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Dynamic Analysis of Vertical and Horizontal Irregular Reinforced Concrete Structure Considering Soil Structure Interaction

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Abstract: Numerous studies have examined soil-structure interaction (SSI) effects on the seismic response of high-rise buildings, comparing them to fixed-base models. These investigations have integrated SSI into dynamic analyses and highlighted key provisions in major seismic codes. However, most research focuses on regular structures with uniform mass, stiffness, and strength distribution, while only a few addresses geometric irregularities. (Stewart, 2012 & J-Priyadarshini, 2013). This study employs ROBOT Structural Analysis 2019 to numerically model an irregular 8-storey reinforced concrete structure (with horizontal and vertical irregularities) under seismic loading, considering SSI and comparing its response to that of a regular structure. The soil is modeled as a homogeneous, linearly elastic medium using spring elements. Four dynamic analyses are performed: one with a fixed base and three incorporating SSI for different soil types per the Algerian Seismic Code (RPA 2024). These analysis results are compared with those of the fixed-base structure. The findings indicate that the effect of the ISS on the dynamic modal response (particularly the fundamental period) grows with soil flexibility and becomes even more pronounced in irregularly shaped structures. Thus, both structural irregularity and the flexibility of soil amplify the ISS's impact on dynamic behavior. Regarding seismic response, fixed-base assumptions lead to overestimated internal forces in walls and columns for all building types, while relative displacements are underestimated in regular buildings and show a more significant increase in irregular ones. The results demonstrate that soil-structure interaction significantly affects the seismic performance of buildings, particularly those with irregular geometry

Keywords: Interaction soil structure, Numerical model, Horizontal and vertical irregularities, Flexibility of soil, Fixed base

Introduction

Traditionally, structural design methods assume a perfectly fixed base, with no possibility of settlement, sliding or rotation. However, during an earthquake, the inertial forces generated create shear at the base and an overturning moment at the foundations (Patro, 202 & Sumit, 2020). Unless the foundation system and the underlying soil are infinitely rigid, these stresses necessarily induce rotations and displacements of the foundations. These movements significantly disrupt the actual dynamic properties of the system. This complex coupling, where the vibrational response of the structure modifies the behaviour of the soil and vice versa, constitutes the phenomenon of soil-structure interaction (SSI). Soil-structure interaction is a fundamental

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phenomenon in civil engineering that studies the reciprocal effects between the soil and a built structure. When designing a structure, it is essential to understand how the soil supports the loads applied by the structure and how, in turn, soil deformations influence the behaviour of the structure. This interaction plays a crucial role in the stability, durability and safety of buildings, particularly in areas subject to complex geotechnical constraints (compressible soils, seismic zones, etc.) (Chetan, 2020 & Karapetrou, 2015). Failure to take these interactions into account can lead to differential settlement, cracking and even collapse.

The analysis of soil-structure interaction is essential to ensure the stability and safety of buildings. Different methods, ranging from simplified approaches to complex modelling, are used depending on the project requirements (Anand, 2018 & Behnanfar, 2017). The scientific literature reports numerous studies on the seismic behaviour of foundations in the context of soil-structure interaction (SSI). At the same time, several studies have analysed the response of high-rise buildings under earthquake conditions, taking SSI into account (Khalil, 2009 & RPA, 2024), with systematic comparisons to fixed-base models. Stewart et al. have established consensus recommendations for the integration of SSI into historical response analyses, proposing a unified conceptual synthesis with a consistent system of units and variables. In a complementary approach, Anand and Kumar have conducted a methodological review of the various techniques for integrating SSI into seismic response analyses, while examining the requirements of the main seismic codes (Bhosale, 2018 & Stewart, 1999). The present study is an approach to investigate the role of soil beneath the superstructure, by analysing a vertical and horizontal geometric irregular building considering soil–structure interaction subjected to ground motion using ROBOT Structural Analysis 2019, and results were compared with a reference regular building having a fixed base.

