BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 64 (68), Numărul 4, 2018
Secția
CONSTRUCȚII. ARHITECTURĂ

THREE DIMENSIONAL FINITE ELEMENT ANALYSIS OF FOUNDATION BEHAVIOR ON SOIL REINFORCED WITH RIGID INCLUSIONS

BY

CLAUDIU CONSTANTIN POPA[*] and VASILE MUȘAT

Gheorghe Asachi” Technical University of Iași
Faculty of Civil Engineering and Building Services

Received: October 10, 2018
Accepted for publication: November 17, 2018

Abstract. The use of rigid inclusions for soil bearing capacity and/or settlement control offers an efficient and economical alternative to the traditional pile foundations. The general approach towards analyzing a slab or a raft foundation on a rigid inclusion system is through the use of unit cell models constructed in programs which incorporate either the finite element or finite difference method. This type of model offers information regarding the interaction of the rigid inclusion with the surrounding soil and with the transfer layer. However, the effect of the inclusions on the global behavior of the slab or raft foundation cannot be anticipated in this manner. As such, three dimensional finite element models are necessary in order to study aspects such as the influence of foundation rigidity and the type and distribution of foundation loading on the bending moments and shear forces that develop in the raft or slab. In this article the results of an analysis of a raft foundation on a rigid inclusion reinforced soil, modelled in the finite element software, Plaxis 3D, are presented and discussed.

Keywords: soil improvement; rigid inclusion; finite element method; Plaxis 3D, raft foundation.

[*]Corresponding author: *e-mail:* claudiu_popa1990@yahoo.com

1. Introduction

A rigid inclusion system implies the presence of a soil transfer layer between the tip of the inclusions and the foundation, which represents the main difference from a pile foundation or a pile-raft foundation (IREX, 2012). Given the much higher stiffness of the inclusions in contrast with the surrounding soil, most of the load from the superstructure is attracted by these elements through the transfer layer, resulting in a reduced load in the natural soil (Simon, 2012). Although soil reinforcement is meant to lead to a shallow foundation design, such situations cannot be treated in a conventional manner and require a more detailed analysis of the foundation-reinforced soil system (Varaksin *et al*., 2016).

Studies of the impact of soil reinforcement solutions on the behaviour of foundations have been mostly focused on the flexible inclusion area (i.e. stone columns). A reason for this could be the fact that the stone column reinforcement method is much older than that of rigid inclusions (Simon, 2012). Balaam and Booker were among the first to study the bending moments and shear forces that develop in a uniformly loaded circular rigid raft on a granular column reinforced soil through an analytical approach of a unit cell model of the problem. They concluded that the magnitude of the bending moments and shear force are mainly dependent on the column spacing and stiffness ratio between the columns and soil (Balaam & Booker, 1981). Das and Deb further extended this analysis by studying a similar problem but in a global manner through the use of a mechanical model in which the columns were modelled as equivalent stone rings in order to analyse the system in axi-symmetric conditions (Das & Deb, 2014). The results were in accordance with the ones obtained by Balaam and Booker and further insight into the influence of the raft flexibility, shear modulus of the granular layer and ultimate load bearing capacity of the soft soil on the settlements, bending moments and shear force was given.

Regarding the influence of rigid inclusions on foundation stresses, Bohn conducted a simple analysis with the use of a finite element unit cell model, by which she illustrated the significantly higher values of the foundation maximum and minimum bending moments in the case of a rigid inclusion reinforcement compared with the case of a granular column (Bohn, 2015). Thus, even with the use of a transfer layer, the effects of a rigid inclusion reinforcement are expected to have a more important influence on the foundation stresses.

Given that the efficiency of rigid inclusions in settlement reduction is already an established factor, this article aims to study the impact of a rigid inclusion system mainly on the bending moments and shear forces that develop in a raft foundation. In this context the influence of the type of external loading is studied. The rigidity of the foundation is also analysed by taking into consideration two values for the raft thickness, one for which the raft falls into the category of flexible behaviour and the other of rigid behaviour. The results are presented in terms of maximum and relative settlement, bending moments and shear forces in the raft, considering the case of foundation lying firstly on the natural, unimproved soil, secondly on a stabilized soil cushion and finally on the rigid inclusion system which involves both the cushion / transfer layer and the reinforced soil.

