Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-40083
www.engineeringscience.rs

iipp publishing

Journal of Applied Engineering Science
Vol. 21, No. 2, 2023
Original Scientific Paper
Paper number: 21(2023)2, 1088, 440-450

NUMERICAL INVESTIGATION OF THE DYNAMIC SOIL-STRUCTURE INTERACTION OF CONCRETE BUILDINGS

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This research is carried out to investigate and assess the dynamic soil-structure interaction features related to a reinforced concrete building. Numerical analysis and mathematical simulations were performed depending on the ABAQUS® software package to achieve the study goal. Structures with floor numbers ranging between one and ten were modelled and simulated, and soil characteristics were explored and measured in terms of base shear, axial force, moment, and displacement, taking into account dynamic soil-structure interaction principles. In addition, the effect of soil type on the building stability and soil performance was assessed and examined. The research findings revealed that the base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil. Also, the base shear for a five-floor building frame reduces by 5% from soft to medium soil and by 23% from medium to hard soil. The base shear for a shear wall system with ten stories on medium soil is 20% less than that on soft soil. On hard soil, this outcome is lowered by 12%. The axial force for a five-floor building frame decreases by 2% from mild to medium soil and by 8% from medium to hard soil. Additionally, axial forces provide a 9% decrease for medium soil and a 4% reduction for hard soil in a 10-floor building frame resistance system. There is a reduction of 3% from soft to medium soil and a reduction of 12% on hard soil regarding axial force. Meantime, the axial forces are lesser for medium soil by 13% compared to soft soil and less by 6 % for hard soil. The displacement is decreased by 6% in a 5-floor building frame system on medium soil and 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil. Displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil. Also, displacement reduces by 20% and 30% on medium and hard soil, respectively.

Keywords: soil type, simulations, base shear, axial force, moment

1 INTRODUCTION

Soil is a considerable element in the construction sector on which building components are settled and installed [1]. Soil is employed to make the construction materials, yet it is also the primary basis on which the facility is settled. During the building's lifespan, there is an interaction between the structure and the ground. This interaction should be considered and optimized to ensure adequate facility stability. Scientists define this interaction as dynamic soil-structure interaction (DSSI), which relies on a group of variables and parameters related to the soil, including soil humidity, density, stiffness, compaction, damping, porosity, and mass [2], [3]. A good DSSI level can distribute mutual stresses and foster the building's stabilization. One of the critical activities civil engineers follow during the first phases of construction is selecting a suitable site containing perfect soil characteristics that enable stable structure. In addition, construction engineers create soil maps to investigate the land surface and its slope. Also, these soil maps are vital to evaluate the soil's physical, chemical, and biological characteristics. Besides, soil maps play a critical role in determining the soil's potential to store and absorb water. All these aspects are critical to consider in ensuring that soil will serve the construction facility without causing future failure or damage to properties. Practical and effective soil that provides the perfect construction environment to build on should include the following substantial aspects: [4].

(1) Neutral pH value and balanced chemistry,
(2) Stabilization during several drying and wetting stages,
(3) Perfect strength under diverse loading and high pressure,
(4) Capability to capture rainfall without damaging the facilities.

Due to different structural conditions, the soil has many parameters and variables that should be explored in every construction project. One of the critical soil areas is the dynamic soil-structure interaction (DSSI) [5], [6]. DSSI analysis is vital to ensure that the facility can have higher performance, workability, and stability on the ground without failure in the future. Some remarkable soil variables comprise soil mass, compaction, stiffness, structure, porosity, and damping. For instance, engineers consider the soil porosity that influences its dynamic characteristics when constructing dams, bridges, reservoirs, and other high-loading facilities. Higher porosity, like sand, would cause massive failure to these structures when it is not adjusted or modified [7], [8]. In addition, soil stiffness is another critical factor influencing a building's stability. Thus, the ensuing optimum rate of soil stiffness can enable higher building workability, performance, and stability. DSSI analysis is performed using numerical investigation via case study simulation software in this work. The solution to the problem can identify the most critical parameters and factors of soil for optimum building stability. [9] Led research that assessed and investigated the dynamic soil-structure interaction. They conducted mathematical simulations and numerical modelling of a case study. They analyzed the dynamic soil-structure interaction of twenty, thirty, and forty-storey high-rise buildings under seismic loading. They used the ABAQUS software tool to conduct their simulations and verify the dynamic soil-structure interaction. They applied four earthquake acceleration measures and used soil class Ee depending on Australian codes. Their simulations and numerical analysis revealed that dynamic soil-structure interaction significantly affected the high-rise buildings' seismic behaviour. Additionally, the research findings indicated that dynamic soil-structure interaction had elevated the inter-floor drifts and lateral deflections and reduced the shear forces of the floors. Also, the findings affirmed that dynamic soil-structure interaction impact could vary depending on the earthquake distance (close or far to the building). [2] Implemented an analysis in which they explored the impact of dynamic soil-structure interaction on the seismic behaviour and distress response due to earthquakes of different construction projects. The research results indicated that dynamic soil-structure interaction is critical in affecting the soil's seismic response to various construction projects when earthquakes occur. In addition, they found that some factors influence the soil's seismic behaviour, including the overlying structure, the number of soil layers, and the seismic excitation at the seismic rock outcrop or bedrock. [3] Guided research to investigate and examine the impacts of dynamic soil-structure interaction on the soil's behaviour and characteristics under specific shear and stiffness conditions. They implemented numerical modelling, optimization, and simulations using computer software to examine and explore the effect and major factors associated with dynamic soil-structure interaction. They used the spectral element approach (SEA) and the Discontinuous Galerkin method (DGM). They also applied micro-vibrations to the soil and used seismic sensors to verify and predict its behaviour related to dynamic soil-structure interaction. Their research findings and numerical analysis revealed that dynamic soil-structure interaction significantly impacted the soil's shear strength related to the buildings' walls. Thus, it is greatly significant to consider flexible foundations that can optimize the shear strength of soil and buildings' walls. Furthermore, the research findings confirmed that the dynamic soil-structure interaction relies heavily on the amount of input frequency. Also, remarkable interval lengthening referred to the structures reached roughly 47%. Moreover, the results recorded a considerable decline in the floor shear, amounting to around 220%. At the same time, they found that the ultimate lateral roof displacement minimization attained a value of 34% compared with stationary roofs. [10] Led research identifying the impact of unconstrained near-fault rupture on the dynamic soil-structure interaction. They followed numerical analysis and simulation work by which Finite Element Analysis (FEA) was implemented using the ABAQUS software tool to predict soil's physical and mechanical properties under unconstrained near-fault rupture with the presence of dynamic soil-structure interaction. The simulation outputs and numerical analysis confirmed that the accelerated motion of the unconstrained near-fault rupture had significant and several lower-frequency parts. The maximum vertical acceleration was roughly one and a half higher than the maximum horizontal acceleration. Also, the study findings indicated that under far-fault and near-fault ground movement conditions, the superstructure response distributions were the same. Moreover, the results showed that these responses were 254.5% higher in near-fault ground movement than in far-fault ground movement, indicating that near-fault ground movement can be significantly destructive to structures.

