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Soil-Structure Interface Modeling and Characterization

Oustasse Abdoulaye Sall[1], Déthié Sarr[2], and Diogoye Diouf[1]

[1]Department of Civil Engineering, UFR SI-Université Iba Der Thiam de Thies, Thies, Senegal

[2]Department of Geotechnics, UFR SI- Université Iba Der Thiam de Thies, Thies, Senegal

ABSTRACT: In this work, we propose to study the influence of soil and concrete mechanical properties on soil-structure interaction parameters. Soil-structure interaction is modeled by two parameters, the vertical (***k***) and horizontal (***T***) reaction modulus. These two parameters depend on the system's geometric and mechanical characteristics. This study shows that the vertical reaction modulus is not an intrinsic characteristic but depends on soil and concrete parameters (E_s ν_s, E_b and ν_b) and foundation dimensions. The analysis shows that soil parameters are more influential than foundation parameters.

KEYWORDS: Interface, Soil-Structure Interaction, Mechanical properties, Modeling.

1 INTRODUCTION

The study of soil-structure interaction is of great importance in the dimensioning of foundation structures. [1] presented a detailed analysis of the problem of soil-foundation interaction, outlining the various approaches proposed to model this interaction. These models assume that the soil reaction is a linear function of the displacements of the soil-foundation interface layer. The response of each of these models is given by the settlement of the soil surface (***w***) under the action of a system of external loads (***q***). This settlement generally represents the displacement of the soil-foundation interface layer, and is an essential part of the information required to model soil-foundation interaction. Specifically, in this work, we will carry out a characterization and parametric study of soil-structure interaction.

2 SOIL-STRUCTURE INTERACTION MODELING

2.1 WINKLER MODEL

The modelling of soil behavior proposed by [2] admits that the soil reaction pressure (***q***), at any point of coordinates (***x, y***) of the interface layer, is directly proportional to the settlement (***w***) of the soil at this point and is independent of settlements at other points (Figure 5):

$$q(x,y) = k.w(x,y) \quad (1)$$

where:

k is the elastic modulus of vertical ground reaction.

This assumption has been established in the work of [3], [4], [5], etc. Physically, Winkler's model likens the soil to a system of elastic springs, infinitely adjacent, independent of each other and possessing a stiffness constant (***k***). Soil settlement occurs in the zone below the loading surface, and outside this zone settlement is equal to zero. On the other hand, settlement in the loaded zone, in the case of a rigid foundation (Figure 1.c), remains the same in the case of a flexible foundation (Figure 1.d).

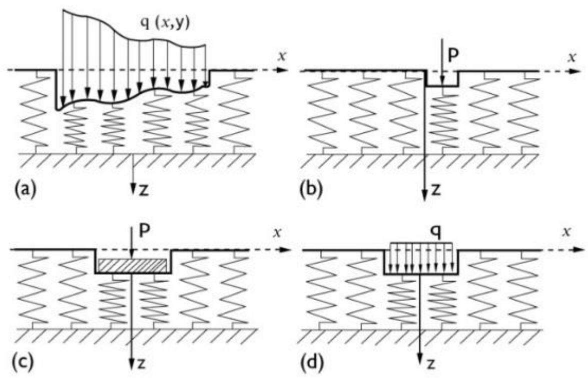

Fig. 1. Ground displacement for Winkler model, (a) any kind of load, (b) concentrated load, (c) rigid foundation, (d) flexible foundation [1]

2.2 Filonenko-Borodich Model

[6] ensures continuity between the springs in Winkler's model by means of a thin elastic membrane under constant tension ***T*** (Figure 7), which connects the springs. Settlement (w) at the soil surface under pressure (q) is given by:

$$q(x,y) = k.w(x,y) - T.\nabla^2 w(x,y) \quad (2)$$

with:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \quad (3)$$

The two elastic constants of the model are the reaction coefficient (***k***) and the tension (***T***). Figure 2 shows typical examples of settlement profiles for a concentrated load (Figure 2.b), a rigid foundation (Figure 2.c) and a flexible foundation with a uniformly distributed load (Figure 2.d). Developments in civil engineering construction and, above all, the disorders observed in load-bearing structures, have prompted practitioners in the field to take greater account of soil-structure interaction in the process of calculating foundation structures. A number of authors have worked on the soil reaction modulus, which is an important parameter in the consideration of soil-structure interface parameters.