2. Problem Description

The global behaviour of a foundation on rigid inclusion reinforced soil was analysed for the case of a 12 × 15 m raft foundation. The considered rigid inclusion system is composed of 0.6 m diameter plain concrete inclusions, with a length of 15 m, placed in a square grid, and a 0.5 m thick transfer layer between the raft and the inclusions, made from stabilized soil. The transfer layer was extended laterally at a distance of 0.5 m from the edges of the raft. The soil stratigraphy is composed of a 20 m thick layer of soft clay which lies on a layer of bedrock. The geometry of the rigid inclusion system is illustrated in Fig. 1.

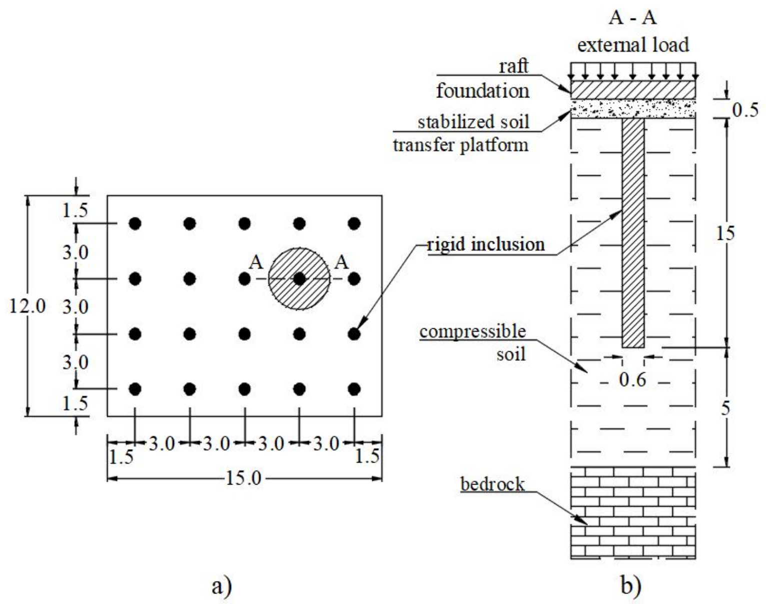


Fig. 1 – Plane view of the raft foundation (*a*) and vertical section through the rigid inclusion system (*b*).

The geotechnical and structural response of the foundation-reinforced soil system was evaluated for two different loading conditions, illustrated in Fig. 2. For both cases considered, the total load was kept equal to 18,000 kN.

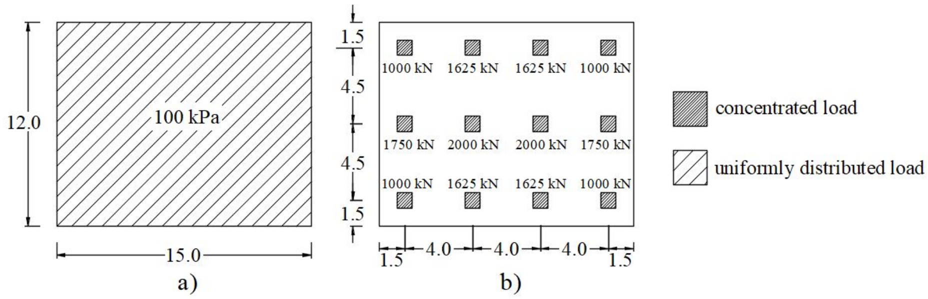


Fig. 2 – Loading conditions considered in the analysis: uniformly distributed load (*a*) and concentrated loads (*b*).

In order to study the influence of the raft flexibility, two values for the thickness of the raft were analysed, 0.5 m and 1.5 m. The flexible or rigid behaviour of the raft was established based on the rigidity index, K_G, calculated with Eq. (1) according to the Romanian standard, NP 112-2014.

$$K_G = \frac{12\pi(1-\nu^2)}{1-\nu_s^2} \cdot \frac{E_s}{E} \cdot \left(\frac{L}{2h}\right)^2 \cdot \frac{B}{2h}, \tag{1}$$

where: B, L are the raft dimensions, [m]; h – the thickness of the raft, [m]; E_s, ν_s are the soil deformation modulus and Poisson's ratio respectively, [kPa], [-]; E, ν are the foundation deformation modulus and Poisson's ratio respectively, [kPa], [-].

For the analysed situation, the soil deformation modulus was taken equal to 8000 kPa and Poisson's ratio was considered equal to 0.35. The reinforced concrete raft was considered with a deformation modulus equal to 1.082×10^7 kPa and a value of 0.2 for Poisson's ratio.

