

# Numerical Modeling of Soil-Structure Interaction: Case of Raft Foundations

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**Abstract** Urban development often requires the use of tall structures to maximize the use of ground space and meet the growing and innovative demands of designers and architects. In most cases, the challenge for these types of projects is to find a fair balance between justifying the stability of structures and the profitability of the project, which is conditioned by optimizing the foundation system. To achieve this, the use of soil-structure interactions, which studies the reciprocal effects between soils and structures in contact with them, allows for a comprehensive response to most technical problems and provides all possible optimizations and better modeling of resilient and adaptable structures that can withstand natural forces and environmental impacts. To achieve this, engineers and scientists are working on improving soil and structure modeling techniques, collecting and analyzing geotechnical and environmental data, using advanced technologies such as numerical modeling and simulation, and designing structures. This case study focuses on a 25-story tower built on a low-bearing sandy-loam soil. The support soil study was conducted based on geotechnical investigations, and soil-structure interactions were calculated using the pressuremeter method for all possible combinations. This study demonstrates that the use of refined calculations by integrating soil-structure interactions allows for significant optimization of foundation solutions and precisely defining and delimiting risk zones where solicitations are maximal.

**Keywords** Soil-Structure Interactions ISS, Limit States, Sollicitations, Foundation, Raft

## 1. Introduction

The soil-structure interaction is one of the most efficient and effective means to approach the geotechnical behavior of a low-consistency soil mass subjected to a complex loading model.

Thus, in these cases, it is essential to understand the interactions between soil and structures to ensure the safety and durability of constructions, especially for large projects where optimizing foundation systems is a critical concern.

Numerical methods for soil-structure interaction (SSI) based on soil modeling using local interaction laws such as reaction coefficient can also be employed [1].

There are different calculation approaches for raft and slab foundations that allow for the assessment of soil bearing capacity and deformation calculations under applied loads while taking into account the soil-structure interaction and the standards related to the structures of slab, raft, and foundation [2].

Fascicule 62-V [3], which pertains to the technical rules for the design and calculation of foundations for civil engineering works, defines the modulus of reaction as the

ratio between the uniform pressure ( $q$ ) applied by the foundation and the equivalent settlement ( $S$ ).

$$Kv = \frac{q}{s} \quad (1)$$

In the simplified approach provided by DUT 13.3 [4], Boussinesq's formulas are used in combination with those related to an infinite plate resting on juxtaposed springs. The settlement of an infinite plate on an elastic soil, under the impact of a concentrated load  $Q$ , is given by the following relationship:

$$w = (Q/8) \{ [12(1 - \nu^2)] / (E_b * H^3 * k) \}^{1/2} \quad (2)$$

where  $k$  is the soil/plate reaction modulus for a concentrated load  $Q$ ,  $E_b$  is the concrete's modulus of deformation,  $\nu$  is the Poisson's ratio of concrete, and  $w$  is the settlement under load.

Vezole [5] also addressed this issue by proposing an approach that involves discretizing the studied structure into multiple segments and combining this discretization with the standard formulas for calculating settlements in a semi-infinite elastic medium.

Furthermore, Eurocode 2 Standard emphasizes the importance of considering the interaction between the supporting soil, foundations, and structure, since the distribution of contact pressures on foundations and loads on columns also depends on differential settlements between supports [6].

In terms of terrain modeling, several models have been established, with the Winkler Model being one of the primary ones. This model assumes that the soil reaction at each point under the foundation is proportional to the foundation's deflection at that point [7].

M. Cassan proposed a simplified approach aimed at examining the interaction between the soil and the raft [8]. Their approach is based on the numerical integration of the Lagrange equation, relying on the Boussinesq stress distribution.

Houlsby notes that the Winkler model is straightforward and compatible with both numerical and analytical methods [9]. Nonetheless, it has two significant drawbacks. First, it fails to consider the interaction between the springs, which means vertical shear in the soil is neglected, resulting in a displacement discontinuity between loaded and unloaded zones beneath the foundation. Second, the model does not account for the possible plasticity of the soil.

The primary limitation of the previously mentioned methods is their inability to account for the interaction between adjacent springs. These approaches share two key characteristics: they use Boussinesq's formulas to calculate settlements and employ a simplified model of thin plates to evaluate the equilibrium of the foundation.

However, in advanced numerical models like the Tasplaq software developed by Terrassol, which treats materials as linear elastic [10], the modeling also

incorporates adjacent springs through "contact" elements and establishes a comprehensive interaction law. This approach unites three essential components: the finite element formulation, an appropriate discretization to accurately represent pressures, and Boussinesq's equations for calculating soil deformations of the supporting foundation [11].

Additionally, this modeling adopts a thin plate method under specific conditions. This method assumes that the plate is homogeneous, isotropic, and primarily functions under pure bending, especially when the thickness of the plate is considerably smaller than its other dimensions. This modeling considers the plate support as initially elastic, which can be represented either by a multi-layer elastic medium characterized by Young's modulus and Poisson's ratios or by the use of surface, linear, or point springs in translation or rotation. This method calculates plate deformation, settlements, and reactions at any point, as well as moments and internal shear strength. Deformations related to bending are considered, while shear deformations are neglected.

However, it is important to note that the choice of the method will always depend on the required accuracy for a particular analysis.

In the present study, the project involves the construction of a 22-storey tower with 4 basement levels. The tower's structure will be made of reinforced concrete, resting on a general raft foundation. However, this project faces geotechnical challenges, including geological variability, complex hydrogeology, the presence of sensitive materials, and weak geotechnical parameters. Moreover, the foundation system must be designed to withstand high loads, even on soft and saturated soils, as no bedrock has been identified to a depth of 80 meters.

In contrast to conventional methods for calculating reaction modules, this article presents the findings of a numerical modeling study of low-consistency soil subjected to exceptional and non-uniformly distributed overloads.

In fact, the soil is modeled as a set of independent springs, enabling both structural displacements and stresses to be deduced for each load combination. The results of the soil-structure interaction in this study illustrate the static behavior of a loading model corresponding to the specific building, which is founded on loose sandy-silty soil with low consistency.

Indeed, in terms of deformations of the supporting soil, the soil-structure interaction calculation model provides greater precision compared to traditional methods that rely on standard reaction modulus approaches.

Of course, this fairly accurate evaluation helps prevent potentially severe damage, such as structural failure and concrete cracking. But does it also optimize foundation models by demonstrating a more suitable, realistic, and well-justified soil-structure behavior?

## 2. Materials and Methods

### 2.1. Geotechnical Investigation

To characterize the in-situ soil, a geotechnical reconnaissance campaign was conducted. This included core drilling, pressuremeter tests, and SPT tests.