2.3 The Terzaghi Method

According to [7], [8] has given orders of magnitude of the reaction coefficient for a 30 cm square rigid plate (Table 1). He proposes the following formulas given in Table 2. The reaction modulus ***k*** is a coefficient of proportionality between pressure (***p***) and deformation (***w***):

$$k = \frac{p}{w} \quad (4)$$

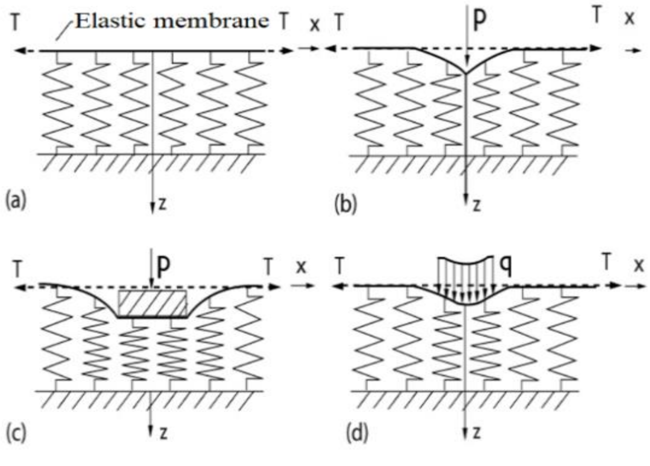

Fig. 2. Filonenko-Borodich model [1]

Table 1. Vertical reaction modulus according to [8]

	Poorly cohesive sandy soils	*Clay soils*	*B/L*	*C_f*
Square or circular foundation	$w = w_0 \left(\frac{2B}{B+B_0}\right)^2$ $K = \frac{p_0}{w_0}\left(\frac{B+B_0}{2B}\right)^2$	$w = w_0 \frac{B}{B_0}$ $K = \frac{p_0}{w_0}\frac{B_0}{B}$		
Rectangular foundation	$w = Cf.w_0 \left(\frac{2B}{B+B_0}\right)^2$ $K = \frac{1}{Cf}\frac{p_0}{w_0}\left(\frac{B+B_0}{2B}\right)^2$	$w = Cf.w_0 \frac{B}{B_0}$ $K = \frac{1}{Cf}\frac{p_0}{w_0}\frac{B_0}{B}$	0,5 0,33 0,2 0,1	1,95 2,27 2,68 3,28

with

- *Bo* = 30 cm

- C_f = form factor

with:

$K_{ref} = p_0 / w_0$, reference values are given in Tables 2 and 3.

Table 2. K_{ref} Values for sands

Sand	Consistency	Let go	Medium	Dense	Unit
Dry sand	Density	13	1-	19	kN/m^3
	K_{ref} limits	0,6 - 0,9	1,9 - 9,6	9,6 - 32	kg/cm^3
	K_{ref} medium	1,3	4	16	kg/cm^3
Drowned sand	K_{ref} medium	0,8	2,5	10	kg/cm^3

Table 3. K_{ref} Values for clay soils

Consistency	Steep	Very steep	Hard	Unit
Simple compression stress	1à2	2à4	> 4	kN/m^3
K_{ref} limits	1,6 - 3,2	3,2 - 6,4	$> 6,4$	kg/cm^3
K_{ref} medium	2,5	5	10	kg/cm^3