The results are indicated in Table 1. As can be seen, for the considered raft dimensions, a thickness of 0.5 m results in a flexible behaviour while a thickness of 1.5 m results in a rigid behaviour.

Table 1

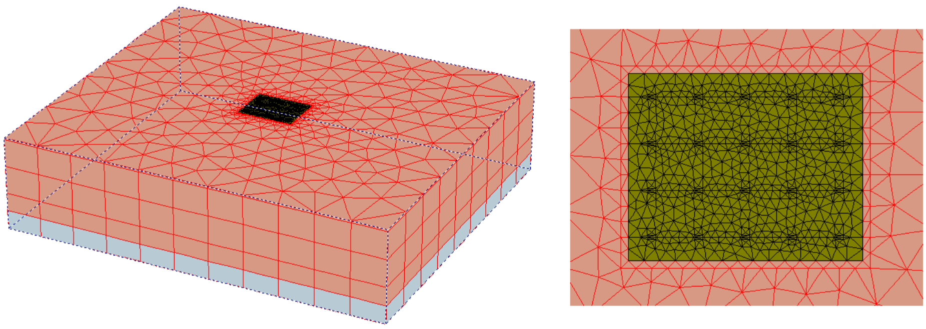
Evaluation of the Raft Foundation Rigidity Index, K_G

Raft thickness, [m]	Rigidity index K_G, [-]	Rigidity criterion: $8/\sqrt{L/B}$	Raft behaviour
0.5	82.33	7.15	$K_G > 8/\sqrt{L/B}$ → flexible behaviour
1.5	3.05		$K_G < 8/\sqrt{L/B}$ → rigid behaviour

3. Numerical Modelling by Finite Element Method

Although unit-cell models are usually employed in order to analyse raft foundations on reinforced soil, they are only representative for the central area of the raft and are limited to the study of uniformly distributed loads. The behaviour of a raft foundation on rigid inclusion reinforced soil can only be analysed in a global manner through the use of three-dimensional finite element or finite difference models (IREX, 2012).

In this case, the problem was studied with the use of the finite element program, Plaxis 3D. The boundaries of the model were placed far enough from the raft foundation so as not to influence the results of the analysis. Consequently, the horizontal boundaries of the model were placed at a distance of 45 m from the edges of the raft in longitudinal direction and at 39 m in transversal direction. Because of the very high stiffness chosen for the layer of bedrock, the position of the bottom boundary wasn't as important as long as it didn't "cut" through the layer of compressible soil. Regarding the level of discretization, in the horizontal plane a coarse mesh was adopted at the boundaries of the model, converging towards a fine mesh in the raft area. In the vertical plane the mesh resulted rather coarse. The discretized numerical model is illustrated in Fig. 3.



a) b)

Fig. 3 – The three-dimensional finite element model (*a*) and the level of discretization in the raft area (*b*).

The rigid inclusions were modelled with pile elements with a linear elastic behaviour. The raft foundation was modelled with a plate element with linear elastic isotropic behaviour. The transfer layer was considered to be made from stabilized soil in spite of the fact that granular materials are generally used.

This option was chosen because the numerical analysis was found to be very time consuming whenever cohesionless materials were used. The constitutive models and parameters used in the analysis for the compressible soil, transfer layer, rigid inclusions and base layer are presented in Table 2.

Table 2
Constitutive Models and Parameters of the Soil Elements

		Compressible soil	Transfer layer	Rigid inclusion	Base layer
Constitutive model		Mohr Coulomb	Mohr Coulomb	Linear Elastic	Linear Elastic
Behaviour		Drained	Drained	Non-porous	Non-porous
Parameter	Symbol and Unit				
Unsaturated unit weight	γ_{unsat} [kN/m^3]	18.0	18.5	24.0	20.0
Deformation modulus	E_{ref} [MN/m^2]	8.0	105.0*	7,400.0	4,000.0
Poisson's ratio	ν, [-]	0.35	0.30*	0.2	0.2
Cohesion	c, [kPa]	10.0	85*	–	–
Friction angle	φ, [°]	14.0	22.0*	–	–
Dilatancy angle	ψ, [°]	0	0	–	–

* the mechanical parameters of the transfer layer correspond to a cement stabilized silt (Okyay & Dias, 2010)

The analysis was carried out in three phases. In a finite element analysis, the first phase corresponds to the generation of the initial in situ stresses. In Plaxis 3D this is done by *Gravity loading*, which means that the stresses are calculated based on the soil self-weight (Plaxis, 2004). The displacements were reset to zero after this step. In the second phase, the volume of soil corresponding to the transfer layer was deactivated and the inclusions were activated. The third phase involved the activation of the transfer layer with the corresponding soil model, the floor element and the external load.