Conducted at depths ranging from 14 to 80 meters, these tests allowed for a better characterization of the soil and, in particular, the development of an appropriate geotechnical model for calculations.

The presented table summarizes the composition of the geotechnical testing program carried out, detailing the types of tests performed, the number of boreholes drilled, and the investigation depths (Table 1).

**Table 1.** Geotechnical Investigations

Test type	Number of tests	Depth (m)
Pressiometric Drilling	3	40
	1	80
Core drilling	3	14
	1	80
Standard Penetration Test	3	30
Identification tests	25	Between 1,5 and 80
Shear tests	11	Between 1,5 and 80
Oedometer compressibility tests	5	Between 3 and 80

The geotechnical characterization of the site required the implementation of a series of in-situ tests, namely:

- Borehole coring: Allowing for the extraction of soil samples for laboratory analysis.
- Pressiometric tests: Measuring limiting pressures, creep pressures, and pressiometric moduli, providing crucial information for foundation design.
- Standard penetration tests: Assessing the density and resistance of the soil.

In parallel, a series of laboratory tests were conducted on the collected samples, including:

- Identification tests: Grain size analysis, Atterberg limits, methylene blue value, allowing for the characterization of the nature and properties of the soil.
- Soil mechanics tests: Direct shear tests and oedometer compressibility tests, providing essential data for evaluating the mechanical behavior of each identified formation.

The investigation depth was adapted to the type of test, with pressiometric boreholes reaching depths of 40 to 80 meters, while standard penetration tests were conducted up to 30 meters deep.

Finally, the combination of these in-situ and laboratory

tests allowed for a comprehensive characterization of the soils in place at significant depths. This knowledge made it possible to determine the geotechnical parameters necessary for the design and justification of the foundation system's stability.

### 2.2. Identification and Shear Tests

Overall, the performed drill cores have revealed the presence of the following lithological formations:

- 0.00-3.00m: Yellowish clayey sand.
- 3.00m-46.00m: Reddish Silty sand.
- 46.00m-54.00m: Compact clayey sand.
- 54.00m-80.00m: Slightly clayey fine sand.

Concerning laboratory testing, Table 2 provides a summary of the findings from identification and shear tests. These tests, combined with the drill core results, enable us to draw the following conclusions regarding the geotechnical layers of the bearing soil:

- The yellowish clayey sands observed down to a depth of 12 meters correspond to Silty Sands with a variable fines content ranging from high to low, grain size with a diameter of 80  $\mu$  varies between 27 and 35%, the plasticity index is average at around 20%. The BM (methylene blue) value is between 0.18 and 0.33. These materials are classified as Silt Sand (SL) according to the LCPC classification or Sandy Clay (SC) according to the USCS classification.
- The clayey sands observed between depths of 12 and 46 meters are characterized by less fine content, not exceeding 17% at maximum with an average of around 13.5%. The measured plasticity index ranges from 5 to 9%, confirming the non-plastic nature of this formation. They are also classified as Silty The clay layer, identified in one of the boreholes, between depths of 46 and 50 meters and confirmed by the identification test results of sample P111 between 48-48 and 57 (Table 2), demonstrating a very high fine content of about 87% with a plasticity index of 25%, classifying it as a highly plastic clay of At or CH groups of USCS classification. However, it seems to be a thin lenticular layer, having a limited influence on the behavior of the sandy mass, especially since this layer is situated more than 26 meters below the lower face of the raft.
- Beyond this, the ground becomes less sensitive to water, the sand fraction increases, and the fine content no longer exceeds 11% at maximum, the formation is classified as sandy or silty sand (Sb-SL). The measured plasticity index demonstrates that this formation is practically insensitive to water where the plasticity index is between 5 and 7%. It's worth noting that the direct shear test conducted on sample P116 between 80-80.5m (Table 2) confirms the non-cohesive sandy nature of this formation ( $C'=0$  kPa;  $\Phi'=28^\circ$ ).

**Table 2.** Results of Identification and Mechanical Tests

Depth (m)		Identification				Mechanical	
		Granulometry			IP	Straight Shear	
From (m)	To (m)	>20 mm	>2 mm	<0.08 mm	Ip	C (Kpa)	$\Phi$ (°)
3	3.46	0	0	35	19	25	32
6.1	6.6	0	0	31	21	-	-
9	9.5	0	1	26	20	-	-
12	12.4	0	2	28	10	28	37
15	15.3	0	1	7	7	-	-
18.1	18.5	0	0	14	5	27	24
24	24.4	0	6	14	6	-	-
30	30.5	0	2	17	3	30	29
36	36.6	0	1	16	8	-	-
42	42.5	0	3	13	7	-	-
48	48.6	0	4	88	25	-	-
54	54.5	0	14	8	6	19	27
60	60.4	3	11	6	5	-	-
66	66.5	3	12	6	6	-	-
72	72.5	0	14	7	7	-	-
80	80.5	0	18	11	7	0	28

### 2.3. Pressuremeter Test

The Ménard pressuremeter test serves as the standard test for soil assessment in the context of geotechnical design. It allows for the evaluation of the mechanical characteristics of the encountered formations. Several parameters are obtained from the pressuremeter. One of the most useful is the PMT modulus derived from the initial loading [12].

The interpretation of pressuremeter curves allows for the determination of the deformation modulus EM during a phase referred to as pseudoelastic, as well as the limit pressure associated with the onset of significant deformations [13].

The results of the realized pressiometric tests are summarized in Tables 3 and 4.

These values have been determined according to the rules for interpreting pressiometric results for the design of foundations [14].

**Table 3.** Results of pressuremeter tests

Soil Classes		PI* (MPa)	qc (MPa)	N SPT	Cu (kPa)
Clays and Silt	Very soft to soft	<0.4	<1.0	-	<75
	Stiff	0.4- 1.2	1- 2.5		75-150
	Rigid	1.2- 2	2.5- 4.0		150-300
	Very rigid	$\geq 2$	$\geq 4.0$		$\geq 300$
Sands and gravels	Very loose	<0.2	<1.5	<3	
	Loose	0.2-0.5	1.5- 4	3- 8	
	Moderately dense	0.5-1	4- 10	8-25	
	Dense	1-2	10- 20	25- 42	
	Very Dense	>2	>20	42- 58	

IC: Consistency Index.PI\*: Limit Pressure.

qc: Peak Resistance. N: SPT number of strokes.

Cu: undrained cohesion.

**Table 4.** Mean values of pressiometric results

Parameters	Ensemble
$p_{te}$ (MPa) <sup>(1)</sup>	2,74
$E_M$ (MPa) <sup>(2)</sup>	38,928
$\alpha$ <sup>(3)</sup>	0,608

(1) Geometric mean of the limit pressure.