2.4 FROM MENARD PRESSURE METER TESTS

[9] gives a method for estimating the vertical reaction modulus ***k*** under a shallow foundation from the results of pressure meter tests. From the vertical displacement **w** of the footing and the pressure ***p*** exerted by the reacting soil, we establish that ***p = kw***. We're now looking to determine ***k,*** for long-term forces. The formulas are given in appendix F3 of fascicule 62. Where E_c and E_d represent the weighted average pressure moduli in the spherical and deviatoric domains respectively. In the case of homogeneous soil, $E_c = E_d = E_M$. According to [9], we have:

$$\frac{1}{k} = \frac{\alpha.B}{9E_M}\lambda_C + \frac{2.B_0}{9E_M}\left(\lambda_d \frac{B}{B_0}\right)^\alpha \quad (5)$$

where

- ***B***: being the width of the foundation,
- B_o: reference width equal to 0.6 m;
- E_M: the pressure meter modulus;
- ***α***: rheological coefficient depending on soil type (Table 4);
- λ_c and λ_d are shape coefficients and are a function of the ***L/B*** ratio, as shown in the following Table 6.

Table 4. Values of the rheological coefficient α for different soils

	Peat	Clay		Silt		Sand		Grave	
Soil condition	α	E /P_{M1}	α	E /P_{M1}	α	E /P_{M1}	α	E /P_{M1}	α
Over consolidated or very tight	-	> 16	1	> 14	2/3	> 12	1/2	> 10	1/3
Normally consolidated	1	9-16	2/3	8-14	1/2	7-12	1/3	6-10	1/4
Altered and reworked or loose sub-consolidation	-	7-9	1/2	5-8	1/2	5-7	1/3		

For rocks, rheological coefficient values are given in the following Table 5**:**

Table 5. Values of the rheological coefficient α for different soils

Rock type	Very slightly fractured	Normal	Very fractured	Very impaired
α	2/3	1/2	1/3	2/3

Table 6. Values of the coefficients λ_c and λ_d for different values of the ratio L/ B

L/B	Circle	Square	2	3	5	20
$\boldsymbol{\lambda_c}$	1,00	1,10	1,20	1,30	1,40	1,5
$\boldsymbol{\lambda_d}$	1,00	1,12	1,53	1,78	2,14	2,65

According to equation (5), as $\boldsymbol{\lambda_c}$ and λ_d increase, ***k*** decreases. This means that for the same applied stress, a slenderer footing (the greater the ***L/B*** ratio) will deform more. The "springs" modelling soil elasticity are less stiff. It can therefore be said that the reaction modulus (***k***) is not an intrinsic characteristic of the foundation soil, but also depends on the structure.

Many authors have been interested in calculating the reaction modulus, which, according to different authors, is within two constants of equation (18). The values of a vary from 0.65 to 0.95 and those of ***Ɣ*** from 1/12 to 0.108, as shown in the following Table 7.

Table 7. Soil modulus reaction (k) according to various authors

Modulus reaction (k)	a	γ	Equations	Authors
$k = 0{,}65\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{1/12}$	0,65	1/12	6	[10]
$k = 0{,}69\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}0868}$	0,69	0,0868	7	[11]
$k = 0{,}74\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}0903}$	0,74	0,0903	8	[12]
$k = 0{,}78\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}0938}$	0,78	0,0938	9	[13]
$k = 0{,}82\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}0973}$	0,82	0,0973	10	[14]
$k = 0{,}87\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}1008}$	0,87	0,1008	11	[15]
$k = 0{,}91\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}1043}$	0,91	0,1043	12	[16]
$k = 0{,}95\frac{E_s}{1-\nu^2}\left(\frac{E_sB^4}{E_bI}\right)^{0{,}108}$	0,95	0,108	13	[17]

2.5 Vertical Modulus Reaction According To [10]

[10] has developed an empirical formula to express ***k***:

$$k = \frac{0,65E_S}{1-\nu^2}\sqrt[12]{\frac{E_S B^4}{EI}} \quad (14)$$

[11] improved on Biot's formula to propose the following relationship:

$$k = \frac{0,95E_S}{1-\nu^2}\left(\frac{E_S B^4}{(1-\nu^2)E_b I}\right)^{0,108} \quad (15)$$

where

E_s: Modulus of the foundation soil,

v: Poisson's ratio of the foundation soil;

B: Foundation width;

E_b: Young's modulus of foundation concrete;

I: moment of inertia of the concrete cross-section.