A specific modelling decision was made for the case of concentrated loads. Rather than using the point load option in the program, the concentrated forces were introduced as distributed loads on 0.5 × 0.5 m areas in order to better illustrate the influence of the rigid inclusions on the bending moments and shear forces.

4. Results

After a validation of the three dimensional model the results are presented firstly from a geotechnical point of view, in the form of total and relative settlements. The structural response is then analysed in terms of bending moments and shear forces in the raft foundation. Three cases are compared in terms of support of the raft foundation. The first case is represented by the unimproved soil (noted U.S.), the second case (noted C.) involves a 0.5 m thick stabilized soil cushion directly under the raft and the third case (noted R.S.) is the rigid inclusion reinforced soil.

4.1. Validation of the 3D Model

In order to test the accuracy of the results obtained from the three-dimensional numerical model, a comparison was made with the results from an axi-symmetric unit cell model, constructed in the finite element program, Plaxis 2D. The total settlements were compared in order to gain a quantitative point of view and the soil reaction at the base of the transfer layer in the central area of the raft was compared for a qualitative point of view. The results are illustrated in Fig. 4.

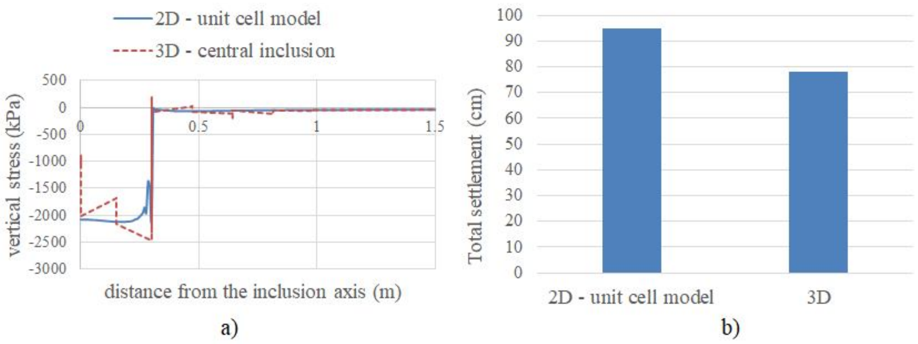


Fig. 4 – Comparative analysis between the 3D and 2D finite element models of the raft foundation on rigid inclusion reinforced soil: soil reaction at the base of the transfe layer (*a*) and total settlements (*b*).

In terms of soil reaction there is a good agreement between the two numerical models. Yet, the unit cell model delivers a value for the total settlement approximately 22% higher than the one obtained in the 3D model. A probable reason for this difference could be the fact that a unit cell model does not allow for lateral diffusion of the load (IREX, 2012), as is the case of a three-dimensional model.

4.2. Geotechnical Response

The settlement profile is presented in Fig. 5 for the uniformly distributed load and in Fig. 6 for the concentrated loads, considering both the flexible and the rigid raft case. A comparison between the two load cases in terms of maximum settlement is presented in Fig. 7. In terms of relative settlements, the results are presented in Fig. 8 only for the case of the flexible raft foundation, as for the rigid behaviour the relative settlements resulted with negligible values in both cases of external loading.

