



**University of Birmingham**

**School of Engineering**

**Soil-Structure Interaction for Nuclear Power Plants under  
Flooding-Earthquake Joint Occurrence**

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## ABSTRACT

The analysis of soil-structure interaction (SSI) is a critical aspect of determining the suitability of a location for a nuclear power plant (NPP). SSI refers to the mutual influence of the soil and the structure on their dynamic response and behaviour. Different types of soils and saturated condition of them can affect the stability and safety of the NPP structure under different loading conditions. One of the loading conditions that NPPs may encounter is flooding, which is one of several potential hazards that can threaten the integrity and functionality of NPPs. Flooding can cause changes in the soil properties and induce additional forces and displacements on the structure which could be critical during earthquake events. Therefore, it is important to evaluate the SSI of NPPs under both non-flooding and flooding conditions, and to consider soft and medium soil that may be present at the site. This study aims to provide a comprehensive understanding of the SSI of NPPs under flooding and non-flooding conditions by using numerical modelling and simulation techniques. This study's findings will enhance NPP locating and design, offering insights for selecting safe and stable sites and designing structures to safely perform during multi-hazard scenarios. Attention will be drawn the significance of site selection and flooding hazard for NPPs.

**Keywords:** Nuclear Power Plant (NPP); Soil-Structure Interaction (SSI) Analysis; Multi-Hazard; Flooding; Earthquake.

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# **1 Introduction**

## **1.1 Background**

The soil has differences, which becomes even more prominent during earthquakes, at its behaviours between its condition which is located under the structure, and its free condition. The ground motions, which is caused by the earthquake, have effects seen as displacements on the structure. The structure weighing tons changes its vibration with these effects. Furthermore, contrary motions of structure to ground in a different mode, which is called inertia interaction, affects back to the ground. This mutual interaction phenomenon is called Soil-Structure Interaction (SSI).

The SSI is related constructed structure on soil and has gained more importance in structures, which require high precisions especially such as Nuclear Power Plants (NPPs), and since its discovery in the late 19th century, SSI has been studied on computers by the Finite Element Method (FEM) (Lou et al., 2011). Moreover, it is possible for NPPs to be exposed to a variety of multi-hazard, such as flooding happened following earthquake. This is what happened at the Daiichi NPP in Fukushima, Japan, in 2011 (The Fukushima Daiichi accident, 2015). An earthquake after a flood, which is the opposite of Fukushima multi-hazard event, can also occur. Assessing the SSI of NPPs in flooding situation because of changed mechanical properties of soil is as much as vital SSI analysis of non-flooding situation. This will be focused on in this paper.

## **1.2 Aim and Objectives**

The aim of this dissertation is to assess SSI on different soil types of a NPP under earthquake following flooding; one of multi-hazard variants. The research will involve conducting numerical simulations by FEM at Abaqus software and analyses to investigate the accelerations, displacements, and settlements of the NPP structure by considering seismic wave loadings in various soil types. The findings of this research will provide insights into the behaviour and performance of the NPP structures in different soil types and under different loading conditions, aiding in the selection of suitable locations for NPPs based on soil types and providing valuable information for NPP design and construction to mitigate potential the accelerations, displacements, and settlements of structure under varying conditions.

Objectives of this dissertation are as follows:

- 1) Conduct a literature review on SSI of NPPs related with flooding conditions, earthquake and in different soil types.
- 2) Develop numerical models using Abaqus software to simulate behaviour of soil and structure under different soil types and loading conditions.

- 3) Analyse the accelerations, displacements, and settlements of soil and structure using Abaqus simulations to understand the effects of soil types and loading conditions on SSI.
- 4) Evaluate NPP structure performance under earthquake following flooding in different soil types and identify potential areas of concern.
- 5) Contribute to the understanding of SSI for NPP safety and resilience and provide insights and recommendations for future research and practical applications.