The reaction modulus ***k*** proposed by [11] can be written as:

$$k = 0,95\left(\frac{1}{1-\nu^2}\right)^{0,108}\frac{E_S}{1-\nu^2}\left(\frac{E_S B^4}{EI}\right)^{0,108} \quad (16)$$

Generally, for foundations, the Poisson's ratio is between 0.15 and 0.4, and the term $\left(\frac{1}{1-\nu^2}\right)^{0,108}$ is between 1.0025 and 1.019 [18]. This leads us to ignore this term in the expression of ***k*** according to [17], which can be rewritten in the following form:

$$k = 0,95\frac{E_S}{1-\nu^2}\left(\frac{E_S B^4}{EI}\right)^{0,108}. \quad (17)$$

We can write ***k*** in a general way expressed by the following equation:

$$k = a\frac{E_S}{1-\nu^2}\left(\frac{E_S B^4}{EI}\right)^{\gamma} \quad (18)$$

where

a and **γ** are constants given by different authors as shown in Table 7.

In what follows, we attempt to highlight the influence of the various parameters (***B, E_s, E, v, e***) on the elastic modulus of soil reaction.

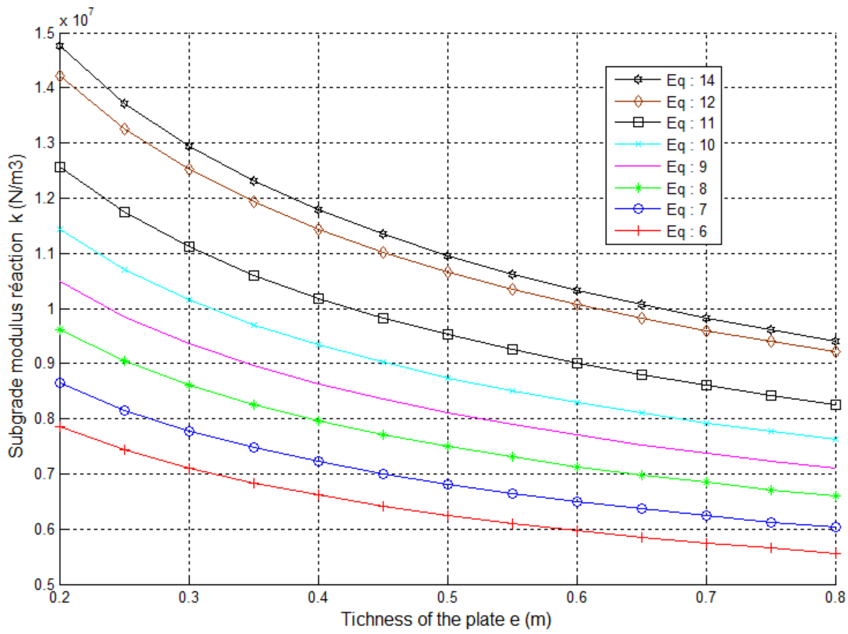

Fig. 3. Modulus of reaction of foundation soil depending on plate width according to various authors

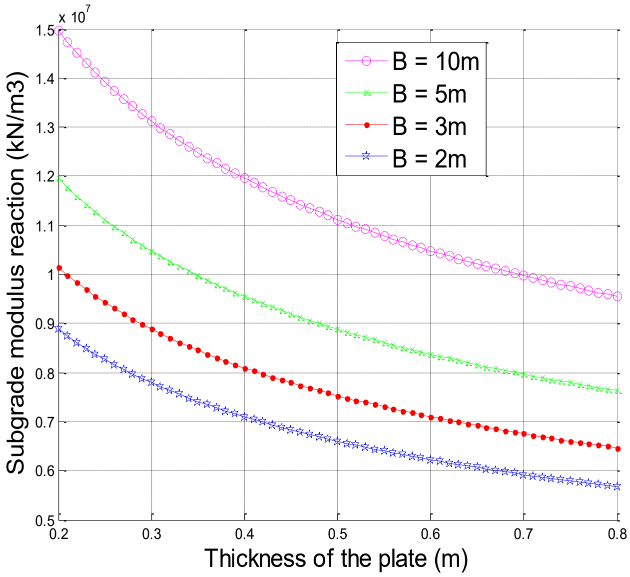

Fig. 4. ***Variation of soil reaction modulus depending plate thickness for various values of plate width***

