an electric actuator.

Several studies have used the mobile plate as a tool to simplify physical models. Works such as Rault et al., (2010), Blanc et al., (2013); Okyay et al., (2014), and Fagundes et al. (2015).

A detail of the mobile plate used can be seen in Figure 5.



(a) (b)

Figure 5. Mobile plate: a) before the test and b) after the test.

In this test, the plate was moved at a constant rate until it was completely separated from the load transfer platform to simulate the most critical condition. After separation from the reinforced soil, the LTP rests totally on the group of 14 inclusions.

The top plate (plate 3) is attached to a pneumatic actuator and allows distributed loads application on the distribution layer.

2.1.2 *Instrumentation*

Of the 14 inclusions, five were instrumented with miniature Futek LCM 200 load cells with a capacity of 1.1 kN. A 13.3 kN capacity Futek LCM 325 miniature load cell installed on the perforated movable plate was also used. The upper pneumatic actuator piston was instrumented with an 8.9 kN capacity Futek LCF 450 load cell. The upper plate settlements were obtained through a Linear Variable Differential Transducer (LVDT)

The details of the geotechnical Instrumentation are shown in Figure 6.

2.2 *Experimental campaign*

The tests were conducted using a geotechnical centrifuge at 30 g; some geometric and behavioral variables of the LTP material were considered that may influence the load transfer mechanism, such as the diameter of inclusions, area ratio, height of the LTP, and the type of compacted material.

Figure 6. *Details of the geotechnical instrumentation*

The experimental program consisted of carrying out 11 centrifugal tests, keeping the separation between inclusions constant (s = 6 cm in the model, s = 180 cm in the prototype), two types of distribution layer (NS and CS), two inclusion diameters, and various load distribution layer heights. Table 1 shows the characteristics of the 11 models, together with the equivalence in the prototype.

Table 1. Summary of tests

ID	Model a (cm)	Model H (cm)	Prototype a (cm)	Prototype H (cm)	H/s (%)	H/(s-a)	α (%)
D1H1NS	1.27	4.00	38.1	120.0	66.7	0.85	4.5
D1H2NS	1.27	4.56	38.1	136.8	76.0	0.96	4.5
D1H3NS	1.27	5.37	38.1	161.1	89.5	1.14	4.5
D2H1NS	2.54	4.00	76.2	120.0	66.7	1.16	17.9
D2H2NS	2.54	4.68	76.2	140.4	78.0	1.35	17.9
D2H3NS	2.54	5.54	76.2	166.2	92.3	1.60	17.9
D1H1CS	1.27	3.36	38.1	100.8	56.0	0.71	4.5
D1H2CS	1.27	4.44	38.1	133.2	74.0	0.94	4.5
D2H1CS	2.54	3.50	76.2	105.0	58.3	1.01	17.9
D2H2CS	2.54	4.60	76.2	138.0	76.7	1.33	17.9
B-D2H1NS	2.54	3.40	76.2	102.0	56.7	0.98	17.9

The test process simulates a critical condition where the lower plate is removed to develop the loading and rupture mechanisms without considering the contribution of the reinforced soil. Later, when there is total separation, the loading process is carried out in stages. The process consists of:

- Rotation of the centrifuge basket to verify connections and installed equipment;
- Rotation until reaching 30g that is maintained until the end of the test;
- Downward movement of the bottom plate (plate 2) at a controlled rate of 0.016mm / s until the bottom surface of the LTP completely separates from the plate;
- Application of loads in steps of 176.5N increments in the model and 158.9 kN in the prototype. The load is maintained for 48 hours in the prototype;
- End of the test, the centrifuge is decelerated, and the rupture geometry is verified qualitatively.

2.3 *Materials*

The material used as the LTP was a tropical soil typical of the Federal District and Central Brazilian plateau, available in large quantities in shallow and deep deposits.

The physical characteristics of the material were presented by Garcia (2021) and Garcia et al. (2021). The tests were performed according to the Brazilian Association of Technical Standards ABNT and ASTM (American Society for Testing and Materials).

The results of characterization tests from the soil are presented in Table 2

The soil presents considerable alterations when the granulometry test is performed with or without deflocculant, which means it presents high aggregations of silts and clays. With deflocculant, the USCS classified the soil as a CL (sandy clay with low plasticity) and without deflocculant as SC (clayey sand).

The MCT tropical soil classification methodology presented by Cozzolino and Nogami (1993) classifies the soil as a lateritic sandy clay (LA'-LG ').