(2) Harmonic mean of the Menard deformation modulus.

(3) Arithmetic mean of the Rheologic parameter

In summary, for each formation, we determined the values of Young's modulus and Poisson's ratio, which are provided in Table 5 below:

**Table 5.** The concluded Young Modulus and Poisson's Ratio according to NF P94-261

Layers	Ey (KPa)	Poisson's Ratio
Silty sand	4,50E+04	0,3
Sand insensitive to water	1,44E+05	0,3

## 2.4. Standard Penetration Test- SPT

The Standard Penetration Test (SPT) is a common geotechnical method used to assess the strength and density of soils. It involves driving a standard sampler (a hollow steel tube with a cone-shaped tip) into the ground using a hammer of known weight.

The corer sampler should be driven into the soil by ramming, where a 63.5 kg rammer dropped from a height of 760 mm onto an anvil or ram head [15]. The results of the SPT test should mainly be used to determine the strength and deformation properties of loose granular soils.

It is important to note that foundation design methods based on the Standard Penetration Test (SPT) are empirical in nature. Modifications have been made to the equipment to achieve more reliable results. As a result, appropriate correction factors must be applied when interpreting the results in accordance with EN 1997-2: Eurocode 7 [16].

The results of the conducted tests can be summarized in Table 6.

**Table 6.** Summary of standard penetration tests (SPT) results

Depth (m)	Soil Nature	N spt	Comment
0.00 - 13.00	Fine sand, medium sand, Clay sand	5-15	Slightly to moderately compact soil.
13.00 - 21.00	Sand	14-20	Moderately compact soil
21.00 - 23.00	Fine sand, medium sand	44-46	Fairly compact soil
23.00 - 30.00	Fine sand; Medium sand	9-23	Slightly to moderately compact soil

By consolidating the findings of the geotechnical investigation presented in the previous tables, we can primarily identify four distinct types of geotechnical formations:

From 0.00 to 12.00m: Sandy Silt, Average  $PI = 0.37$  MPa; Average  $EM = 4.61$  MPa. Classified as **loose sand/soft silt** according to the NF P 94-261 [1] standard for shallow foundations.

From 12.00 to 20.00m: Sandy Silt, Average  $PI = 0.64$  MPa; Average  $EM = 7.60$  MPa. Classified as **moderately dense sands/firm silts** according to the NF P 94-261 standard [1].

From 20.00 to 41.00m: Sandy Silt, Average  $PI = 0.90$  MPa; Average  $EM = 11.82$  MPa. Classified as **dense sands/firm silts** according to the AFNOR standard [1].

From 41.00 to 80.00m: Sand-Sandy Silt, Average  $PI = 5.16$  MPa; Average  $EM = 66.07$  MPa. Classified as **dense sands** according to the NF P 94-261 standard [1].

The clayey layer mentioned previously is manifested between depths of 55.00m and 56.50m.

## 2.5. Explanation of Calculation Procedures

Based on various observations of common calculation

methods, theories, and on-site findings, the calculations were performed using the pressiometric method.

The pressiometric method is a commonly used technique for the design of shallow foundations, deep foundations, ground anchors, soil improvement, and various types of structures [17].

The settlement beneath the foundation of the project (raft) is formulated based on the pressiometric modulus  $EM$  using an "Oedometric condition approach". It is calculated by integrating over the thickness of the compressible layer the ratio of the surcharge to a modulus equal to  $EM/\alpha$  while considering the influence factor due to load diffusion [18].

In fact, for cases where large loaded surfaces are involved, such as rafts where the pre-consolidation pressure may be exceeded, an oedometer-type modulus can be defined using the following relationship [1]:

$$M = EM/\alpha \quad (3)$$

With:

$EM$ : Menard deformation modulus

$\alpha$ : the rheological coefficient.

Considering that the rheological coefficient significantly affects settlement predictions, this coefficient was determined by examining the ratio  $EM/PL$  for each formation [19]:

## 2.6. Calculation Model

The obtained results lead, according to regulatory provisions, to the following parameters (Table 7):

**Table 7.** Geotechnical Calculation Model

Depth under raft (m)	Formation	EM (MPa)	Ey (MPa)	Poisson's Ratio
0.00-5.00	Silty Sand	9	45	0.3
5.00-66	Sand Insensitive to water	38	144	0.3

The numerical modeling of the Raft-Soil system was conducted using a soil-structure interaction approach, which allows for the consideration of the effects of all applied loads, including distributed, point, and linear loads.

The method used to model the interaction between a plate and its foundation relies on a clever combination of three complementary approaches [11]:

- Finite element modeling of the plate: The plate is divided into a multitude of interconnected elements, which are subjected to numerical treatment by the finite element method. This approach allows for the resolution of solid mechanics equations for the plate, integrating its intrinsic properties and the external loads applied.
- Discretization of interaction pressures: The distribution of pressures between the plate and the

ground is itself discretized, meaning it is represented by point values on the mesh of the plate. This approach allows for consideration of the non-uniform distribution of contact pressures, which is rarely homogeneous in reality.

- Application of Boussinesq's formulas: To calculate the deformations of the ground under the influence of interaction pressures, Boussinesq's formulas are used. These formulas, based on elasticity theory, allow for the determination of ground deformation based on its intrinsic properties and the distribution of applied pressures (Figure 1).

The combination of these three approaches provides an effective and accurate simulation of the plate-ground interaction. The finite element method allows for modeling the behavior of the plate under the effect of loads and interaction pressures, while the discretization of pressures

and application of Boussinesq's formulas account for the complex behavior of the supporting ground

In this approach, the raft is represented as a homogeneous isotropic plate that operates under pure bending. The behavior of the raft is assumed to be linearly elastic, meaning that only deformations due to bending are considered, and the contribution of shear deformations is neglected.

Indeed, the soil is approximated as an elastic multilayer massive [20], infinite in the horizontal (OX) and (OY) directions. Each layer is characterized by its Young's modulus ( $E_y$ ) and Poisson's ratio. Young's modulus was obtained through the correlation with the pressiometric modulus.

Thus, the problem we aim to address involves calculating the essential parameters for the justification of foundations, namely the settlement of the plate, the soil reaction, and especially the bending moment of the slab.