## **2 Literature Review**

This literature review aims to analyse the existing literature on the evaluation of SSI of NPPs under non-flooding and flooding conditions in different soil types.

### **2.1 Evaluation of SSI under non-flooding conditions**

Several studies have evaluated the SSI of NPPs under non-flooding conditions for different types of NPPs, seismic waves, and topographic features. For example, Cheng et al. (2023) investigated the SSI of AP1000 NPP under three seismic waves and compared the results with the current codes. Yue et al. (2013) analysed the SSI of US-APWR NPP, which has two buildings with a certain distance between their foundations. Li et al. (2023) developed an efficient method for SSI analysis of NPPs considering hills and valleys and applied it to AP1000 NPP. These studies show the importance of SSI analysis for various seismic conditions.

Some studies have also evaluated the potential damage and risk of NPPs due to SSI effects and suggested ways to improve the design and assessment. For instance, Farahani et al. (2016) used FEM to model the SSI of a Diesel Generator Building (DGB) of NPP and made recommendations for its low stiffness and basic frequency, which can cause cracks on concrete elements during severe earthquakes. Ghiocel et al. (1998) assessed the seismic risk of an Eastern US NPP with SSI effects following the IPEEE program and found that SSI effects were important and that the current practice was not conservative.

Another aspect of SSI analysis is the nonlinear behaviour of soil and structure during intense earthquake shaking, which is not covered by the code. Some studies have focused on this aspect and proposed methods to capture it more accurately. For example, Coleman et al. (2016) presented a methodology for nonlinear soil-structure interaction (NLSSI) analysis of nuclear facilities, including NPPs, to capture the sliding and other nonlinear effects. Lv & Chen (2022) compared the results of nonlinear and linear analysis of seismic response characteristics of NPPs with a developed partitioned method for nonlinear SSI.

Finally, some studies have demonstrated the effect of SSI analysis on the isolation performance of NPPs and emphasized the need to consider it in the design process. For example, Zhou & Wei (2016) observed the seismic response of an isolated NPP for changed soil and isolator properties and highlighted that ignoring SSI analysis or assuming a rigid base can significantly influence the SSI response of NPPs.

### **2.2 Evaluation of SSI under flooding conditions**

Flooding, a severe hazard for NPPs near coastlines or rivers, alters the soil's mechanical properties due to saturation and requires a thorough examination of SSI under flooding conditions, as existing studies emphasize below.

One study proposes a model that incorporates a viscous boundary to describe pore pressure and plastic deformation in saturated soil under assumed undrained soil conditions. This model highlights the need for accurate SSI analysis in critical structures (Er-Xiang et al., 1998). Another study investigates the effects of liquefaction on shallow foundations of low-rise buildings using 3D numerical simulations. Compared to 2D models, these simulations provide a detailed assessment of displacements, settlements, bearing capacity reductions, and drifts. Nonlinear SSI analysis is necessary for a realistic evaluation of structural performance due to deformations and settlements (Forcellini, 2020).

Furthermore, a study compares dynamic centrifuge tests to evaluate the seismic performance of low-rise structures under SSI effects. Different shallow foundations, including strip and raft foundations, are examined in the presence of liquefiable soil and adjacent heavier structures of the same foundation type (Qi & Knappett, 2020).

Especially for NPPs, SSI analysis studies of multi-hazard scenarios, which is earthquake and flood combination, are not many as it can be observed in past studies.

### **2.3 Evaluation of SSI in different soil types**

The type of soil can significantly affect the behaviour of SSI. Several studies have evaluated the SSI of NPPs in different soil types.

Some studies have used FEM to model the SSI of NPPs on soft soil, such as alluvial soil, and found that SSI analysis is necessary and useful to observe the response of soil and structure. For example, Firoj & Maheshwari (2018) studied the SSI of Narora NPP in India. De Borbón et al. (2020) studied the SSI of CAREM-25 NPP in Argentina and compared two soil profiles: actual and stiff.