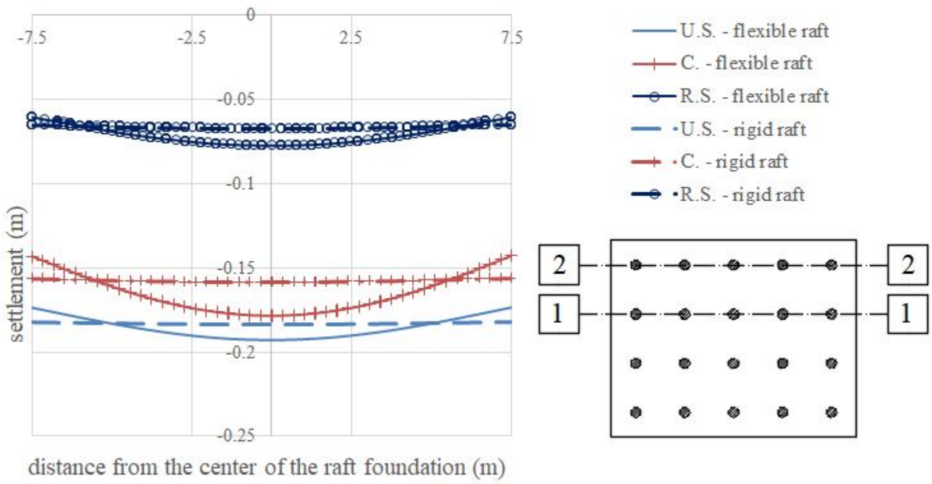


Fig. 5 – Settlement profile in section 1-1 for the uniformly distributed load case.

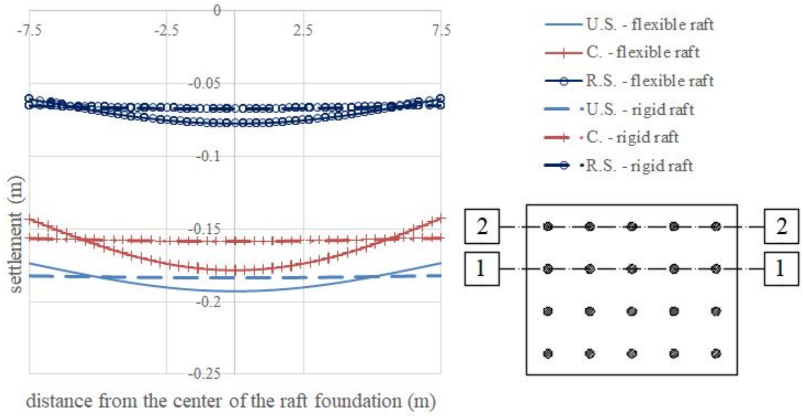
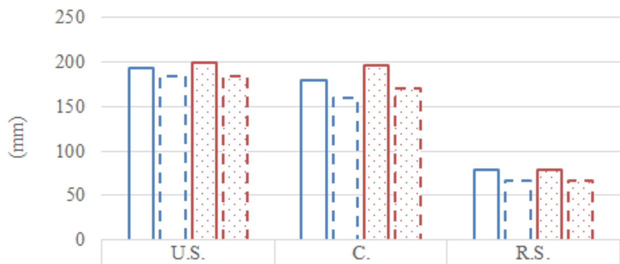
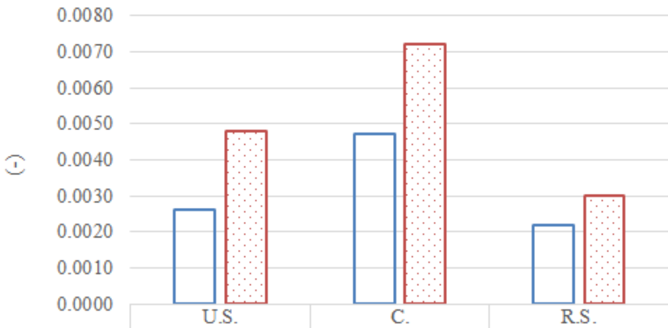


Fig. 6 – Settlement profile in section 1-1 for the concentrated loads case.



	U.S.	C.	R.S.
uniform load - flexible raft	193	180	78
uniform load - rigid raft	184	159	67
concentrated loads - flexible raft	199	196	79
concentrated loads - rigid raft	185	170	67

Fig. 7 – Comparison of maximum settlement between the two load cases considered.



	U.S.	C.	R.S.
uniform load - flexible raft	0.0026	0.0047	0.0022
concentrated loads - flexible raft	0.0048	0.0072	0.0030

Fig. 8 – Comparison of relative settlement between
the two load cases considered.

Analyzing the three cases of ground support it is observed that the presence of a 0.5 m thick stabilized soil cushion under the raft foundation leads to only a slight reduction in maximum settlement in relation to the case of unreinforced soil, with values between 1.5% and 13.6% depending on raft behavior (flexible or rigid) and type of external loading. The rigid inclusion reinforcement case led to a significant reduction in maximum settlement, with values between 59% and 64%. It is also noticed that a flexible foundation will undergo slightly larger settlements as the load deviates from uniformity while in the case of rigid foundation the maximum settlements are negligibly influenced by the type and distribution of external loading.