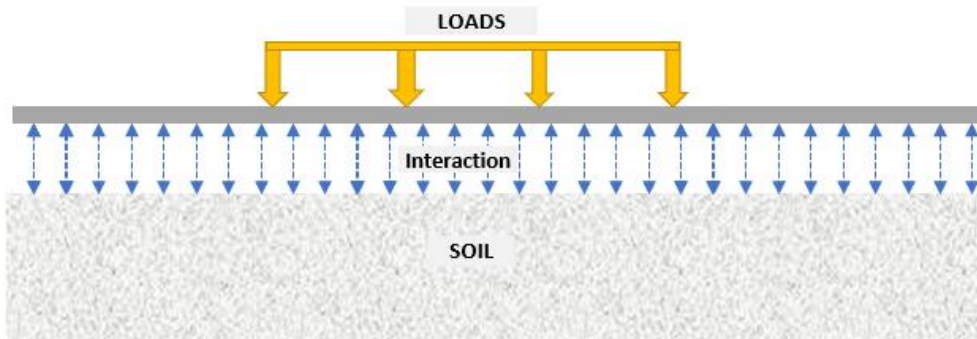


Figure 1. Soil-Structure Interaction-Slab on Elastic Foundation Model

The Figure 2 below depicts the representative plate of the raft while modeling the applied loads.

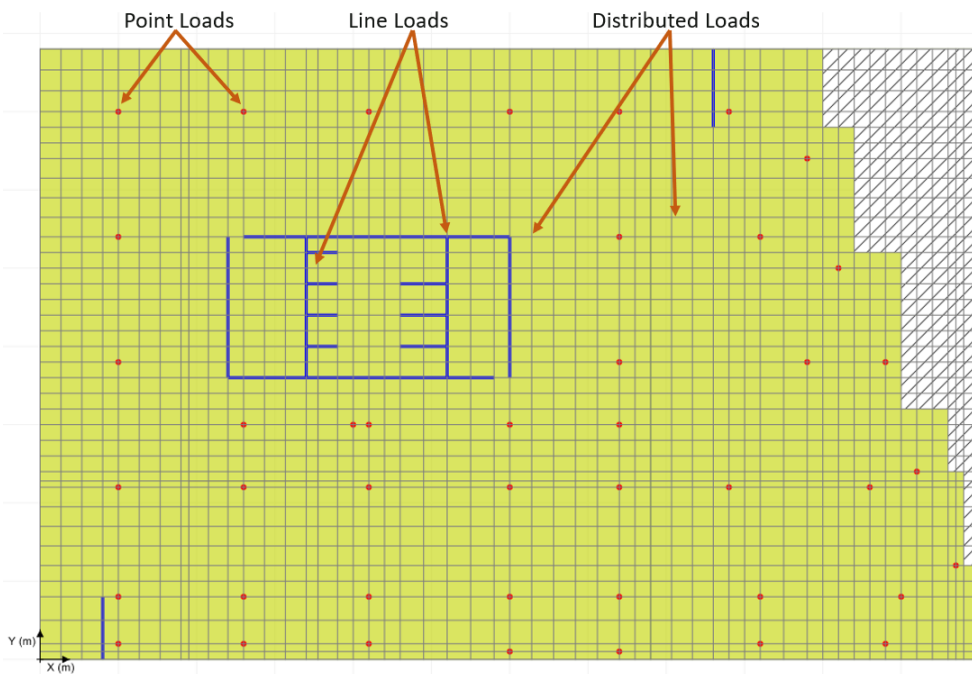


Figure 2. Tapslaq Model of the raft and the applied loads

The raft is modeled using finite elements and is considered homogeneous, isotropic, and subjected to pure bending. It is discretized using a rectangular mesh.

The deformations were calculated at the service Serviceability Limit State (SLS) according to the following combinations (Table 8):

**Table 8.** Load combinations

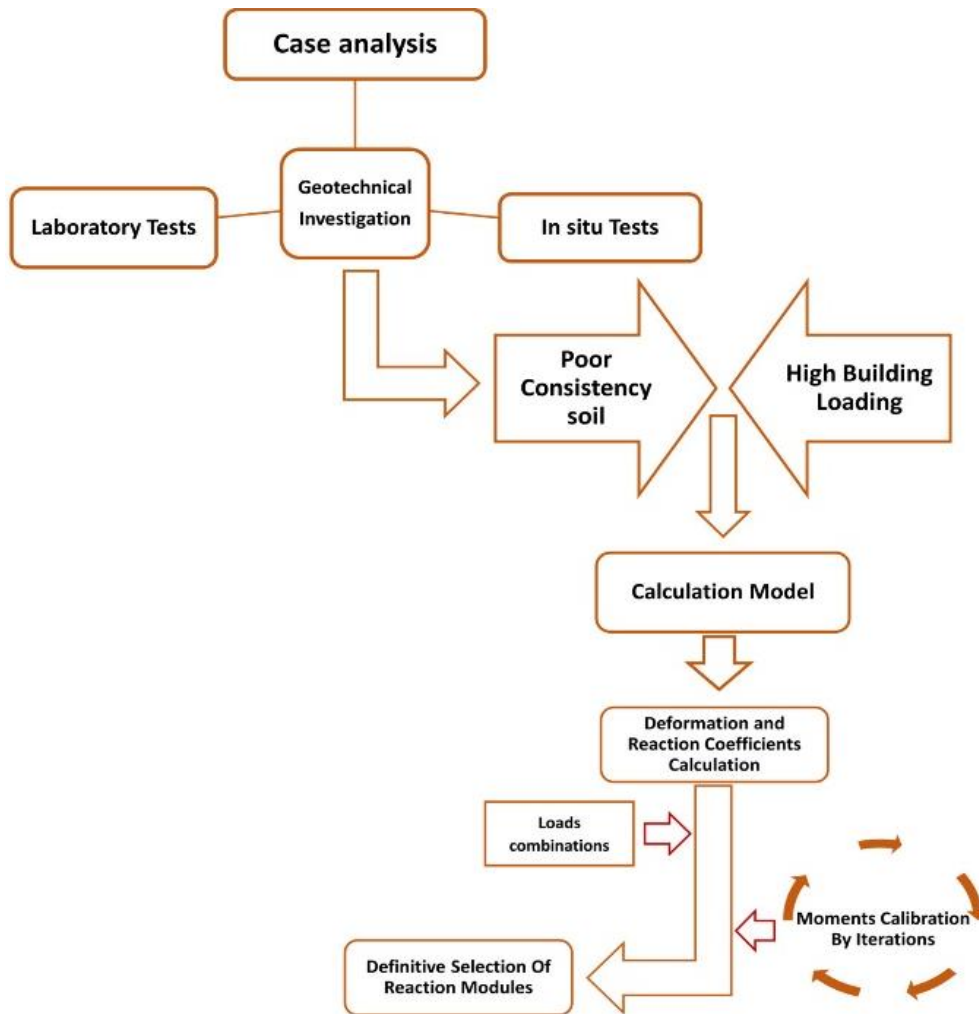
Combinations	SLS
Permanent Loads	1
Operating Loads	1
Wind (max)	0.6
Wind Min)	0
Temperature	0.6

Below are the calculation results for deformations and soil reactions that have been obtained:

- Deflection, settlement, and reaction at every point.
- Plate forces such as shear force and bending moment have also been calculated.