Other studies have investigated the SSI of NPPs on medium or soft soil sites and suggested ways to improve the design and performance of NPPs. For instance, Wang et al. (2017) evaluated the SSI of High Temperature Gas Cooled Reactors (HTGRs), a type of NPP, and made recommendations for their development. Xiaohui et al. (2020) conducted shake table tests to model the SSI of CAP1400 NPP on non-rock sites and emphasized the importance of considering SSI in the seismic design.

Another aspect of SSI analysis is the effect of foundation type on the settlement and rotation of NPPs, which are heavy structures designed for rock ground. Some studies have focused on this aspect and proposed solutions to reduce the differential settlements and rotations. For example, Patil et al. (2021) analysed the contribution of a combined piled–raft foundation (CPRF) for NPPs on medium and soft ground using FEM. Nguyen et al. (2020) evaluated the behaviour of a nuclear reactor building under seismic loading with different ground motions and soil types in a nonlinear, three-dimensional simulation with SSI.

## **2.4 Conclusion to Literature Review**

As seen in per the studies, it has been emphasized that the effects of soil type and multi-hazard such as earthquakes and floods, geographically, should be considered in the construction and site selection of important buildings such as NPPs. Moreover, the necessity of conducting a detailed SSI analysis to assess these effects and design accordingly has been underscored. Flooding is a significant hazard that can affect the behaviour of NPPs, and the SSI analysis is critical for evaluating the stability and integrity of the structure under flooding conditions. The behaviour of SSI can vary significantly depending on the type of soil, and therefore, the evaluating SSI in different soils is essential. The literature review highlights the need for further research on the evaluation of SSI of NPPs under flooding conditions in different soil.



### **3 Methodology**

The SSI is an analysis that requires intensive numerical calculations. Therefore, to observe this effect, analysis was done in finite element software which is called Abaqus. At different type of soils, to compare and observe the earthquake scenario after flooding with the earthquake scenario alone, structure and soil modelling was performed.

For the study, a sample NPP that is aimed to be studied is determined. NPPs are private and government-controlled projects. For this reason, the geometric and physical parameters could only be approximated. The model developed in this work has been mapped from Sinha et al. (2017) as it was considered accurate enough to represent a NPP plan interacting with the ground.

The structure was modelled locating on soft and medium soil respectively to compare its response on wide range of soil conditions. Moreover, to observe and compare flooding effect, the analysis was repeated by changing the soil parameters to parameters of saturated soil for representing soil which is after the flooding. To simulate the soil, a certain size of soil piece is modelled with semi-infinite elements. Furthermore, the seismic wave of Kobe earthquake was applied to four different model prototypes considering different soil conditions namely soft, medium, saturated soft, and saturated medium. The earthquake was applied on one horizontal direction, and the response of the structure was compared considering acceleration, lateral displacement, and settlement.

This study was carried out in compliance with the University of Birmingham's ethical procedures, including any relevant principles for research integrity and responsible research conduct.

The following titles emphasise the intricacies of the structural and soil models, as well as the processes used to construct the models. The results of the study were analysed, and recommendations were made.

#### **3.1 Assumptions and Development of Finite Element Model**

In this section of the study, a model is created for numerically analysing the structure's reaction to various soil conditions using Abaqus, a finite element programme that accurately represents a non-linear model.

##### **3.1.1 Structure Model**

###### **3.1.1.1 Structural Assumptions**

The modelled structure which represents the standard NPP with auxiliary and containment building is the same NPP structure which is used by Sinha et al. (2017) with minor changes. The structure consists auxiliary building consisting of reinforced walls and slabs, containment building consisting of prestressed concrete, and surface foundation. The auxiliary building is symmetrical building which has four floors and a roof. Thickness of floor systems is 0.6 m and thickness of roof is 1.0 m. The thickness

of exterior walls and interior walls, which are in auxiliary building, are 1.6 m and 0.4 m respectively. Having a symmetrical and repetitive dimension parameter of the structure will facilitate analysis and modelling. Dimension parameters is shown on plan and section views of the modelled structure from out and in at *Figure 1* and *Figure 2* respectively.