Modeling of Superstructures

Two types of building have been used in the present study, regular building, vertical and horizontal irregular geometric building. Both of building have eight storeys with the storey height of 3,40 m and ground floor 3,57m. The dimension of buildings is 23,30mx24,95m and height is 33,77m see fig.3. buildings are modelled as fixed (without SSI) and Flexible base (with SSI), which is modelled using indirect method. All structural member dimensions are selected as per: RPA2024 (Algerian Seismic Code), and DTR (Regulatory technical Document) for considering ductile detailing of the members and structure as whole (Table1), (Fig 1, 2).

Table 1. Member dimension and properties

Element	Storeys	Dimension			Units
	GF	(65x65)			
Columns	1-2				cm^2
	3-5	(60x60)			
	6-8	(55x55)			
	Direction	L	h	b	
Beams	Sens X-X	800	65	40	cm
	Sens Y-Y	800	65	40	
Shear wall thickness	All	30			cm
Slab thickness	All	20			cm
Resistance of Concrete	F_{c28}	Compression			30
		Traction			2,4
Resistance of Rebar used	Fe	500			235

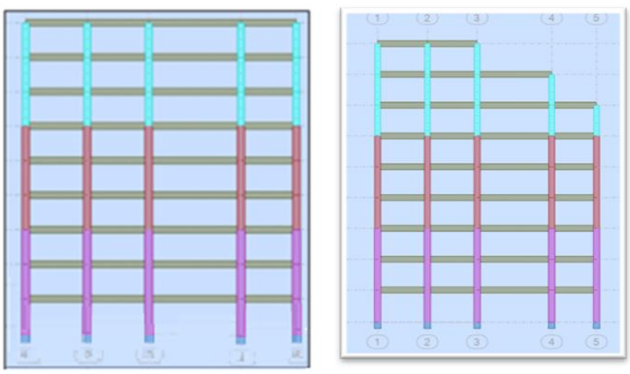

Figure 1. Fixed base model for regular and irregular building

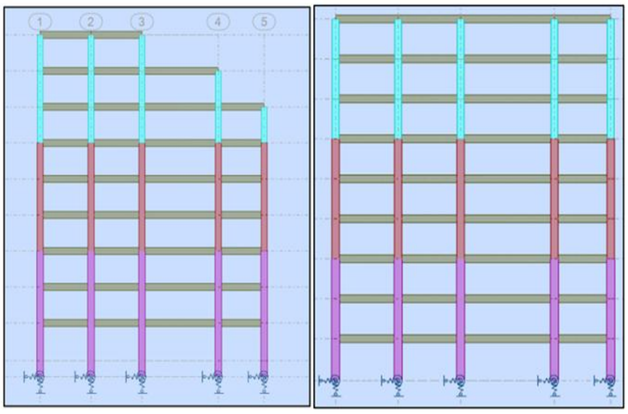

Figure 2. Flexible base model for regular and irregular building

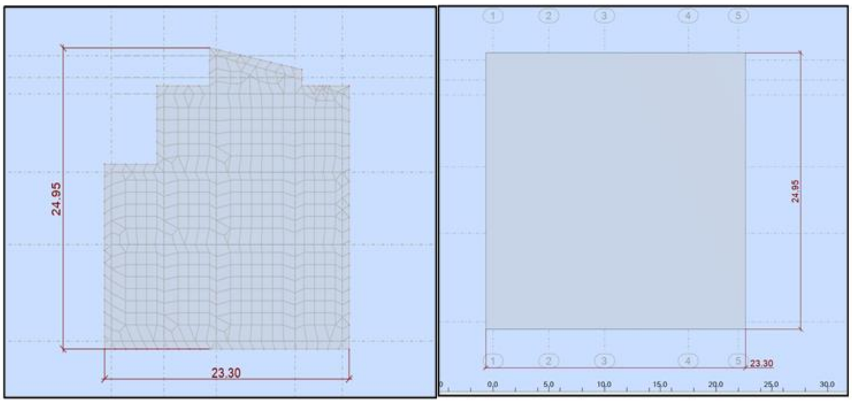

Figure 3. Plan views

The columns, beams, shear walls and slabs of the structure were considered to be made of reinforced concrete with linear elastic behavior. The material proprieties are summarized in Table 2 (Anand, 2018), the behavior of the structural elements was considered as linear elastic. A structural Rayleigh damping ratio ξ (Stewart, 1999), was assigned for all the elements in the concrete frame-shear wall building.