The deformations were computed for both considering a raft with varying thickness from 1.5 to 2.3 meters.

This visual representation in the flowchart illustrated in Figure 3 below clearly summarizes the fundamental principles and steps of the methodology followed in this article:



**Figure 3.** Methodology Flowchart

This research piece presents a soil-structure interaction model that enhances soil behavior representation, enabling optimized foundation solutions and better support in load-sensitive areas.

### 3. Results

#### 3.1. Settlement, Moments

Indeed, the modeling of the load combinations, using Foxta software, enables an informed selection of the reaction module by providing all the justifying parameters for each scenario:

The maximum settlement obtained is approximately: 7,7cm (Figure 4).

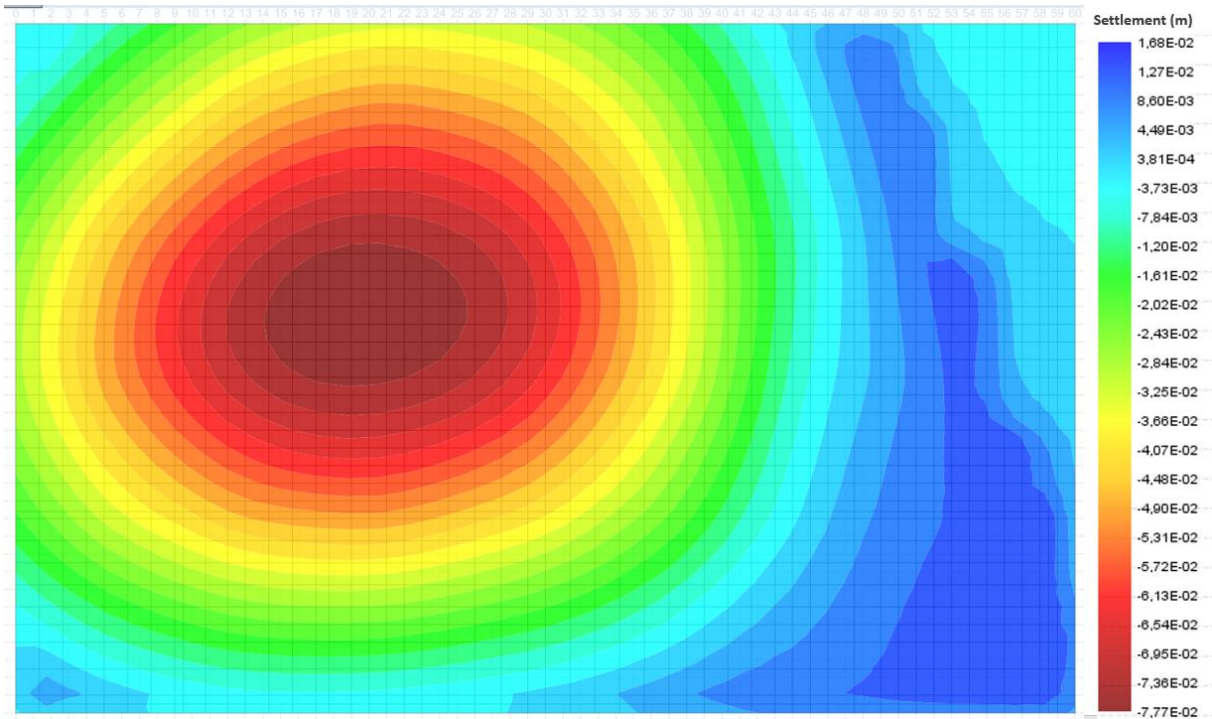


Figure 4. Settlement Mapping (prior to calibration iterations)

The profile presented in Figure 5 below illustrates the evolution of settlements along the OX axis (section at Y=22m).

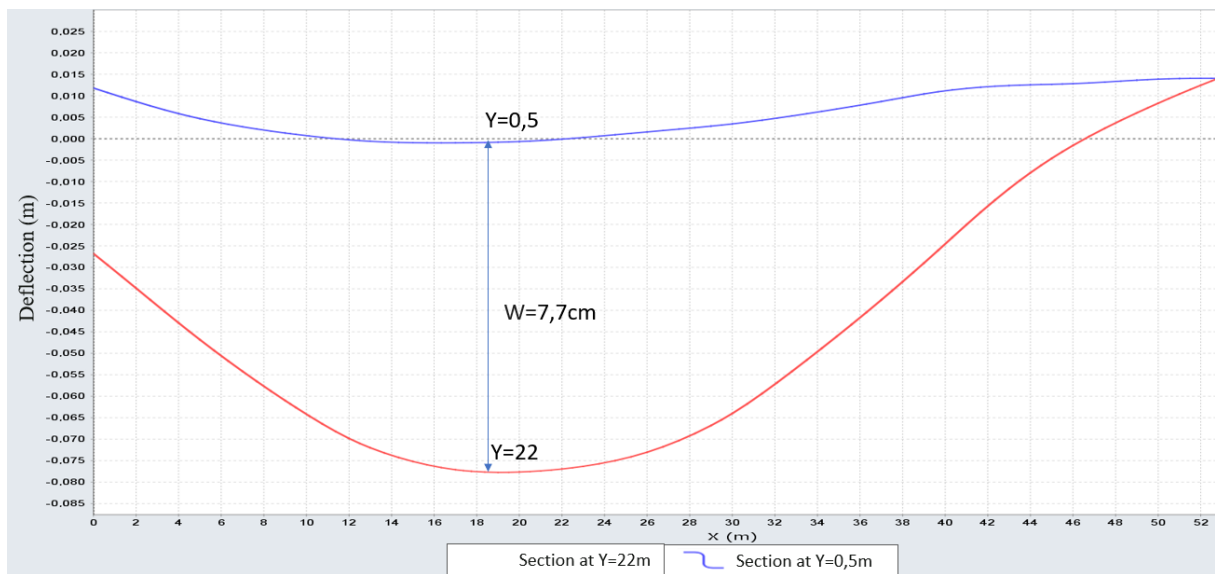
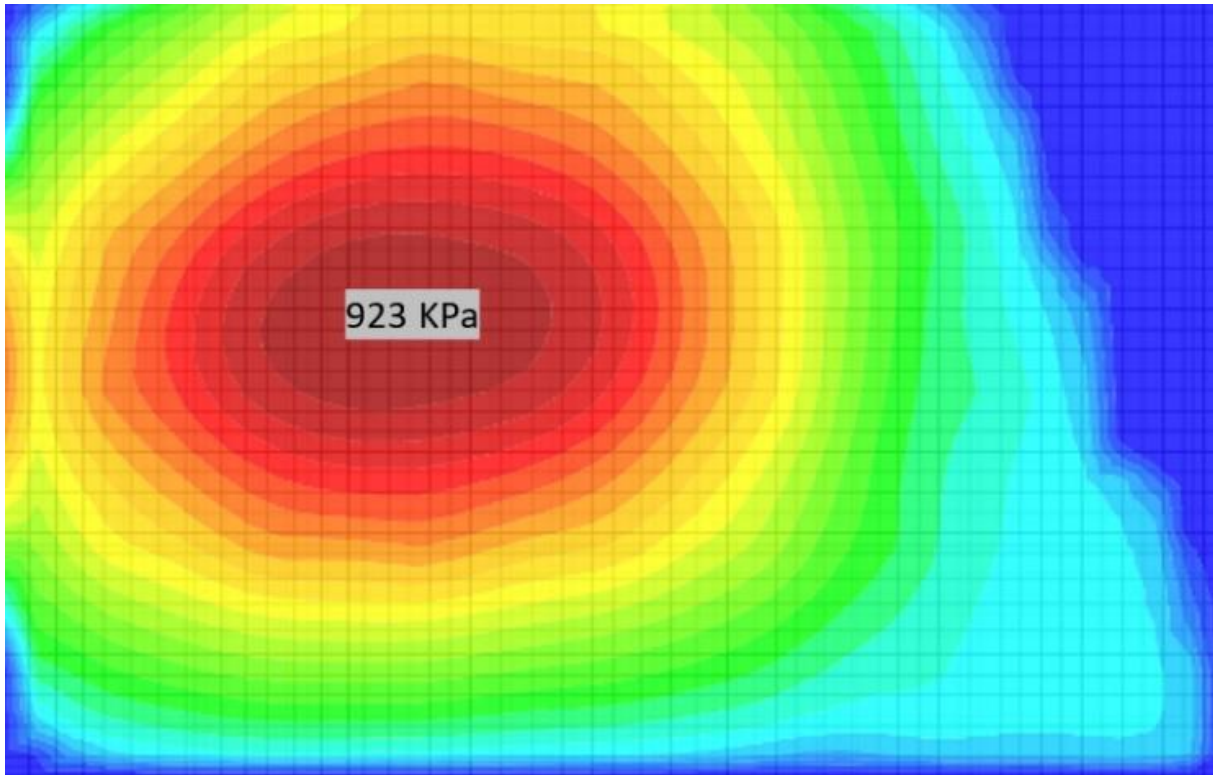