2 MATERIALS AND METHODS

2.1 Materials

"f'c=45" was chosen as the compressive strength of concrete. Regarding steel characteristics, the yield stress for flexural steel was set at 400 MPa and for shear reinforcement at 320 MPa. Table 1 and Table 2 show the features of concrete and steel correspondingly. In addition, the soil properties are represented in Table 3. The cohesiveness of soft, medium and hard soils is 10, 30, and 50.8 kPa, respectively. The angle of friction is zero in all three soil types.

Table 1. Concrete properties [11]

Concrete mix	Compressive strength (MPa)	Flexural strength (MPa)	Elasticity modulus (MPa)
C45	45	5.5	37900

Table 2. Steel properties

Steel grade	Yield strength (MPa)	Ultimate strength (MPa)	Elasticity modulus (MPa)
T400	400	500	200000
T320	320	400	200000

Table 3. Soil properties

Soil Type	Unit weight (kN/m^3)	The angle of friction (Ø)	Cohesion (kPa)
Soft	20	0	10
Medium	20.1	0	30
Hard	20.8	0	50.8

2.2 Loading conditions

The structural systems are exposed to three types of Primary Loads superimposed dead load, live load and lateral seismic load in the x-direction. As indicated in Table 5, the superimposed dead load is 5 kN/m2. The live load is adopted for residential buildings 3 kN/m2 as per ASCE 7-16-table 4-1.

Table 4. Loading conditions

Gravity load	kN/m^2
SDL	5
Live	3

The behaviour of all models is investigated for Seismic Zone 2.5. The typical El Centro earthquake waves are utilized as the input seismic waves in this study, which is the classic and widely used earthquake. To investigate seismic zone 2.5, the data were fitted on a scale using a graph, as shown in Figure 1.

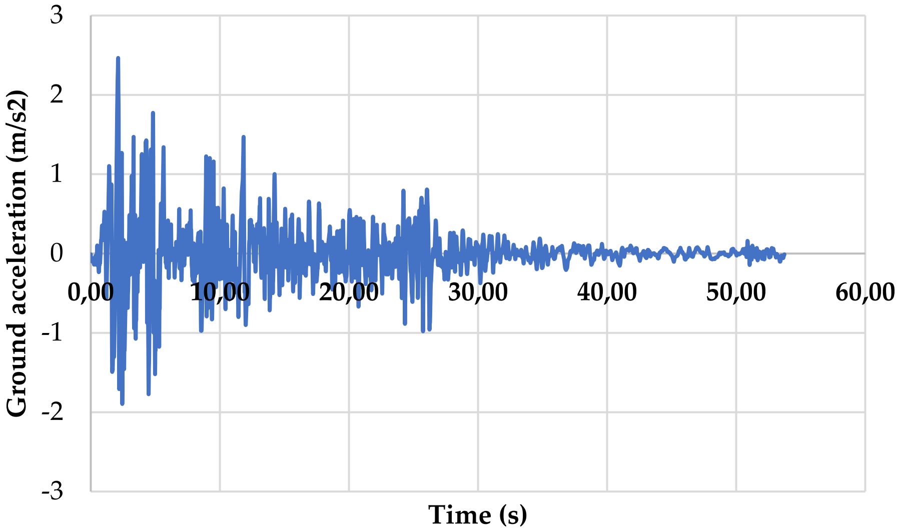


Figure 1. El Centro seismic data

2.3 Numerical Modelling

ABAQUS® finite element analysis of the seismic response in different lateral load-resisting systems for the cases listed above [12]. This program is frequently used by static and dynamic researchers (Seismic and impact) [13]-[19]. ABAQUS is a finite element analysis tool that can evaluate structures’ behaviour under different loads [20]-[23]. Columns and beams are modelled as frame members. Further, the walls and slabs were considered shell components. Meanwhile, the soil and footings are investigated as volumetric elements, as described in Figure 2 and Figure 3.