Table 2. Properties of the LTP material

Grain size distribution	with deflocculant	Gravel (%)	0
		Sand (%)	30
		Silt (%)	17.5
		Clay (%)	52.5
	without deflocculant	Gravel (%)	0
		Sand (%)	87.5
		Silt (%)	12.1
		Clay (%)	0.4
Natural Unit weight - γ (kN/m³)			17.7
Specific gravity – G_s			2.8
Water content - w (%)			27
Liquid limit - w_L (%)			45
Plastic limit - w_P (%)			26
Plasticity index - I_P (%)			19
SUCS Classification (with deflocculant)			CL
SUCS Classification (without deflocculant)			SC
MCT Classification			LA'-LG'

The material of the load transfer platform was compacted in the optimal conditions of the Proctor standard (dry unit weight for the LTP is 14.95 kN/m3, and the optimum water content is 24.0%).

To compare the LTP formed by natural soil with a material having better strength and rigidity characteristics, the same material improved with 6% cement was used. According to Garcia (2021), with 6% cement, the unconfined compressive strength increased by approximately 80%. The rigidity increases approximately five times, and the cohesion and peak strength of the material increases.

Table 3. Properties of the LTP material

Material	σ_3 kPa	Peak strength c' kPa	Peak strength φ' °	Residual strength c' kPa	Residual strength φ' °	ψ °	ε_f %	q_f kPa	E_{50} MPa
NS	50	51	26	34	28	5	4.0	231	13
	100					0	4.0	340	17
	200					0	4.7	465	26
CS	50	66	41	33	42	10	0.5	455	76
	100					6	0.8	723	110
	200					4	1.1	1038	108

3 EXPERIMENTAL RESULTS AND DISCUSSION

The loads on each of the instrumented inclusions (Fi), the loads on the perforated mobile plate (Fp), and the loads on the load application piston (F1) were measured.

From the reading of the five load cells located in the inclusions, it was possible to calculate the approximate total load of the group of inclusions due to the symmetry conditions of the distribution of the instrumented inclusions (Figure 7).

3.1 *General behavior of the LTP formed by NS*

Figure 8 presents an example of typical results obtained for the D1H1NS test. The test procedure was divided into two phases, phase 1 corresponds to the displacement of the mobile plate, and phase 2 corresponds to the application of loads.

$$F_i = 4\left(F_4 + F_2 + \frac{F_3}{2} + \frac{F_5}{2} + \frac{F_6}{2}\right)$$

Figure 7. *Total load of the group of inclusions*

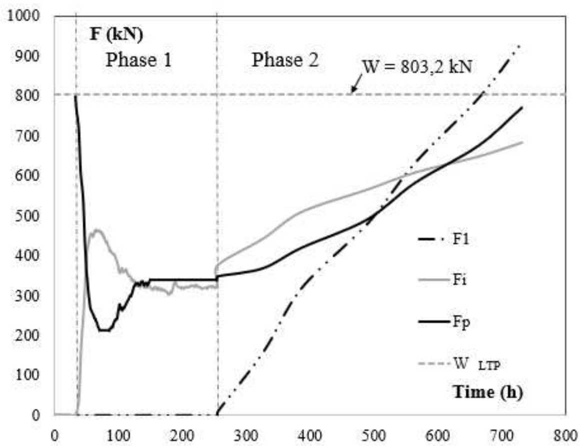


Figure 8. F_1, F_i, F_p versus time during the D1H1NS test

It is possible to observe that in phase 1, as the perforated mobile plate moves, the total weight of the distribution layer (W = 803.2 kN) is partially transferred to the group of inclusions (Fi), and the load Fp is relieved. It is possible to observe that the LTP shows a partial failure by leaning on the plate; thus, the FP force increases at the end of the displacement.

During the application of loads, it is possible to see that as the force F1 increases, the Force FP also increases, which indicates that punching shear failure occurs. Figure 9 shows the load transfer platform after the test, where the punching of the inclusions in the material is evident. In the three tests carried out with a diameter of 38.1 cm and a load transfer platform made up of natural soil (D1H1NS, D1H2NS, D1H3NS), the failure occurred in the same way.

Figure 9. *Typical punching failure of the D1H1NS, D1H2NS, D1H3NS tests*

Three tests were also carried out with an LTP formed by natural soil and a diameter of 76.2 cm. Figure 10 shows the variation with time of the forces F1, Fp, Fi during the two phases of the D2H1NS test.

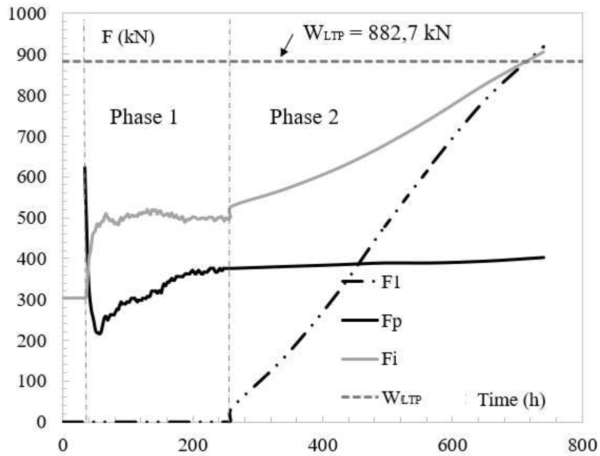


Figure 10. F_1, F_i, F_p versus time during the D2H1NS test

In this case, it is possible to see that during phase 2 of load application, the force on the plate is almost constant, indicating that the rigid inclusions fully assume the self-weight of the LTP, and the applied loads make the efficiency high. The system remained stable, as indicated in Figure 11.