Figure 5. Settlement Profiles along OX (prior to calibration iterations)

In the following Figure 6, we present the results of the soil reaction mapping along the X and Y axes:



**Figure 6.** Soil Reaction Mapping (prior to calibration iterations)

Table 9 below presents the obtained moments:

**Table 9.** Summary of the obtained moments

$M_{y_{max}}$	$M_{x_{Min}}$	$M_{y_{max}}$	$M_{y_{min}}$
8225 KN.m/ml	-1 416 KN.m/ml	<b>8 886 KN.m/ml</b>	-1 020 KN.m/ml

The maximum moment is in 8,886 kN.m/m calculated along the OY axis.

In Table 10 below, we present the results of the reaction module calculations for SLS:

**Table 10.** Load combinations

Zone	Settlement (St)	Reaction module (MPa/m)		
		Min	Max	Mean
Zone A	$7,7\text{cm} \leq St \leq 5\text{cm}$	8,34	9,88	9
Zone B	$3\text{cm} \leq St < 5\text{cm}$	9,5	18	11
Zone C	$St < 3\text{cm}$	9,5	47,1	22

We therefore conclude with the following Figure 7:

- Maximum settlement: **7.8 cm**
- Soil reaction: The raft is divided into three zones:
  - Zone A: 9 MPa/m.
  - Zone B: 11 MPa/m.
  - Zone C: 22 MPa/m.

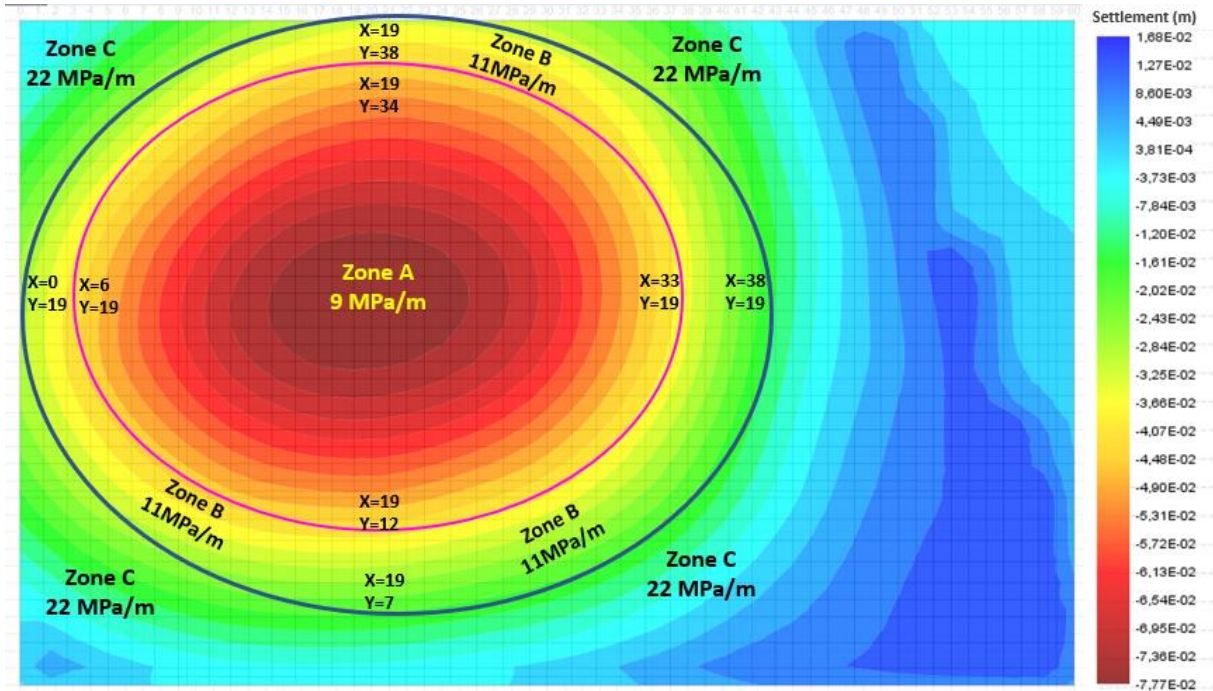


Figure 7. ELS Reaction Module Mapping (MPa/m) (prior to calibration iterations)