Table 2. Material properties considered for the structural elements in the building

Parameter	Notation	Columns, beams and shear walls
Young modulus (GPa)	E	32
Shear modulus (GPa)	G	12.5
Volumic weight (kg/m^3)	ρ	2500
Poisson ratio	ν	0.2
Damping ratio	ξ	0.085

To study the effect of the interaction soil structure on the dynamic response of the structure, the seismic action is introduced using a design response spectrum. The dynamic characteristics of the structure according to RPA 2024 are shown in Table 3.

Table 3. Dynamic properties of the building

Behavior coefficient R	Acceleration coefficient zone A	Quality factor Q	Correction factor λ
4,5	0,15	Qx 1,30 Qy 1,25	0,85

To study the influence of the interaction soil structure on the dynamic response of the irregular structures, we carried out a spectral modal analysis using ROBOT Structural Analysis 2029 based on the finite element method (FEM). The columns and beams were modeled with frame elements. The slab floors were modeled with deck elements. The shear walls and slabs were modeled by shell elements (Anastassiaadis, 1993). Beam structural elements were two-noded, straight, finite elements with six degrees of freedom per node, including three translational components and three rotational components. The shell structural elements were four-noded, flat finite elements with 20 degrees of freedom. For the Response Spectrum Analysis RSA, SSRS (square root of the sum of square) and CQC (Complete quadratic Combination) are considered (Anastassiaadis, 1993 & Mohamadi , 2023). A sufficient number of modes (9 modes) are considered in the analysis such that to get the sum of mass for all modes assumed 90% of the total seismic mass, according to the RPA 2024. The mesh size used is the default mesh size in the ROBOT software. The arrangement of the braced walls was made in such a way that the first and second modes of vibrations are translations along X and Y and the third mode is a rotation around Z. The eccentricity between the center of mass and the center of rigidity at each floor (ex=0.0216m and ey=0.0215m). The first vibration mode is translation along X with a period T_1= 0.69s, the second vibration mode is translation along Y with a period T_2= 0.66s, while the third mode is rotation around Z with a period T_3= 0.55s. The response of the structure is calculated in both directions for the most unfavorable load combination:

$$G+\psi Q+E \qquad (1)$$

G: Dead load**, Q:** Live load**, E:** Seismic load**,** ψ**:** accompanying coefficient

Different loads on structure are taken as per DTR B.C. 2.2 for dead and live loads, for seismic load RPA 2024 (Algerian Seismic Code), and load combination is taken per BAEL 91/99 and RPA2024. To understand Response of structure and influence of Soil structure interaction effects in different soil conditions, a fixed and flexible base G+7model is taken, which is assumed to be in Seismic ZONE V.
The values of G and Q for the various elements are given in Table 4.

Table 4. Dead and live loads

Element	Terrace floor	Current floor	Balcony
G (KN/m^2)	8,7	7,6	7,6
Q (KN/m^2)	1	2,5	3,5

Soil Springs

The soil is assumed to be homogeneous with linear elastic behaviour and modelled by springs and characterized by its density ρ and behaviour parameters, shear modulus G, Poisson's ratio ν and shear wave velocity V_s. Table 5. The interaction of the structure with the soil is modelled using discrete elastic springs (Vertical, Horizontal direction and Rocking and for Rocking and Twisting movements). The stiffness coefficients of these springs are given by GAZETAS (Anastassiaadis, 1993), which depends upon dimensions and characteristic of footing (L: length and B: breadth, A_b: aria, $I_{x,y,z}$: inertia moments, $\zeta_t = I_x + I_y$: polar moment of inertia) (Mohamadi, 2023), shear modulus (G) of soil and Poisson's ratio (ν) of soil. Tables 6 and 8.