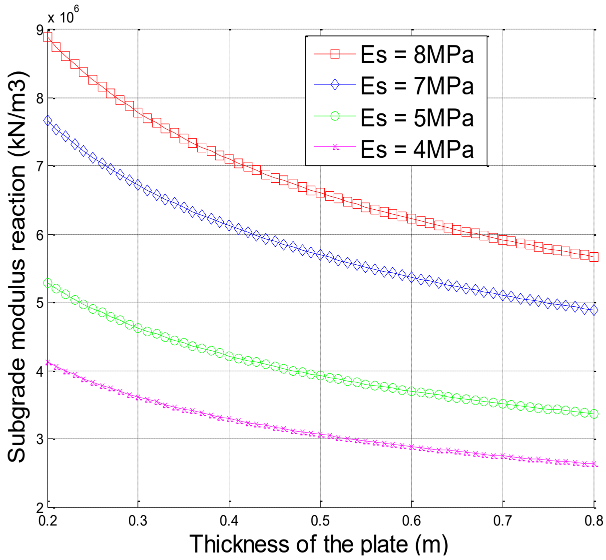

Fig. 5. ***Variation of soil reaction modulus depending on plate thickness for different values of elastic modulus of foundation soil***

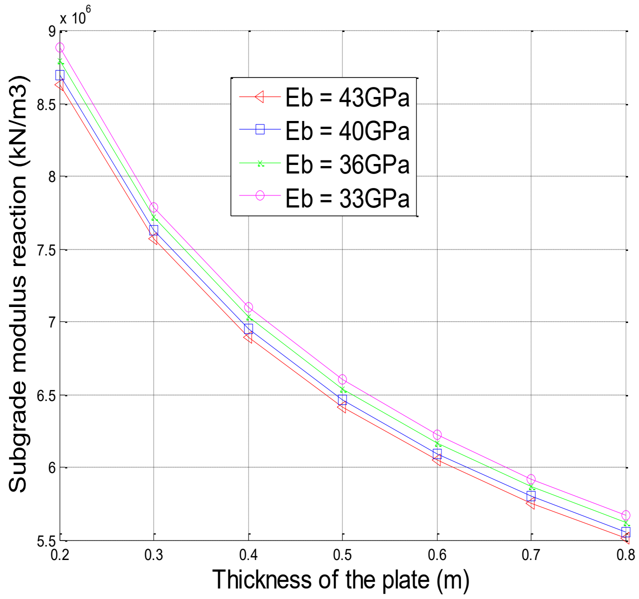

Fig. 6. ***Variation of soil reaction modulus with plate thickness for different values of elastic modulus of foundation concrete***

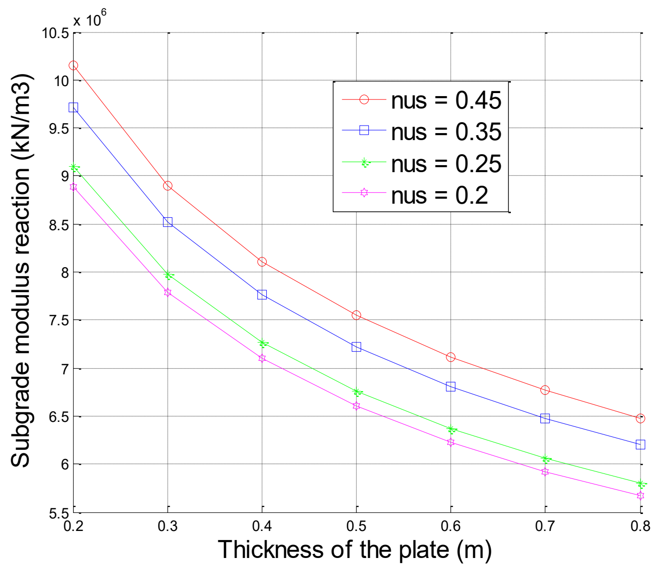

Fig. 7. ***Variation of soil reaction modulus depending on plate thickness for different values of vs***