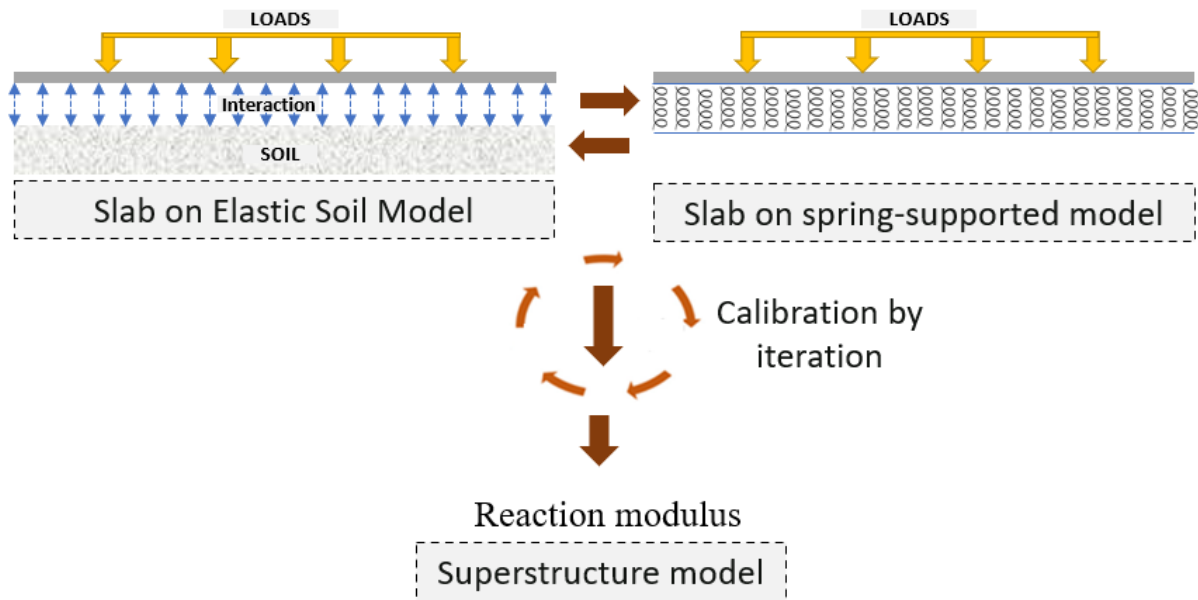


Figure 8. Soil-Structure Interaction; Slab on Elastic Foundation Model

**3.2. Iterations Results**

The obtained reaction modulus of 9 MPa results from the modeling of a slab resting on an elastic mass known as "soil"; this model allows for the determination of the reaction coefficient to be provided to the structural engineer.

However, when this same modulus is used in a spring-based slab model, it becomes apparent that the generated moments are not equivalent [21]. This difference is explained by the fact that the reaction coefficient varies

depending on the distribution of loads.

Thus, it is crucial for the geotechnical engineer to assess the relevance of the reaction coefficient assigned to the structural engineer through a series of iterations aimed at establishing a reaction coefficient that accurately reflects the results of the reference calculation (slab resting on an elastic mass).

The methodology uses a simplified "plate on continuous elastic supports" model, treating the soil as interconnected springs, rather than the more complex

multi-layered soil model used initially. This simplification allows for a more efficient iterative calibration (Figure 8). The distributed vertical stiffness,  $K_z$ , representing the soil's reaction, is adjusted iteratively until the target bending moment is achieved.

In this context, the maximum bending moment obtained from the previous analysis, which is 8.886 kN.m/m, serves as the target value for this calibration.

To do so, we revisited the calculations by introducing an equivalent stiffness “Plate on continuous elastic supports” The soil reaction coefficient is thus introduced as a distributed vertical stiffness  $K_z = 9\text{MPa/m}$ .

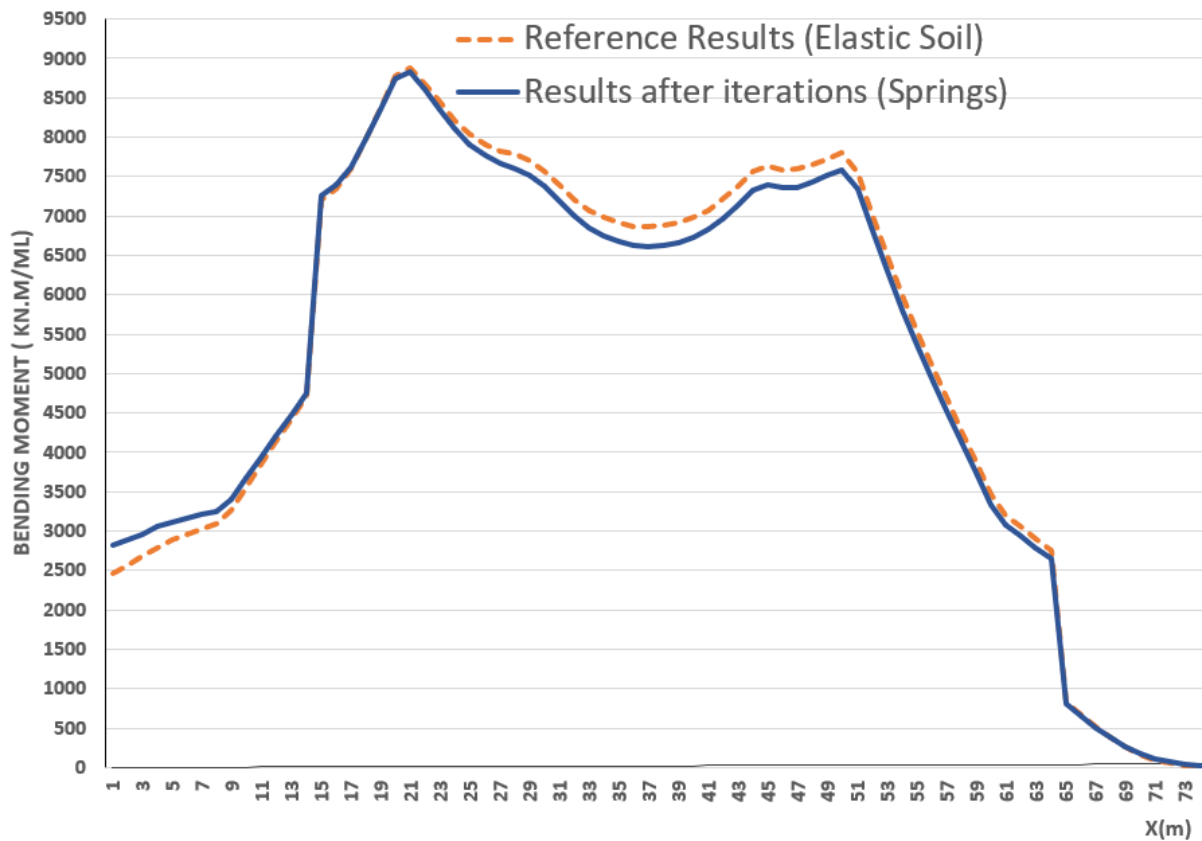
Table 11 below summarizes the various iterations performed to converge towards the target value of maximum moment of 8,886 kN.m/m.