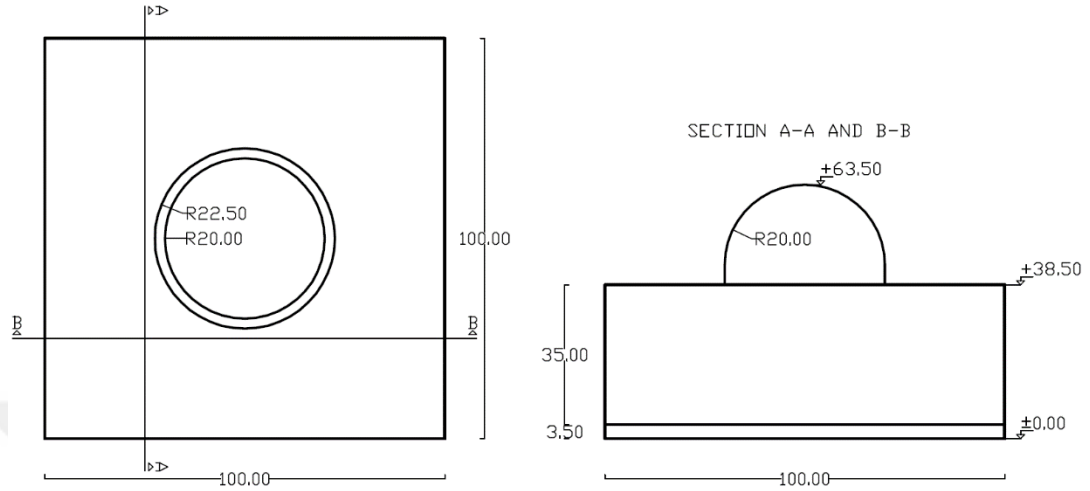


Figure 1. General plan (on the left) and section of the structure (on the right).

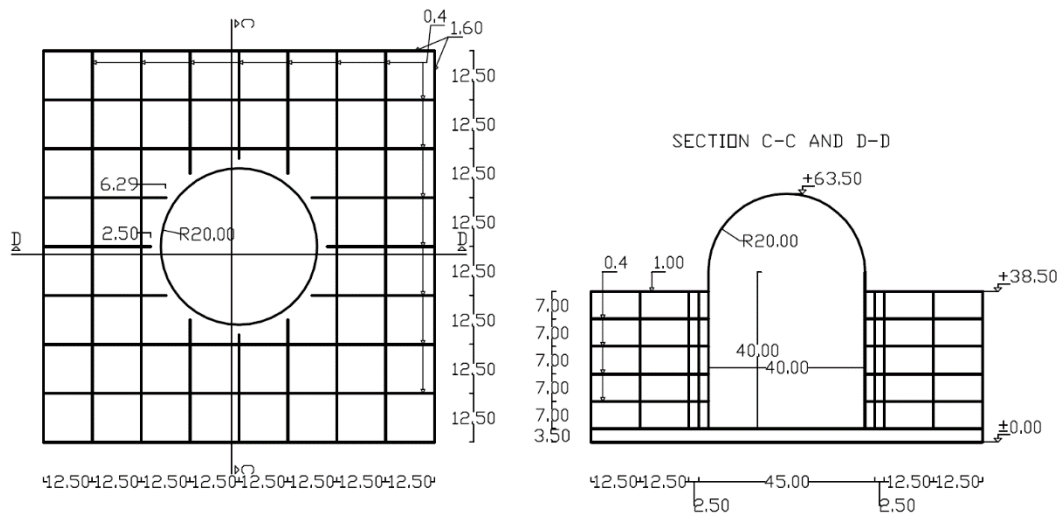


Figure 2. Floor plan (on the left) and section of the structure (on the right).