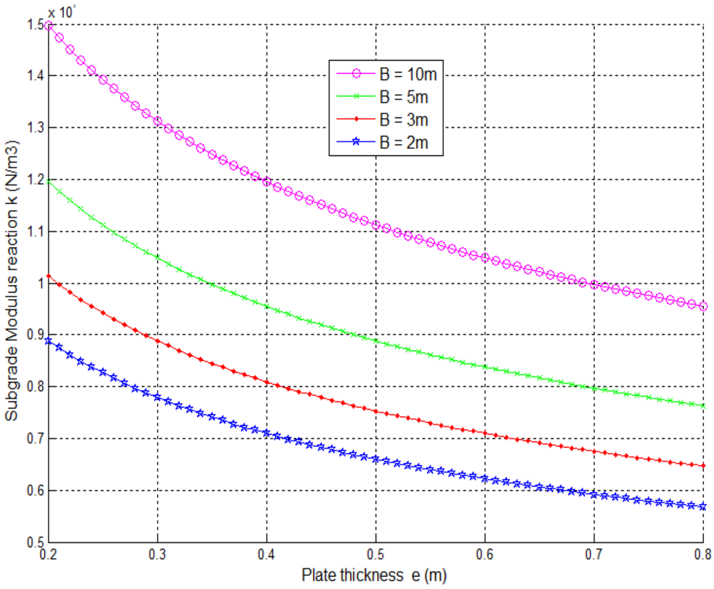

Fig. 8. Variation of soil reaction modulus as a function of plate thickness for different values of B

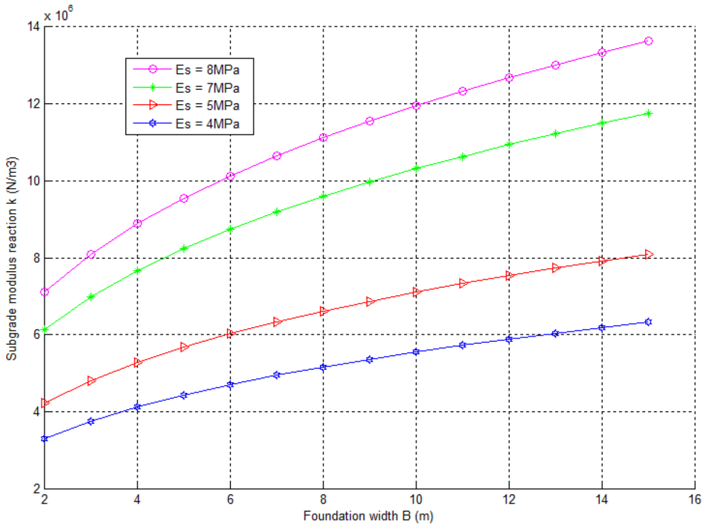

Fig. 9. Variation of soil reaction modulus depending plate width for different values of elastic modulus of foundation soil

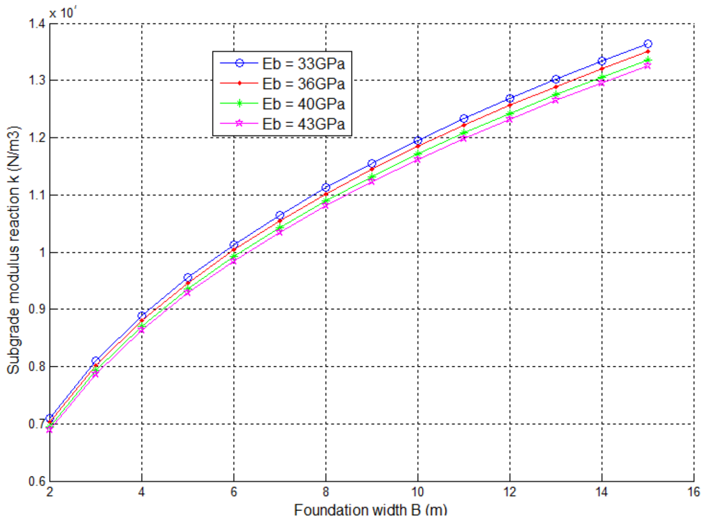

Fig. 10. Variation in soil reaction modulus depending plate width for different values of elastic modulus of foundation concrete