The maximum relative settlements were found in section 2-2 of the raft foundation. Between the three cases of ground support, the maximum relative settlement was found for the stabilized soil cushion case, because of the higher soil reaction in the marginal area of the raft, while the minimum relative settlement was found for the case of reinforced soil. It is also noticed that the maximum relative settlements are strongly influenced by the type and distribution of external loading, with much higher values recorded in the case of concentrated loads.

4.3. Structural Response

The distribution of the bending moments and shear forces in the raft foundation are presented in Figs. 9 and 10 for the case of uniformly distributed load and in Figs. 11 and 12 for the case of concentrated loads.

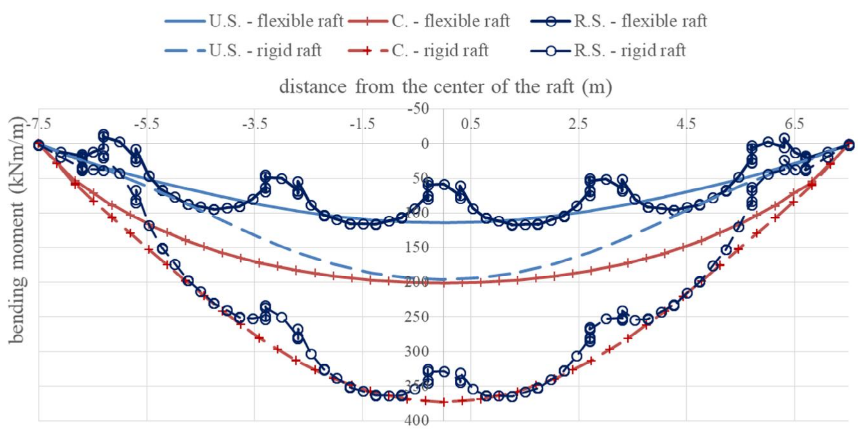


Fig. 9 – Bending moment distribution in the raft for the uniform load case (section 1-1).

The maximum values of the bending moments (M^+) and shear forces (V) in the analyzed sections are compared in Table 3 for the uniform load case and in Table 4 for the concentrated loads case. The percentage deviations between the three cases of ground support are also indicated.

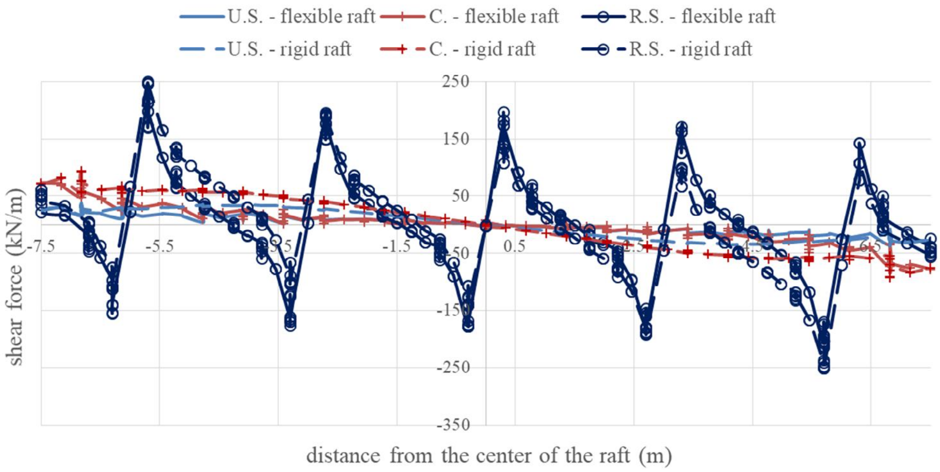


Fig. 10 – Shear force distribution in the raft for the uniform load case (section 1-1).