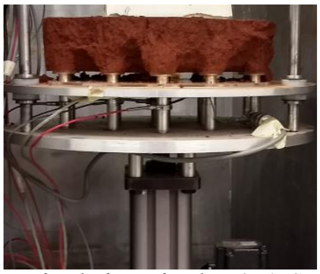


Figure 11. *Load transfer platform after the D2H1NS test*

Figure 11 shows that the load transfer platform did not break with the maximum loads applied in the test. The behavior was similar for the D2H1NS, D2H2NS, and D2H3NS tests.

3.2 *General behavior of the LTP formed by CS*

The results obtained for the CS showed total stability of the system during all the test phases, including for the group of inclusions with the minor diameter (diameter = 38.1 cm), the forces at the head of the inclusions are much higher than in the case of the load transfer layer made up of natural soil. This phenomenon can be explained by the fact that the stiffness of the CS is more than four times the stiffness of the natural soil. This load transfer platform is much more efficient in controlling settlements. Figure 12 shows that after the test for the minor diameter, the distribution layer did not present punching failure.

Figure 12. *Load transfer platform after the D1H2CS test*

3.3 *Load distribution in the center and border inclusions*

It was possible to analyze the load distribution between the center and border inclusions. The center elements receive most of the loads. Border inclusions do not contribute significantly to load distribution during phase 2. These inclusions lose confinement due to some partial failures. For example, Figure 13 shows the distribution of the loads in the inclusions during phase 2 of load application for the D2H1NS test.

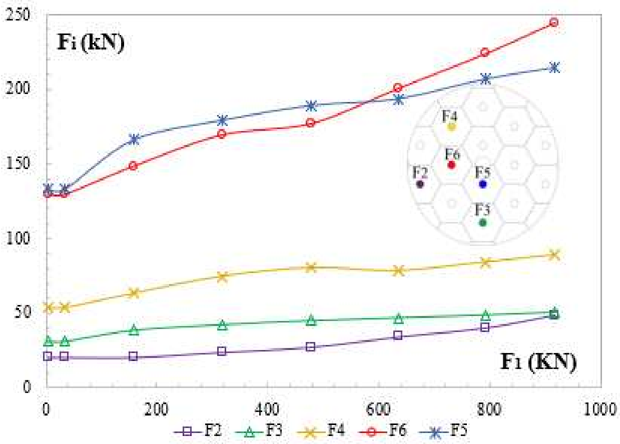


Figure 13. *Evolution of the forces at the head of the inclusions fo the D2H1NS test*

Figure 14 shows the total load percent received by the instrumented inclusions in each of the physical models made. It is observed that there is no uniform load distribution during the test. The center inclusions (inclusion 5 and 6) received between 10 and 21% of the total applied load in most cases. On the other hand, the border inclusions (inclusion 2, 3, 4) received between 1 and 7% of the load. The dashed line shows the theoretical load that each inclusion should receive if the uniform load distribution is considered.

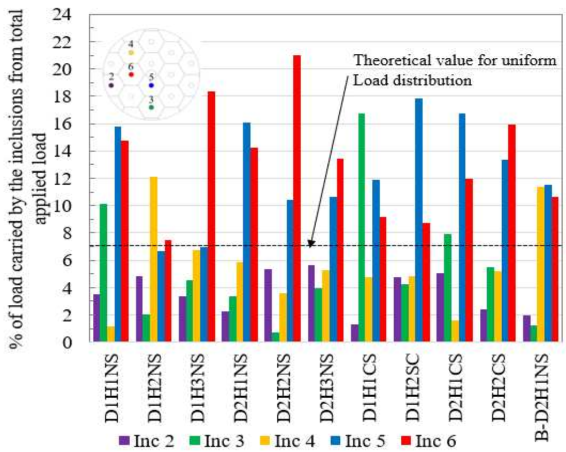


Figure 14. *% of load carried by instrumented inclusions*

3.4 *Failure mechanisms*

The tests D1H1NS, D1H2NS, and D1H3NS, failed by punching, as shown in Figure 9. There was no failure for the level of loads applied between 900 kN and 1600 kN in the other tests. It is clearly shown that the central part remains stable and the edges collapse, which proves that there is a need to construct a peripheral ring of rigid inclusions to increase confinement and control settlement. Figure 15 shows the partial collapse in various models.