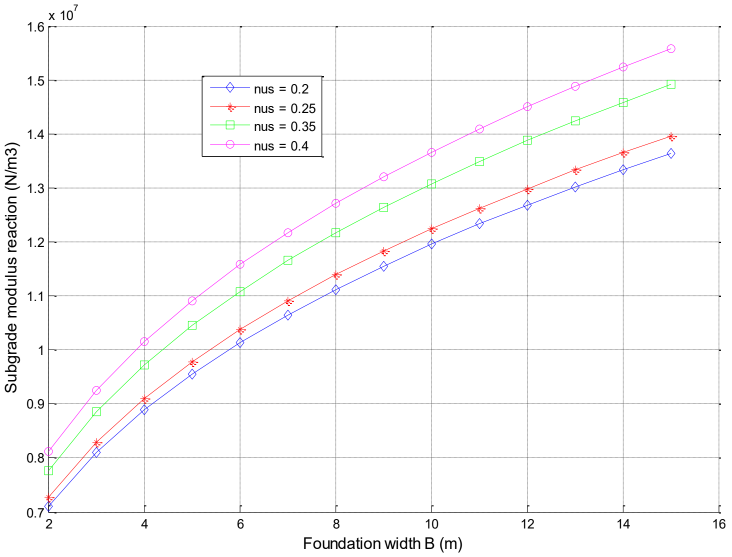

Fig. 11. Variation of soil reaction modulus as a function of plate width for different values of the coefficient vs

3 DISCUSSION

According to the equations in Table 7, it is clear that the soil reaction modulus is influenced by the mechanical and geometric characteristics of the soil, rather than those of the foundation concrete. It should be noted that all subsequent authors [10] tend to give the soil reaction modulus higher values depending on the input parameters. This observation prompts us to address one of our concerns, which is to find the appropriate value for the apparent elastic modulus of reinforced concrete, which should be considered in the calculations, rather than the elastic modulus of simple concrete. As our aim is to gain a better understanding of the deformations of the infrastructure, we believe that in the context of this research work (for greater safety), it would be preferable to use the reaction modulus proposed by [10] in the calculations, as we know that the higher the reaction modulus of the soil, the lower the displacements of the plate points will be.

Figures 3 to 11 show the evolution of the soil reaction modulus as a function of the various behavior model parameters. Figures 3 to 7 show a decrease in the reaction modulus of the foundation soil, which is highly dependent on soil parameters (**E_s, v_s**) and the geometry of the structure. These figures also show that, for certain fixed parameters, the reaction modulus of the soil varies very little with the mechanical characteristics of the foundation concrete, which suggests that variations in the displacements of the structure will be more dependent on the mechanical parameters of the foundation soil than those of the foundation concrete. Figures 8 to 11 show an increase in the reaction modulus of the foundation soil with increasing values of foundation width. It can also be seen that, for a fixed value of ***B,*** the soil reaction modulus is strongly influenced by soil parameters (***Es,***ν_S). These figures also show that for certain fixed parameters, the soil reaction modulus varies very little with the mechanical characteristics of the foundation concrete, which suggests that variations in structural displacements will be more closely related to the mechanical parameters of the foundation soil than those of the foundation concrete.

4 CONCLUSION

In this work, we studied the influence of the mechanical properties of soil and concrete on soil-structure interaction parameters. The interaction between soil and structure is modeled by two parameters, the vertical (***k***) and horizontal (***2T***) reaction moduli. The results show that the soil reaction modulus increases with the geometric characteristics of the foundation. The results also show that the soil reaction modulus is strongly influenced by soil parameters (***Es,***ν_S). The results also show that for certain fixed parameters, the soil reaction modulus varies very little with the mechanical characteristics of the foundation concrete.

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