Table 5. Soil properties

Site	Description	V_S (m/s)	E(MPa)	ν
S_2	Firm	580	830	0.44
S_3	Soft	270	300	0.40
S_4	Very Soft	180	127	0.37

Table 6. Geometrical characteristics of footing for irregular building

L (m)	B (m)	Ab (m2)	Iz (m4)	Ix (m4)	Iy (m4)
12,475	11,65	495,24	87592,4265	39839,7388	47793,9577

Table 7. Soil springs stiffness values (irregular building)

	Unit	Site 2	Site 3	Site 4
G	kN/m^2	830000	300000	127000
$K_{z,surf}$	kN/m	48978407,759	14090173,857	5964840,266
$K_{y,surf}$		36768275,456	11614561,043	4916830,842
$K_{x,surf}$		36494375,456	11543061,043	4886562,508
$K_{zz,surf}$		13760709113	4618482405	1955157551
$K_{yy,surf}$		9487091237	2729259097	1155386351
$K_{xx,surf}$		7963584197	2290974554	969845895

Table 8. Geometrical characteristic of footing for regular building

L (m)	B (m)	$I_x(m^4)$	$I_y(m^4)$	$\zeta_t(m^4)$
12,475	11,65	54622,3244	684392,374	739014,699

Table 9. Soil stiffness values (regular building)

	Unit	Site 2	Site 3	Site 4
G	kN/m^2	830000	300000	127000
$K_{z,surf}$	kN/m	52981917,8	15241909	6452408,14
$K_{y,surf}$		39490171,31	12474368,18	5280815,862
$K_{x,surf}$		39216271,31	12402868,18	5250547,528
$K_{zz,surf}$		58576838868	19660040584	8322750514
$K_{yy,surf}$		69836457673	20090645556	8505039952
$K_{xx,surf}$		10090178454	2902756034	1228833388

Spring stiffness values for the different directions and as a function of the shear wave velocity of the soil associated with the different site categories for a rectangular foundation, both for regular and irregular building. Table 7 and 9 above.

Results and Discussion

Natural Time Period

According to the seismic analysis, it can be observed that each time the soil stiffness increases, the ratio (T_{fixed}/T) also increases. This variation is particularly pronounced in the case of an irregular structure located on very soft ground (S4). The increase in the natural period of the structure when soil–structure interaction is accounted for is primarily due to the reduction in overall system stiffness caused by foundation translation, rocking and soil deformation. This effect becomes more pronounced with decreasing soil stiffness (softer ground) and is further amplified in plan/vertical irregular structures where modal coupling is stronger (Thambi & Foong, 2016; Yang et al., 2024). The results show that the period (with soil-structure interaction, SSI) is systematically longer than (fixed base model) for the first three vibration modes. This significant increase in periods can be explained by the flexibility introduced by the SSI, which reduces the overall stiffness of the system. An increase in natural periods indicates that the structure becomes more sensitive to low-frequency seismic excitations, thus increasing its exposure time to dynamic solicitations. Consequently, the ISS can increase the risk of damage during an earthquake, requiring special attention in seismic design for both types of structures. Fig 4 and 5.