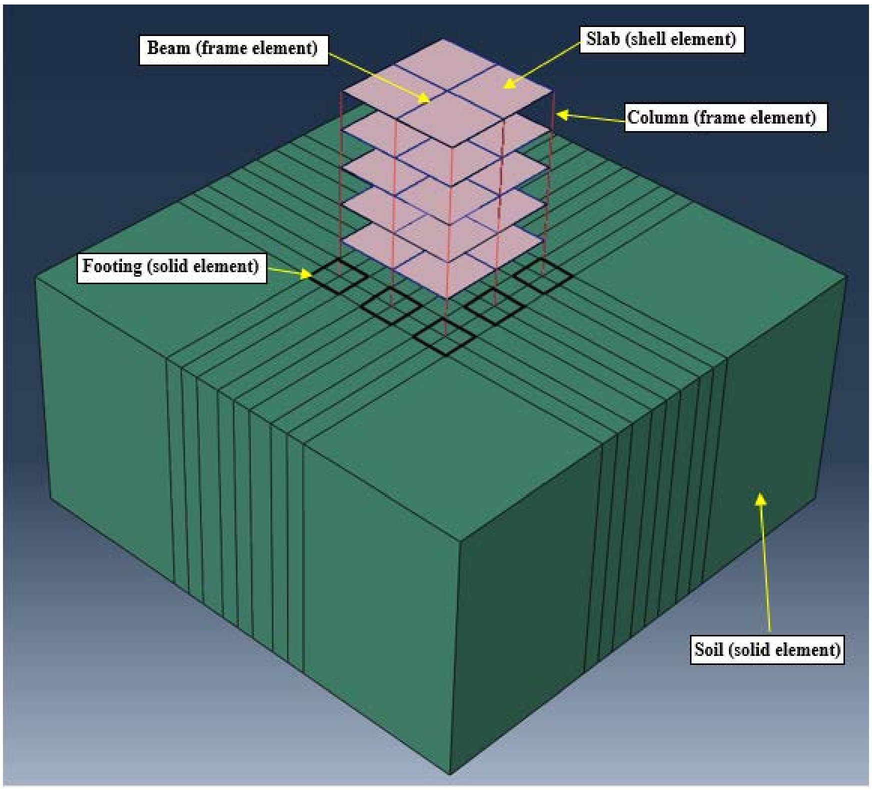


Figure 2. Elements modelling in Abaqus for Building frame system

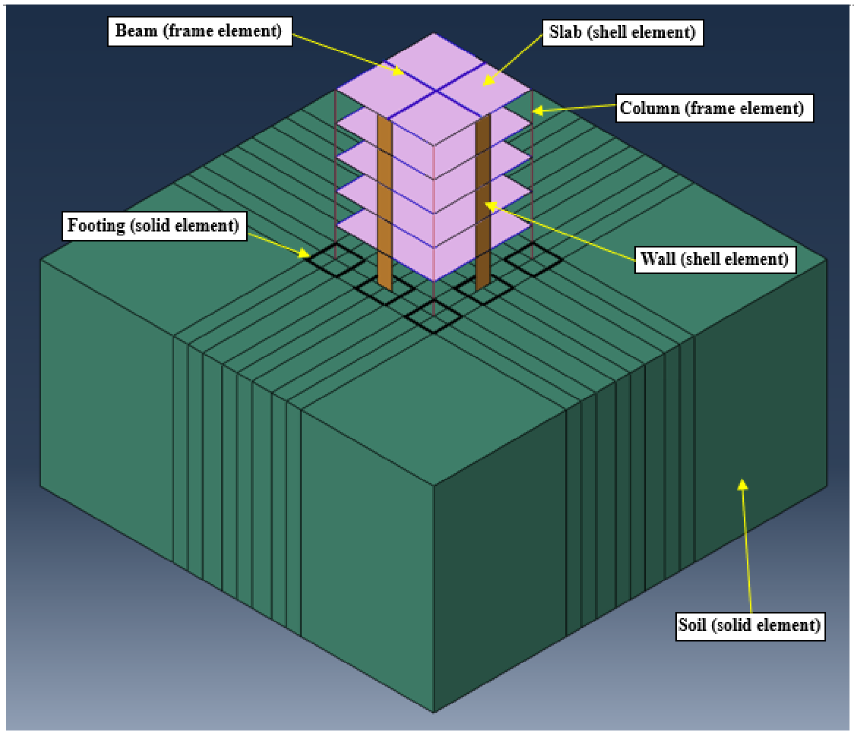
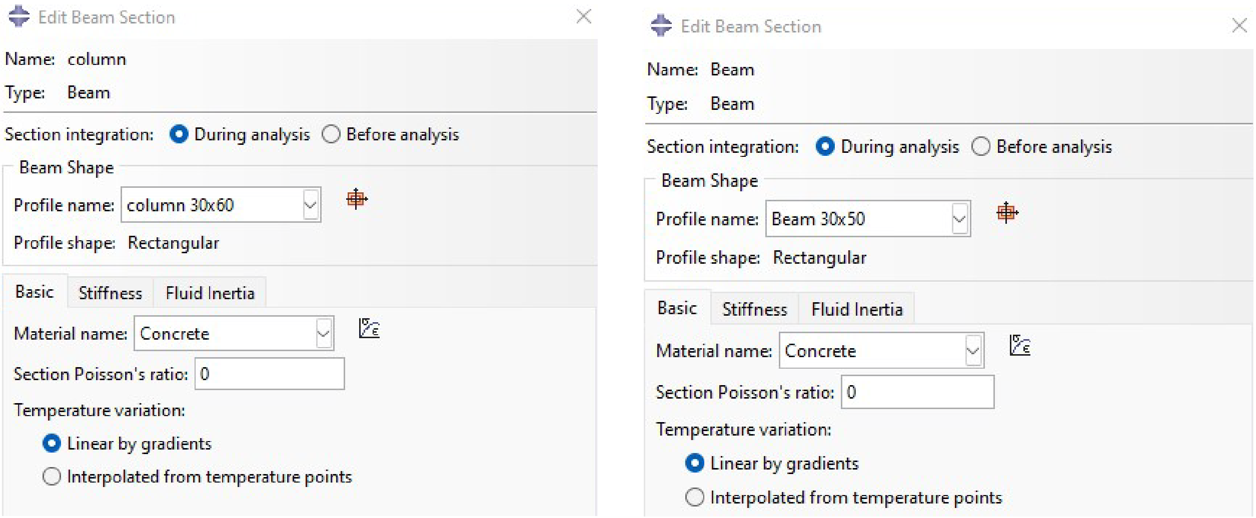