**Table 11.** Iterations - SLS Moments

Iteration	Reaction coefficient $k_z$ (KPa/m)	Maximum moment obtained (kN.m/ml)
Iteration N°1	9000	7661
Iteration N°2	7500	8113
Iteration N°3	7000	8650
Iteration N°4	<b>6700</b>	<b>8831</b>

This table summarizes the iterative process. Starting with an initial guess of  $K_z = 9000$  kPa/m, the maximum bending moment obtained was significantly lower than the target value. Subsequent iterations involved systematically decreasing  $K_z$ , resulting in a gradual increase in the calculated maximum bending moment. This iterative refinement continued until a value of  $K_z = 6700$  kPa/m was found to yield a bending moment very close to the target value of 8886 kN.m/m. The convergence of the iterative process highlights the sensitivity of the bending moment calculation to the choice of the soil reaction coefficient and demonstrates the need for a careful calibration procedure. The graph (Figure 9) visually presents this iterative process, showing the convergence of the spring model's moment response toward the reference elastic soil model.

Thus, we can deduce that in SLS, a reaction modulus of 6.7 MPa/m is the most representative of the supporting medium in terms of the maximum loads observed in the core. Therefore, different reaction modulus values can be selected for each loading zone. This approach avoids oversizing the entire raft area and allows for the choice of an equivalent reaction modulus for each zone, accurately reflecting the soil-structure interaction within that zone.



**Figure 9.** Soil-Structure Interaction; Slab on Elastic Foundation Model

## 4. Discussion and Perspective

This study presents a compelling example of numerical modeling of soil-structure interaction (SSI) in the context of raft foundations, specifically applied to a 22-story tower built on a weak-bearing sandy-silt soil. In the examined case, a comprehensive geotechnical investigation was conducted, incorporating both in-situ and laboratory testing, which provided a detailed characterization of the geotechnical model of calculations.

This model served as the foundation for establishing a refined soil-structure model, utilizing interconnected springs to effectively represent the soil behavior, which significantly improved upon traditional methods that rely on constant reaction modules. The study clearly demonstrated that partitioning the raft foundation into loading zones with specific reaction modules is markedly more efficient than employing a single value, particularly in scenarios with important loads.

This segmentation was achieved through a model based on springs, conceptualizing the soil as a series of independent springs, allowing for a more accurate calculation of the soil's response and structural displacements under various load combinations. However, when the same module is applied in a spring slab model, it becomes evident that the resulting moments are not equivalent. This discrepancy can be attributed to the fact that the reaction coefficient varies according to the load distribution.

Therefore, through an iterative calibration process, it can be concluded that the predictions from the model represent an accurate reflection of actual soil behavior, bridging the gap between a simplified model that is computationally efficient and a more realistic portrayal of the structure's behavior. Consequently, it is essential for the geotechnical engineer to assess the relevance of the reaction coefficient assigned to designers through a series of iterations aimed at establishing a reaction coefficient that accurately mirrors the results from reference calculations (a slab resting on elastic mass). This meticulous process ensures that the engineering design is both sound and reflective of real conditions, ultimately leading to safer and more reliable structures.

With respect to settlements and moments, the obtained model accurately predicts the settlements and bending moments of the raft under various loading scenarios.

It is important to note that the results were validated and further refined through a series of iterations to improve the definition of the equivalent reaction coefficient. Nevertheless, it is crucial to recognize that the proposed approach has certain limitations, which we will outline in the following sections:

- **Simplified Modeling:** Representing soil with springs does not always capture the full complexity of actual soil behavior, such as nonlinear effects or complex interactions.

- **Limited Precision:** This approach may lack precision for projects requiring highly detailed modeling, particularly in heterogeneous soils or with nonlinear behaviors.

Thus, to enhance precision, especially in the case of highly heterogeneous soils, it is advisable to use nonlinear soil behavior models, intensify geotechnical investigations to refine calculation values, and acknowledge the complexity of interactions by conducting systematic experimental verification to validate and adjust model predictions.

Ultimately study serves as a crucial foundation for further exploration. Therefore, it is advisable to expand the application of this method across a broader range of cases to assess the effectiveness of the proposed approach in various contexts, particularly in cases involving heterogeneous soils

## 5. Conclusions

The proposed soil-structure interaction model in this article provides a modeling method that enhances the representation of soil behavior compared to the traditional approach based on the standard reaction modulus.

This approach allows for a more informed selection of reaction modules specific to each zone, leading to improved foundation solutions and strengthening of vulnerable areas, particularly where significant loads are applied.

In our example study, instead of using a general average reaction modulus of 9 MPa, we observe that after segmenting the structure into loading zones and performing specific treatment for each zone, the chosen reaction modulus values are much more aligned with reality and correspond to the actual loads in each loading zone.

In summary, this modeling approach based on interconnected springs holds the definite advantage of considering the unique characteristics of each loading zone. It also allows for better adaptation of foundation solutions based on these specifics, providing a more precise and suitable approach in foundation design.

The presented soil-structure interaction calculation model offers a modeling method that better represents soil behavior compared to the traditional reaction modulus approach. It enables an informed selection of reaction modules on a zone-by-zone basis, optimizing foundation solutions and reinforcing vulnerable areas with substantial load transfer.

In our study example, instead of using a generalized average reaction modulus of 9MPa, we can deduce that after discretization and processing by load zone, we adopt modulus values that are significantly realistic and suitable for the actual surcharges in each load zone.

To sum up, employing this modeling approach with interconnected springs evidently facilitates the

incorporation of individual load zone characteristics, leading to a more precise adaptation of foundation solutions.

In the Moroccan context, as in many other countries, the soil exhibits significant heterogeneity, ranging from soft, muddy areas to very hard quartzite rocks. With the intensification of urban development, particularly in large cities, tall structures are often required to meet the growing demand from designers. In such situations, it is crucial to adopt design approaches based on soil-structure interaction to ensure informed decisions regarding the foundation methods for large-scale projects.

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