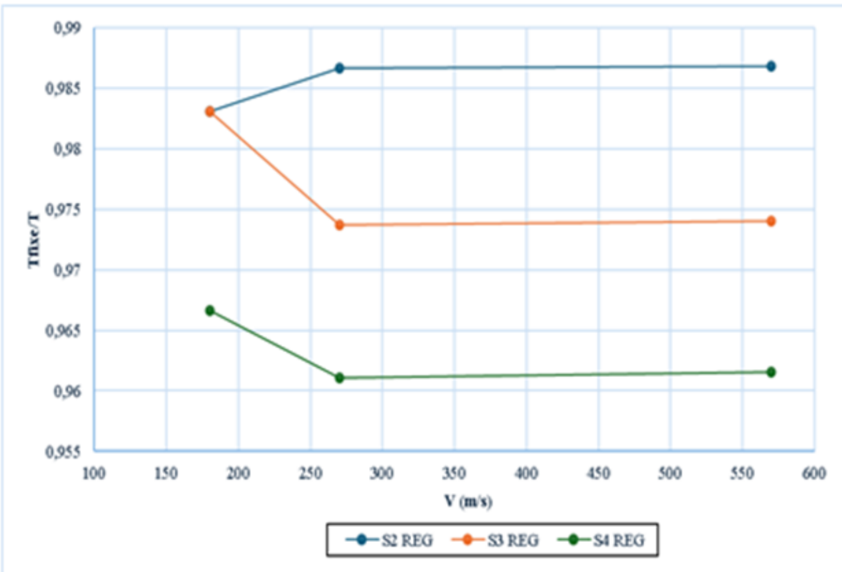

Figure 4. Variation in the ratio of T_{fixed}/T regular structure

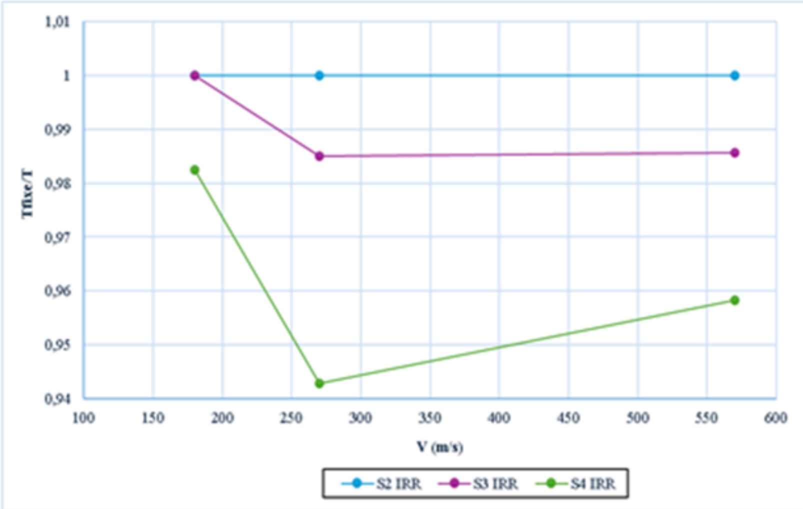

Figure 5. Variation in the ratio of T_{fixed}/T irregular structure.

Relative Displacement

From results of seismic analysis, the displacements in the X and Y directions are significantly greater when soil-structure interaction (SSI) is taken into account, compared to when it is neglected. This difference can be explained by the flexibility of the soil, which, by deforming under seismic load, influences the behaviour of the structure. On the other hand, relative displacements are underestimated for regular buildings, with a much more noticeable increase in the case of irregular structures. Fig 6, 7 and 8

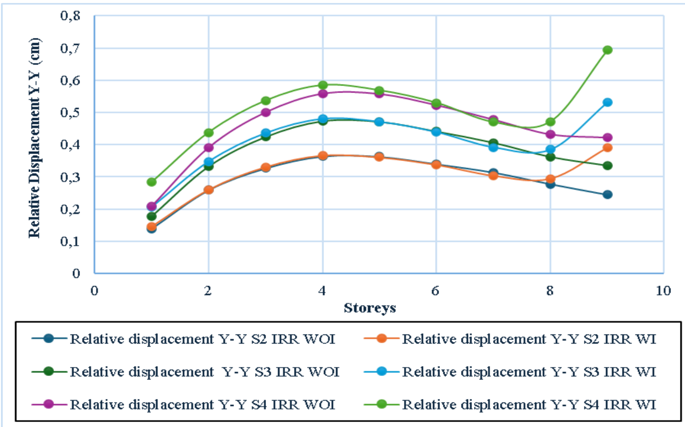

Figure 6. Relative displacement Y-Y (cm) irregular structure, with ISS (WI) and without ISS (WOI)

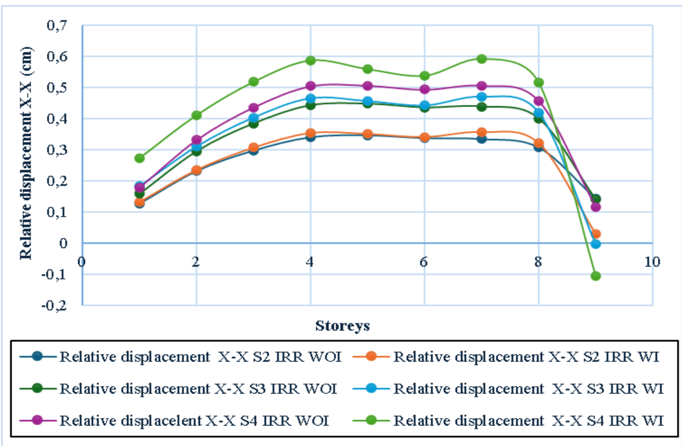

Figure 7. Relative displacement X-X (cm) irregular structure, with ISS (WI) and without ISS (WOI)

The relative displacements in both horizontal directions increase significantly under SSI because the deformable soil permits greater foundation movement and rotation, thereby increasing story drifts and top displacements compared with the fixed-base assumption (Kuhlemeyer et al., 2014; Yang et al., 2024)."