Figure 3. Elements modelling in Abaqus for Shear wall system

Figures 4 to 6 show the details for the section and reinforcement definition for all structural components.



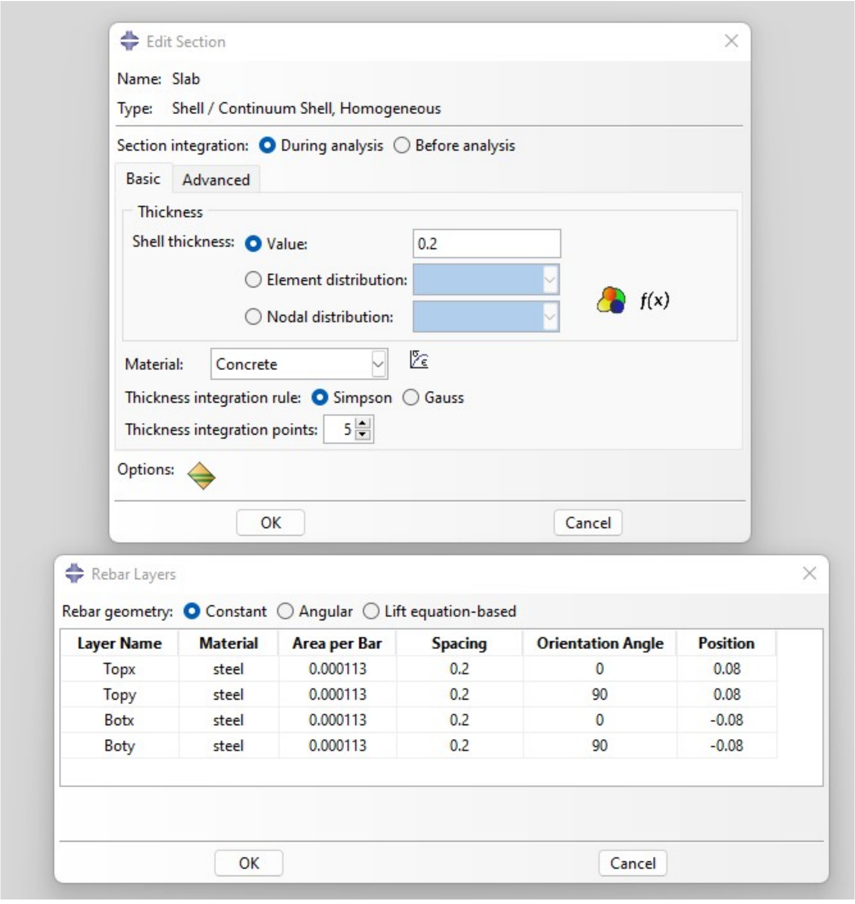
Edit Beam Section

Name: column
Type: Beam
Section integration: ● During analysis ○ Before analysis
Beam Shape
Profile name: column 30x60
Profile shape: Rectangular
Basic | Stiffness | Fluid Inertia
Material name: Concrete
Section Poisson's ratio: 0
Temperature variation:
● Linear by gradients
○ Interpolated from temperature points

Edit Beam Section

Name: Beam
Type: Beam
Section integration: ● During analysis ○ Before analysis
Beam Shape
Profile name: Beam 30x50
Profile shape: Rectangular
Basic | Stiffness | Fluid Inertia
Material name: Concrete
Section Poisson's ratio: 0
Temperature variation:
● Linear by gradients
○ Interpolated from temperature points