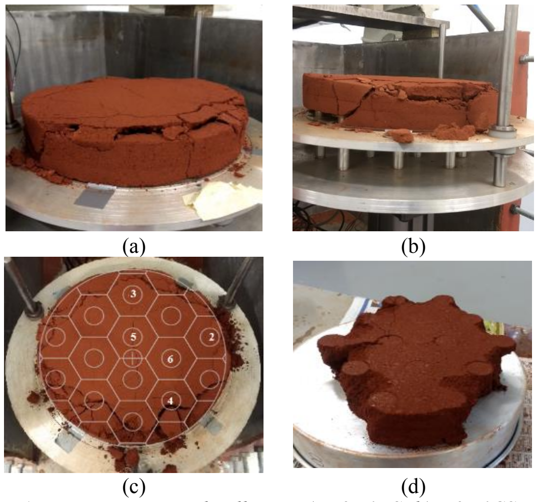


Figure 15. *Perimeter partial collapse: a) D2H1NS, b) D2H1CS, c) top view after the B-D2H1NS test, and d) contact area with the head of the inclusions after the D2H3NS test.*

The formation of an inverted truncated cone-shaped volume was observed in the head of the inclusion after the test, indicating the development of soil arching (Figure 16). The external angle varies depending on the properties of the LTP material.

Figure 16. *Soil-arching development after the B-D2H1NS test*

In the NS test, the mobilized rupture plane was close to 60˚, and for the CS tests, it was close to 65˚ (Figure 17). The geometry observed for each type of soil tested is consistent with Coulomb's theory (1776), where ($\beta = 45^\circ + \varphi / 2$).

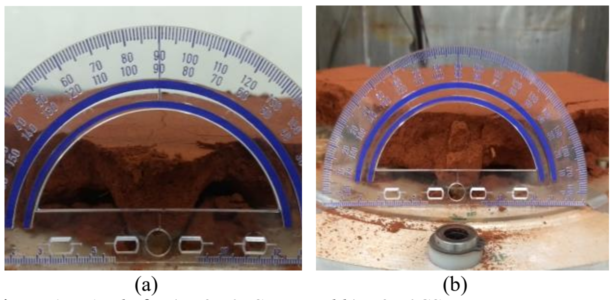


Figure 17. *Angle β: a) D2H1NS test and b) D2H1CS test*

3.4 *Settlement measures*

Figure 18 shows the normalized settlements for all the tests carried out. The maximum deformations were observed for the models with the minor diameter and LTP made up of natural soil; on the other hand, the minimum deformations for the tests carried out with the largest diameter and LTP formed by CS.

4 CONCLUSIONS

Geotechnical centrifugal physical models were performed to study the load transfer mechanism and failure mechanism in foundations reinforced by rigid inclusions when a rigid slab is used. The influence of the inclusion diameter, the height of the LTP, resistance, and rigidity of the LTP on the system's behavior was evaluated.

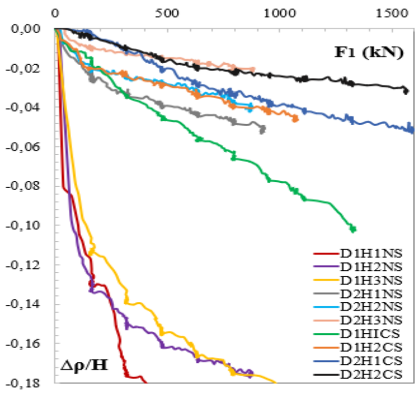


Figure 18. *Normalized total settlements (Δρ/H) versus applied load (F_1)*

For the same material, the settlements are lower for greater heights of the distribution layer and greater diameters of the inclusion, indicating that for higher heights, the arching of the soil develops better, and the increase of the diameter of the inclusion means of capitals improves the efficiency of the system considerably.

From the analysis of the failure mechanism and soil arching effect, a truncated cone-shaped volume was observed starting at the head of the inclusion and ending at the surface of the load transfer platform. The zone outside the truncated cone can generate reinforced soil pressures. The truncated cone external angle (β) varied for the CS material, which shows a direct relationship between the cone angle and material strength parameters, especially the friction angle. The mean angle β measured in the tests was 60° for NS and 65° for SC. The rupture angle was compatible with Coulomb's theory (β=45+φ/2).

There is no uniform distribution of loads in the group of inclusions; center inclusions receive much more load than border elements. The addition of cement in the LTP improved the system's performance. Increase the rigidity material, settlements decrease, but the forces at the head of the inclusion increase; these forces must be considered in the structural design of the foundation.

5 ACKNOWLEDGEMENTS

This study was financially supported by the Fundação de Apoio à Pesquisa do Distrito Federal - Brazil (FAPDF, project 9885.56.40280.07042016), the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brazil (CNPq).

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