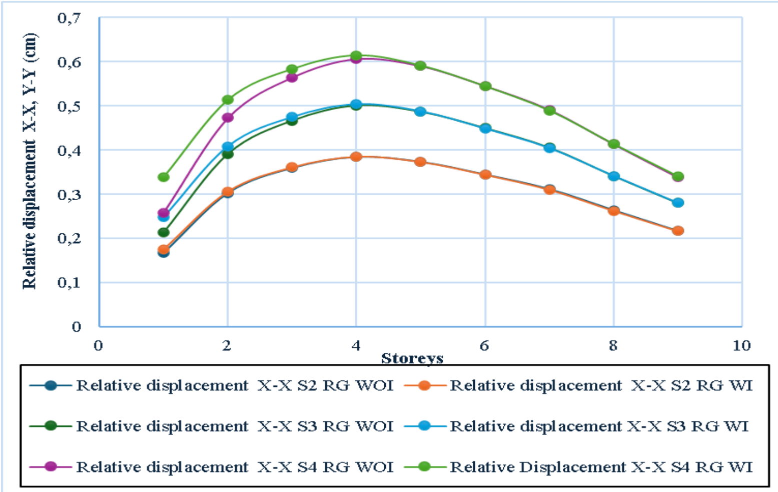

Figure 8. Relative displacement X-X (cm) and Y-Y (cm) regular structure, with ISS (WI) and without ISS (WOI)

Shear Forces

From results of seismic analysis, there is a reduction in the shear force at the base in the case of soil-structure interaction (SSI), with an average reduction of 40% for Shear walls when considering soil-structure interaction (SSI) in the case of a regular structure. And 60% for irregular structures. In columns, the average reduction is 40%. The observed reduction in base shear with SSI (≈ 40 % for shear walls in regular structures, up to ≈ 60 % in irregular cases, and ≈ 40 % in columns) is consistent with documented studies that show the lengthening of the dynamic period and additional soil damping reduce the seismic demand transferred to the structural system (Yang et al., 2024; IJERT, n.d.). If the shear force at the base of the structure is reduced in the case of the ISS, the reinforcement (transverse reinforcement) is generally reduced. Fig 9, 10.

In summary, the numerical results align with existing research: softer soils and irregular structures accentuate SSI effects, leading to increased periods, larger displacements and reduced base shear. These phenomena must therefore be considered in seismic design and analysis to avoid under-estimating seismic demands or over-estimating capacity.