Figure 4. Column (on the left) and beam (on the right) section properties

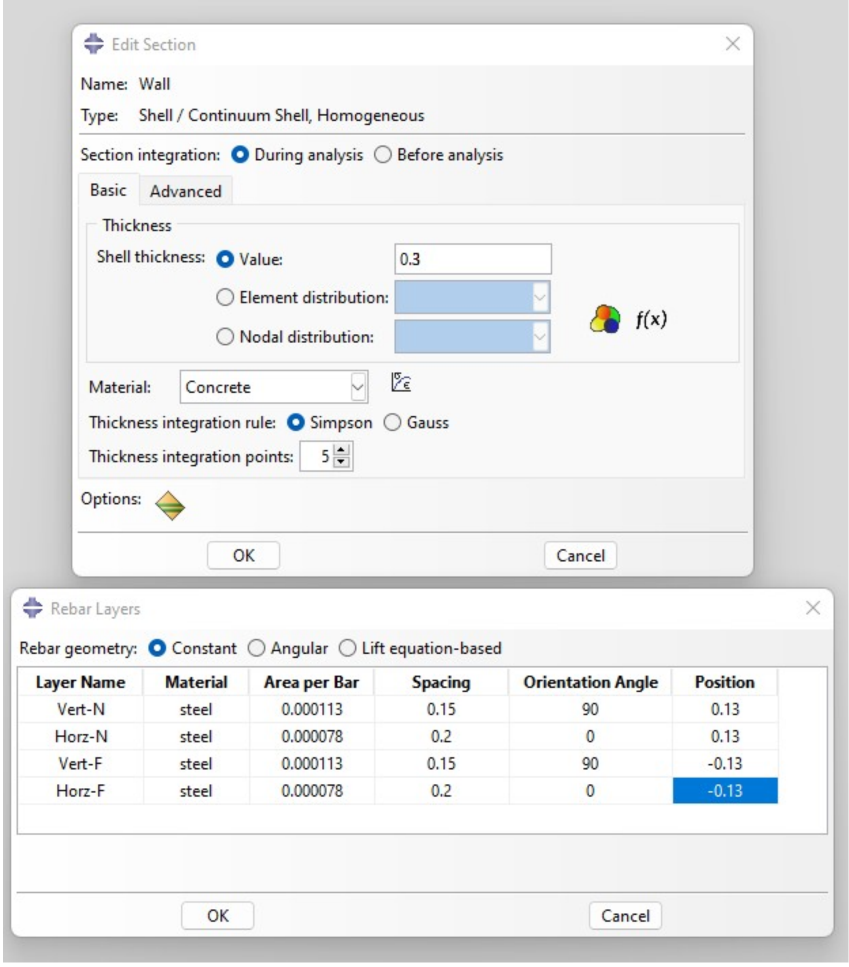


Name: Slab
Type: Shell / Continuum Shell, Homogeneous
Section integration: ● During analysis ○ Before analysis
Shell thickness: ● Value: 0.2
○ Element distribution:
○ Nodal distribution:
Material: Concrete
Thickness integration rule: ● Simpson ○ Gauss
Thickness integration points: 5
Options:

Rebar geometry: ● Constant ○ Angular ○ Lift equation-based

Layer Name	Material	Area per Bar	Spacing	Orientation Angle	Position
Topx	steel	0.000113	0.2	0	0.08
Topy	steel	0.000113	0.2	90	0.08
Botx	steel	0.000113	0.2	0	-0.08
Boty	steel	0.000113	0.2	90	-0.08

Figure 5. Slab section and steel reinforcement properties



Name: Wall
Type: Shell / Continuum Shell, Homogeneous
Section integration: ● During analysis ○ Before analysis
Shell thickness: ● Value: 0.3
○ Element distribution:
○ Nodal distribution:
Material: Concrete
Thickness integration rule: ● Simpson ○ Gauss
Thickness integration points: 5
Options:

Rebar geometry: ● Constant ○ Angular ○ Lift equation-based

Layer Name	Material	Area per Bar	Spacing	Orientation Angle	Position
Vert-N	steel	0.000113	0.15	90	0.13
Horz-N	steel	0.000078	0.2	0	0.13
Vert-F	steel	0.000113	0.15	90	-0.13
Horz-F	steel	0.000078	0.2	0	-0.13

Figure 6. Shear wall and steel reinforcement properties

The boundary conditions of finite elements in the model are illustrated in Figure 7. Slabs, columns, shear walls, and beams are all susceptible to a fixed support. At the same time, the footing and soil were tied together to prevent relative motion. Further, the bottom surface of the soil was fixed in the y- and z-directions but released in the x-direction to analyze the lateral displacement caused by the lateral seismic load. A mesh size of 20 cm was employed in this research for all the elements.

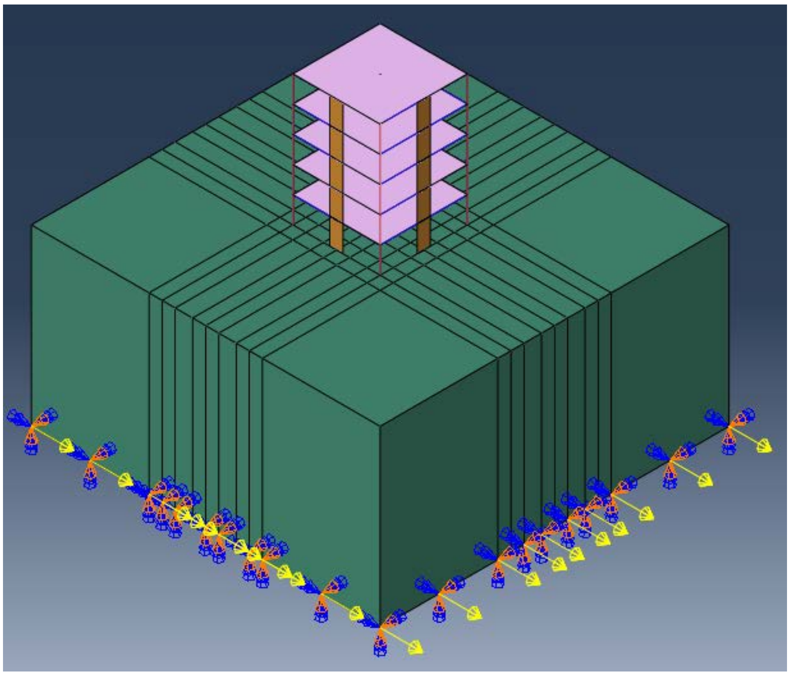


Figure 7. Boundary conditions of the model

One of the constitutive models for modelling concrete behaviour was the concrete damaged plasticity model (CDP model) created in ABAQUS. The CDP model accounts for nonlinear concrete behaviour by describing input variables such as inelastic strain, cracking strain, stiffness deterioration, and recovery. This approach is significantly successful in examining concrete under dynamic and impulsive pressures. The various characteristics and inputs of concrete are summarized in Table 5. In addition, the soil was modelled using Mohr-coulomb built in a model in Abaqus, referring to soil properties represented in Table 3.