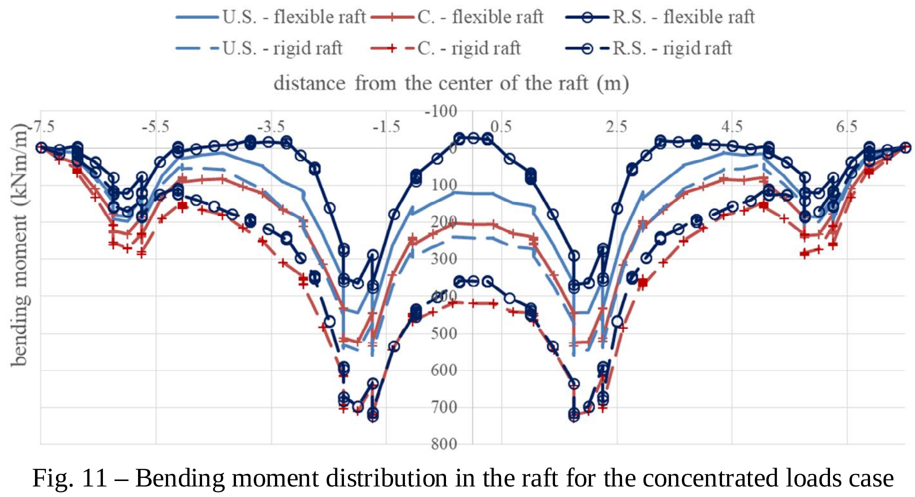


Fig. 11 – Bending moment distribution in the raft for the concentrated loads case (section 2-2).

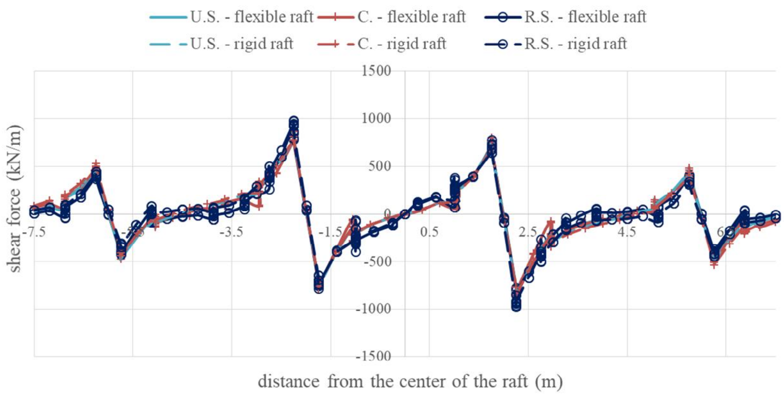


Fig. 12 – Shear force distribution in the raft for the concentrated loads case (section 2-2).

Table 3

Maximum Values of the Bending Moments and Shear Forces in Section 1-1 for the Uniformly Distributed Load Case

	Flexible raft		Rigid raft	
	M^+, [kNm]	V, [kN]	M^+, [kNm]	V, [kN]
Unreinforced soil (U.S.)	114	35	196	37
Stabilized soil cushion (C.)	201	78	373	94
Reinforced soil (R.S.)	117	219	365	251
Deviation of C. from U.S.	+76 %	+123 %	+90 %	+154 %
Deviation of R.S. from U.S.	+3 %	+526 %	+86 %	+578 %
Deviation of R.S. from C.	–42 %	+181 %	–2 %	+167 %

Table 4

Maximum Values of the Bending Moments and Shear Forces in Section 2-2 for the Concentrated Loads Case

	Flexible raft		Rigid raft	
	M^+, [kNm]	V, [kN]	M^+, [kNm]	V, [kN]
Unreinforced soil (U.S.)	454	837	560	853
Stabilized soil cushion (C.)	534	836	728	863
Reinforced soil (R.S.)	377	974	722	983
Deviation of C. from U.S.	+18 %	0 %	+30 %	+1 %
Deviation of R.S. from U.S.	–17 %	+16 %	+29 %	+15 %
Deviation of R.S. from C.	–29 %	+17 %	–1 %	+14 %

For a uniformly distributed load, the presence of the rigid inclusions produces a significant increase in shear force values yet has a positive influence on the bending moment, with only a 3% increase in maximum bending moment in relation with the unreinforced case and a 42% decrease in relation with the case of the stabilized soil cushion. These values correspond however to a flexible behavior of the raft. The positive effect of the rigid inclusions on the bending moment is cancelled by the rigidity of the foundation as for the rigid raft the maximum value was found to be 86% higher than the one corresponding to the unreinforced soil case and almost equal to the value obtained for the cushion case. The shear force values are only slightly higher in the case of a rigid raft.

In the case of concentrated loads the main influence of the rigid inclusions is on the bending moment for which the maximum positive value was found to be 17% lower in relation with the case of unreinforced soil and 29% lower in relation with the case of the stabilized soil cushion. Same as for the uniformly distributed load, the positive influence of the rigid inclusions is only valid for a flexible behavior of the raft. For the rigid raft, the maximum positive bending moment was found to be 29% higher than in the case of unreinforced soil and also almost identical with the value obtained for the cushion case. Regarding the shear force, the maximum values were found to be 16% and 17% higher in the case of reinforced soil in relation with the other two cases of ground support and, same as for the uniformly distributed load, they were negligibly influenced by the rigidity of the foundation.