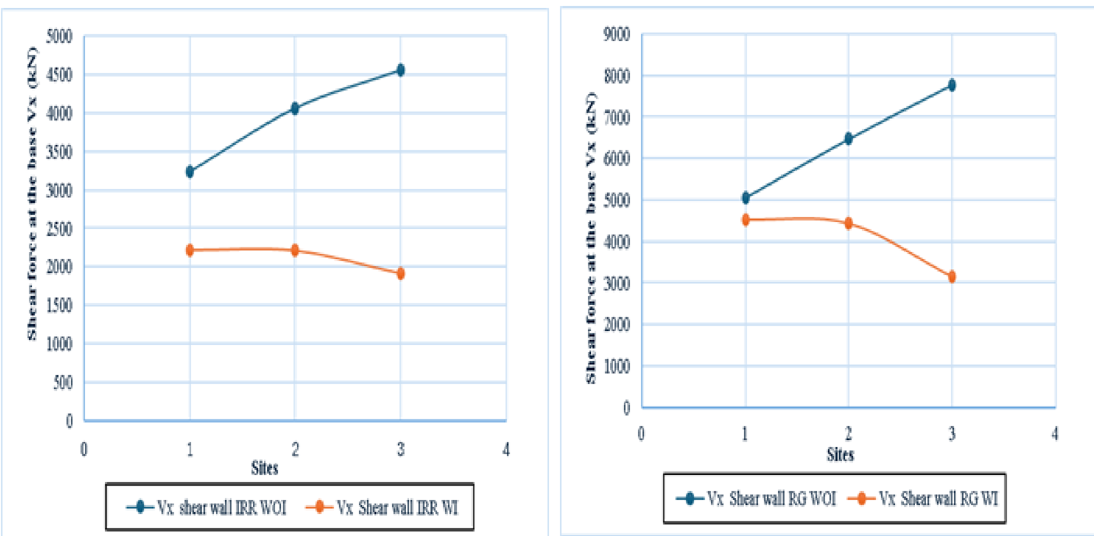

Figure 9. Shear force $V_{X\text{-}X}$ (Shear wall), irregular and regular structure, with ISS (WI) and without ISS (WOI)

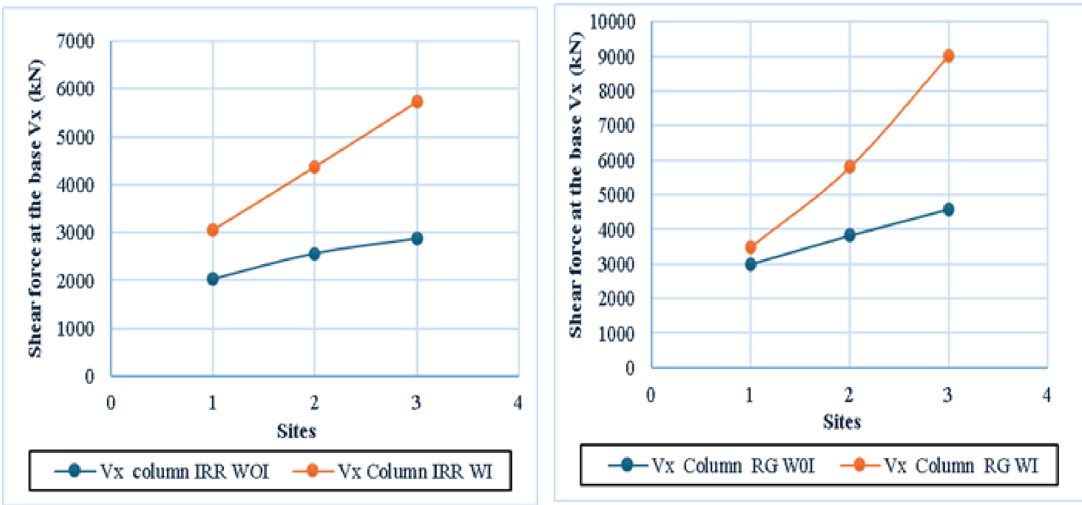

Figure 10. Shear force $V_{X\text{-}X}$ (Columns), regular and irregular structure, with ISS (WI) and without ISS (WOI)

Conclusion

This study investigated the influence of soil–structure interaction (SSI) on an irregular, eight-storey reinforced concrete building located in a high seismic zone (Zone V), in accordance with the RPA 2024 provisions. Three soil types-firm, loose, and very loose-were considered, and the response spectrum analysis was performed using ROBOT 2019 software. The results reveal that accounting for SSI leads to an increased vulnerability of structures compared to those analyzed with a fixed-base assumption. Buildings exhibiting geometric irregularities, whether in plan or elevation, demonstrate a significantly higher probability of failure than regular configurations. For structures founded on rigid soils, the discrepancy between models with and without SSI remains relatively minor. However, for irregular structures and softer soil conditions, this difference becomes substantial, underscoring the combined effect of structural irregularity and soil flexibility on seismic performance. Moreover, the findings indicate that the influence of SSI on the dynamic response amplifies with increasing soil deformability. This effect is particularly pronounced in irregular structures, where both the natural period and relative displacements are more sensitive to soil flexibility. A notable reduction in base shear was also observed in models with flexible foundations compared to fixed-base models, confirming the significant role of SSI in modifying seismic demand.

In conclusion, soil–structure interaction constitutes a critical factor in seismic design, especially for irregular buildings erected on deformable soils. Accurate assessment of this phenomenon requires advanced numerical modeling tools and a high level of engineering expertise to ensure reliable predictions and enhance structural safety under seismic loading

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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