Table 5. Concrete CDP inputs

Parameter	Symbol	C45
Elastic Modulus (MPa)	E	37900
Poisson’s ratio	υ	0.2
Density (Kg/m^3)	ρ	2400
Compressive strength (MPa)	f'_c	45
Peak Compressive strain (mm/m)	$\acute{\varepsilon}_c$	2.4
Tensile Strength (MPa)	f_t	5.5
Dilation angle (º)	ψ	36
Eccentricity	ε	0.1
Bi-axial to Uni-axial strength ratio	f_{b0}/f_{t0}	1.16
Second stress invariant ratio	K	0.67
Viscosity parameter	μ	0

The elastoplastic behaviour of steel rebar material is used in this investigation as elastic-perfectly plastic behaviour. Till reaching the yield point, steel material acts elastically. After yielding, it is entirely plastic. Table 6 shows the mechanical parameters of steel grades utilized in the ABAQUS model.

Table 6. Steel inputs

Parameter	Symbol	T400	T320
Elastic Modulus (MPa)	E	200,000	200,000

Parameter	Symbol	T400	T320
Poisson's ratio	υ	0.3	0.3
Density (kg/m^3)	ρ	7,850	7,850
Yield strength (MPa)	fy	400	320
Ultimate strength (MPa)	f_u	500	400

As indicated in Figures 8 a and b, the design consists of two bays of 5 m span each along the X direction and two bays of 5 m span each along the Z direction. The typical Ten-Floor building has a floor height of 3.0 m along the Y-direction. For both systems, the columns were 30×60 cm at the borders and 60×60 cm in the centre with 10 T16 mm reinforcement. The cross-section of the beams and the thickness of the slab were 30×50 cm and 20 cm, respectively. The primary flexural and secondary flexure reinforcement were placed as 3T16 mm and 3T10 mm, respectively.

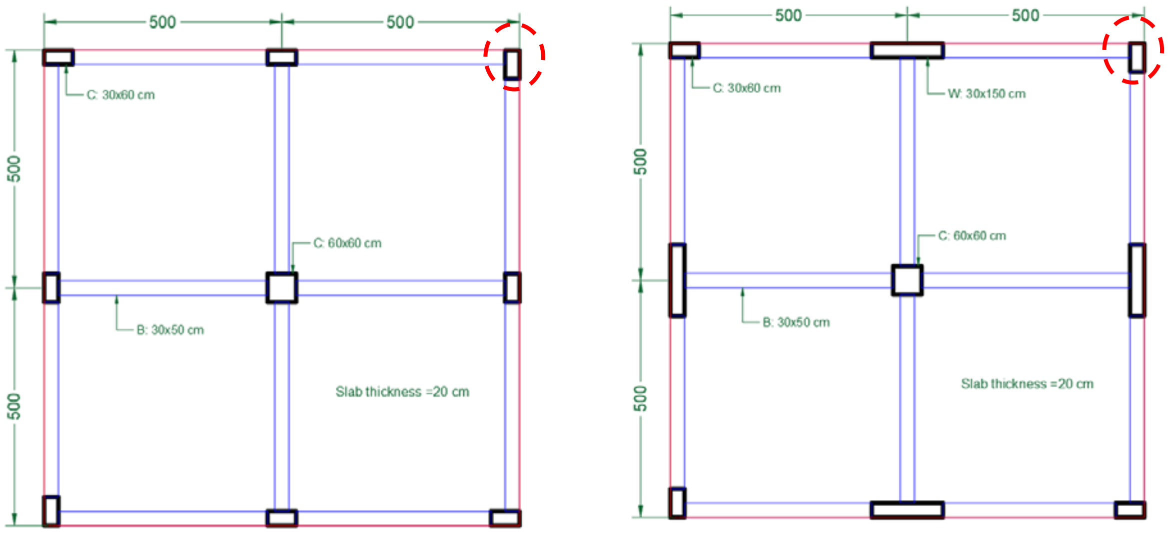

(a)
(b)

Figure 8: Configuration of (a) building frame system and (b) shear wall system.

Eighteen cases were considered to help the ABAQUS carry out simulations and numerical analysis to predict the dynamic soil-structure interaction. Details on these cases are illustrated in Table 7.

Table 7. Cases Description

Case ID	Number of floors	Soil type	Lateral load resisting systems type
C1	1	Soft	Building frame
C2	1	Medium	Building frame
C3	1	hard	Building frame
C4	5	Soft	Building frame
C5	5	Medium	Building frame
C6	5	hard	Building frame
C7	10	Soft	Building frame
C8	10	Medium	Building frame
C9	10	hard	Building frame
C10	1	Soft	Shear wall
C11	1	Medium	Shear wall
C12	1	hard	Shear wall
C13	5	Soft	Shear wall
C14	5	Medium	Shear wall
C15	5	hard	Shear wall
C16	10	Soft	Shear wall
C17	10	Medium	Shear wall
C18	10	hard	Shear wall

3 RESULTS

3.1 Base Shear

Figure 9 (on the left) depicts the base shear findings for the building frame system for 5 and 10 floors. Using a building frame, it shows a base shear of 1500, 1425, and 1095 kN for soft, medium, and hard soil for a five-floor building. Generally, base shear for a five-floor building frame decreases by 5% from soft to medium soil and 23% from medium to hard soil. For a ten-floor building frame system, base shears of 2100, 1680, and 1512 kN for soft, medium, and hard soil, respectively, as shown in Figure 9. It provides a 20% decrease for medium soil and a 10% reduction for hard soil in a 10-floor building frame resistance system. Cases 1, 2, and 3 are not presented as their results were similar.