5. Conclusions

The results of a finite element analysis of a raft foundation on soil reinforced with rigid inclusions were presented and discussed. The three-dimensional approach towards the problem allowed for the study of the influence of rigid inclusions on the bending moments and shear forces that develop in the raft. In this context, the influence of raft flexibility and type of external loading were also studied. Although the main effect of rigid inclusion reinforcement is settlement reduction, it was found that the inclusions also have an important influence on the raft stresses. The magnitude of this influence is dependent on raft flexibility and on the type and distribution of external loads. For a flexible behavior of the raft foundation the presence of the rigid inclusions tends to reduce the positive bending moments, regardless of the type of external load. However, for a practical application of the rigid inclusion reinforcement method, the negative bending moments should also be studied, as the presence of the rigid inclusions could lead to higher values than other cases of ground support. In terms of shear force, for a uniformly distributed load the rigid inclusions led to significantly higher values than the other two cases of ground support while for the case of concentrated loads the maximum shear force values were found to be only slightly higher. For both cases of foundation loading, a rigid raft tends to cancel the positive effect which the rigid inclusions have on the positive bending moments while the influence of the raft rigidity on the shear force was found to be negligible.

REFERENCES

Balaam N.P., Booker J.R., *Analysis of Rigid Rafts Supported by Granular Piles*, International Journal for Numerical and Analytical Methods in Geomechanics, **5**, 379-403 (1981).

Bohn C., *Serviceability and Safety in the Design of Rigid Inclusions and Combined Pile-Raft Foundations*, Civil Engineering, Universite Paris-Est, 2015.

Das A.K., Deb K., *Modeling of Uniformly Loaded Circular Raft Resting on Stone-Column Improved Ground*, The Japanese Geotechnical Society – Soils and Foundations, 2014.

Okyay U.S., Dias D., *Use of Lime and Cement Treated Soils as Pile Supported Load Transfer Platform*, Engineering Geology, **114**, 34-44 (2010).

Simon B., *General report S5 Rigid Inclusions and Stone Columns*, ISSMGE-TC211 International Symposium on Ground Improvements IS-GI, Brussels, 2012.

Varaksin S., Hamidi B., Huybrechts N., Denies N., *Ground Improvement vs. Pile Foundations?*, ISSMGE-ETC3 International Symposium on Design of Piles in Europe. Leuven, Belgium, April 2016.

* * * IREX. *Recommendations for the design, construction and control of rigid inclusion ground improvements.* Project National ASIRI. Presses des Ponts, ISBN 978-2-85978-426-1, 2012.

* * * *Normativ privind proiectarea fundaţiilor de suprafaţă*, NP 112-2014.

* * * Plaxis 3D Foundation – version 1, Delft University of Technology & Plaxis bv, Editors: Brinkgreve R.B.J. & Broere W., The Netherlands, 2004.

ANALIZĂ TRIDIMENSIONALĂ CU ELEMENTE FINITE A COMPORTĂRII FUNDAŢIILOR AMPLASATE PE TEREN RANFORSAT CU INCLUZIUNI RIGIDE

(Rezumat)

Utilizarea incluziunilor rigide pentru controlul tasărilor şi îmbunătăţirea portanţei terenului de fundare reprezintă o alternative eficientă şi economică în raport cu clasicele sisteme de fundare de adâncime. Abordarea generală a unor probleme de tipul plăcilor pardoseală sau a radierelor amplasate pe teren ranforsat cu incluziuni rigide presupune realizarea unor analize bazate pe conceptul de celulă modulară, în programe ce integrează metoda elementelor finite sau metoda diferenţelor finite. Astfel de modele

furnizează informații privind interacțiunea incluziunii rigide cu terenul înconjurător şi cu stratul de transfer însă efectul incluziunilor la nivel de comportare globală a plăcii pardoseală sau a radierului nu poate fi anticipat în acest mod. Ca atare, pentru a studia aspecte precum influența rigidității fundației, tipul şi distribuția încărcării exterioare asupra eforturilor secționale ce se dezvoltă la nivelul acesteia, sunt necesare modele tridimensionale de analiză. În acest articol sunt prezentate şi discutate rezultatele unei analize a fundației de tip radier general amplasată pe un teren ranforsat cu incluziuni rigide, modelată în programul de analiză cu element finit, Plaxis 3D.