Figure 9 (on the right) depicts the base shear findings for the shear wall system for 5 and 10 stories on different soil types. It displays a soft, medium, and hard soil base shear of 2088, 1984, and 1504 for a five-floor structure. This represents a 5% reduction for medium soil and a 24% reduction for hard soil in a shear wall system. The base shear for a 10-floor shear wall system was 2952, 2362, and 2066 for soft, medium, and hard soil, respectively. Base shear for a shear wall system with ten stories on medium soil is 20% less than base shear on soft soil. On hard soil, this outcome is lowered by 12%.

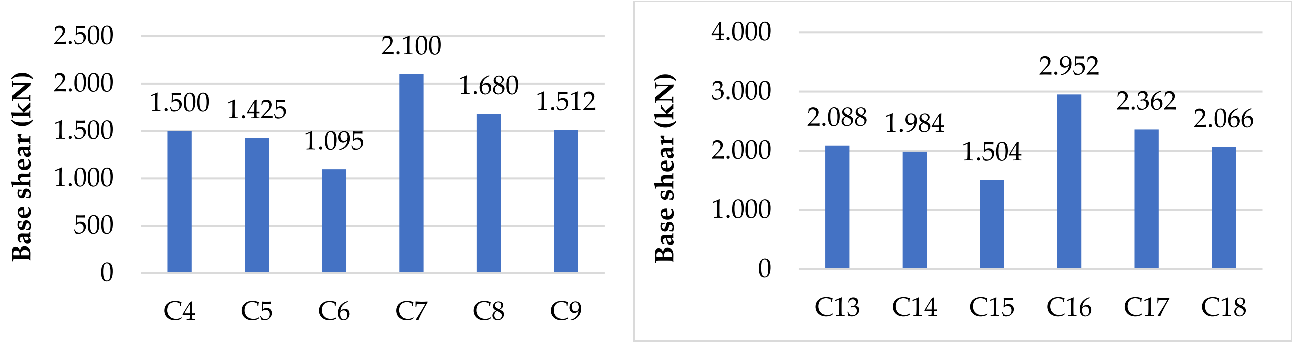


Figure 9. Base Shear results of Building frame on different soil types

3.2 Axial Forces

Figure 10 (on the left) depicts the axial force findings for the building frame system for 5 and 10 stories. It shows an axial force of 4160, 4077, and 3744 kN for soft, medium, and hard soil for a five-floor building using a building frame. Generally, the axial force for a five-floor building frame decreases by 2% from soft to medium soil and 8% from medium to hard soil. For a ten-floor building frame system, the axial force of 12480, 11356, and 10858 for soft, medium, and hard soil, respectively, are shown in Figure 1. It provides a 9% decrease for medium soil and a 4% reduction for hard soil in a 10-floor building frame resistance system.

In comparison, Figure 10 (on the right) represents the axial forces for the shear wall lateral load resisting system for 5 and 10 stories. The axial force for this system on soft, medium and hard soil for five stories was 1430, 1387 and 1215 kN. There is a reduction of 3% from soft to medium soil and a decrease of 12% on hard soil regarding axial force. Meanwhile, axial force in KN for shear wall system was 2210, 1922, and 1812 KN for soft, medium and hard soil in 10 stories buildings. The axial forces are lesser for medium soil by 13% compared to soft soil and less by 6 % for hard soil.

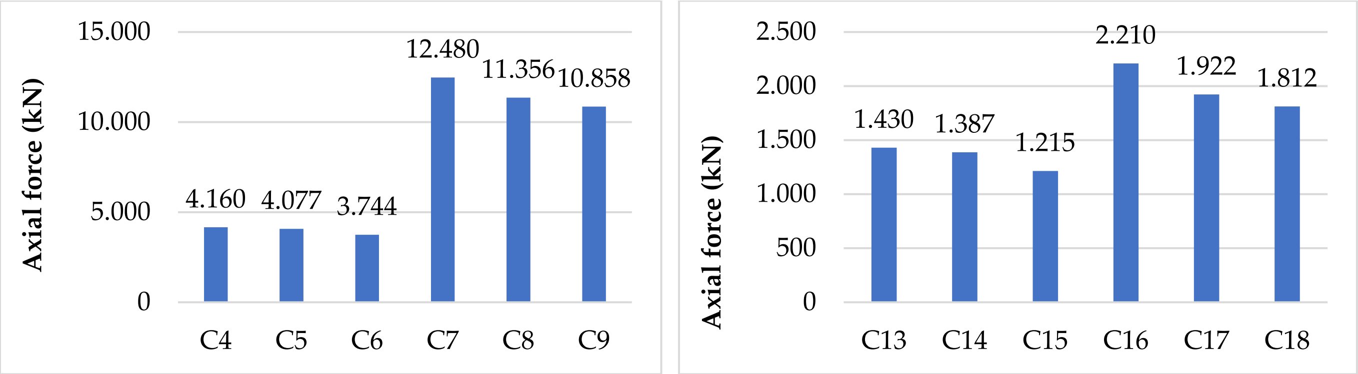


Figure 10. Axial force results in shear wall building on different soil types

3.3 Moment

Figure 11 illustrates the moment values on columns. The moment values on columns for a 10-floor building frame system. The moments for a five-floor building frame system were 1600, 1520, and 1200 kN.m. This aspect represents a 5% reduction in the moment on medium soil and a 21% reduction on hard soil. On the other hand, 2240, 1792, and 1568 kN.m were for the three soil types. Generally, the moment of a 10-floor building frame system on medium soil is 20% less than that of soft soil, while the moment on hard soil is 13% less than that of medium soil. As the moment of the column is taken by the shear wall in the shear wall system, the moment values were not significant in columns.

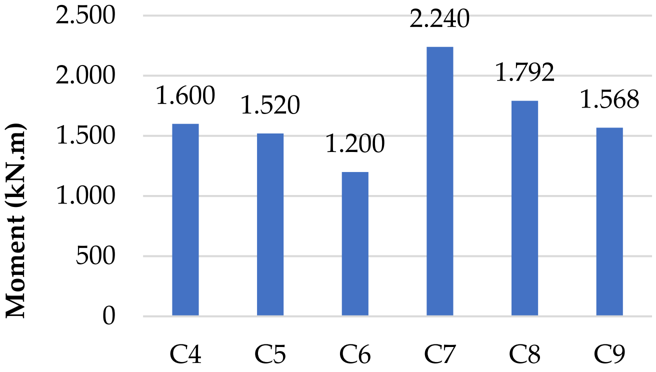


Figure 11. Moment results for building frame system on different soil types

3.4 Displacement

Figure 12 illustrates the displacement findings for the building and shear wall frame systems. The displacements for the building frame system for 5 floors were 45, 38.3, and 33.9 mm for soft, medium, and hard soil, respectively. Displacements for a 10-floor building structure were 75, 67.5, and 52.5 mm for soft, medium, and hard soil, respectively. Also, displacements for the shear frame system were 3, 2.8, and 2.3 mm for soft, medium, and hard soil, respectively, for five stories. The 10-floors shear frame systems displacements are 30, 24, and 21 mm for soft, medium, and hard soil, respectively. The displacement is decreased by 6% in a 5-floor building frame system on medium soil and 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil. On the other hand, displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil, correspondingly. Furthermore, the findings of a ten-story shear wall system demonstrate that displacement reduces by 20% and 30% on medium and hard soil, respectively.

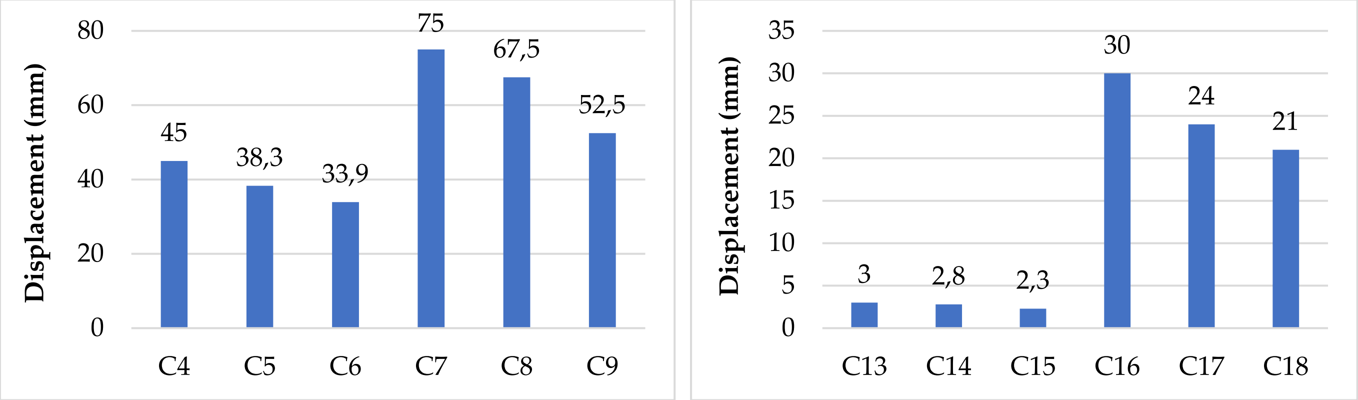


Figure 12. Displacement results for the shear wall system on different types of soil

4 DISCUSSION

The results of this study reveal that the dynamic soil-structure interaction is affected by the base shear, axial forces, type of soil, displacement, and moment. Also, the findings indicate that number of floors plays a critical role in influencing the load on soil, which can affect soil stability and performance. These results are consistent with [2], [3], [5]-[10] . They conducted an analysis examining the critical role of dynamic soil-structure interaction and major factors that influence soil stability. They found that soil characteristics, such as soil structure, soil porosity, overlying structure, the number of soil layers, and the seismic excitation at the seismic rock-outcrop or bedrock can influence the behaviour of soil, which affect the dynamic soil-structure interaction. They also found that soil humidity, density, stiffness, compaction, damping, porosity, and mass are critical in affecting dynamic soil-structure interaction.

5 CONCLUSIONS

This work is executed by identifying major soil characteristics related to the dynamic soil-structure interaction features of a reinforced concrete building. Numerical analysis and simulations were followed and adopted, relying on the ABAQUS® software package to assess the base shear, axial force, moment, and displacement, considering different soil types. Based on the research work, the following results can be drawn:

1. The base shear for a five-floor building frame decreases by 5% from soft to medium soil and 23% from medium to hard soil. Also, the base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil.
2. The base shear for a shear wall system with ten stories on medium soil is 20% less than that on soft soil. On hard soil, this outcome is lowered by 12%.
3. The axial force for a five-floor building frame decreases by 2% from soft to medium soil and 8% from medium to hard soil. Additionally, axial forces provide a 9% decrease for medium soil and a 4% reduction for hard soil in a 10-floor building frame resistance system.
4. There is a reduction of 3% from soft to medium soil and a decrease of 12% on hard soil regarding axial force. Meantime, the axial forces are lesser for medium soil by 13% compared to soft soil and less by 6 % for hard soil.
5. The displacement is decreased by 6% in a 5-floor building frame system on medium soil and 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil.
6. Displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil. Also, displacement reduces by 20% and 30% on medium and hard soil, respectively.

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Paper submitted: 10.09.2022.

Paper accepted: 09.12.2022.