The NPP structures are designed to show elastic behaviour to withstand dynamic loads without permanent deformation, cracking, or damage, which characterise plastic behaviours, to prevent or mitigate accidents that could harm the public or the environment. In this study, it is considered that the structure exhibits a completely elastic behaviour. Material properties of structure have been shown at *Table 1*.

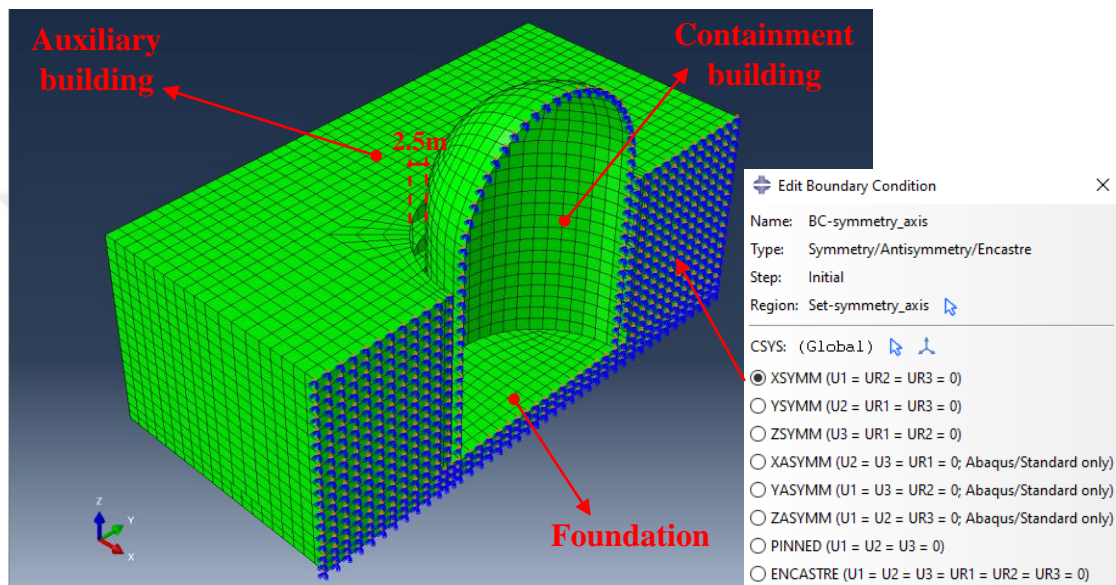
Table 1. The mechanical properties of concrete.

Density, $\rho$ (kg/m <sup>3</sup> )	2400
Young's Module, E (N/m <sup>2</sup> )	20000e6
Poisson's Ratio, $\nu$	0.21

### 3.1.1.2 Structural Modelling

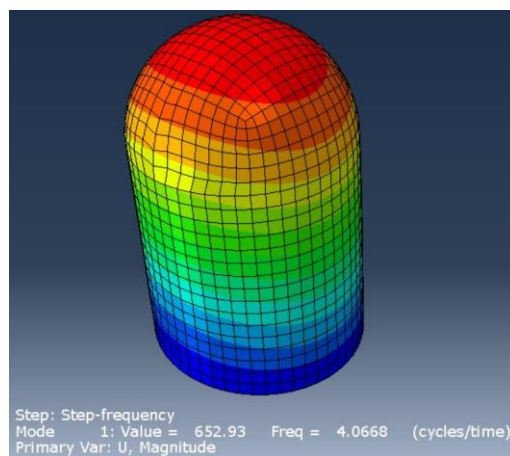
The using finite element model method for the NPP structures to examine the behaviour of structure, soil, and effect of these behaviours on each other under dynamical loads such as earthquake saves than losing time and expensive investigations or surveys.

*Figure 3* illustrates how the shape of the NPP was modelled as a half section by utilising proper connection and boundary conditions to reduce the number of elements and compute each element's reaction using Abaqus. By reducing the workload of ongoing analysis, this application enables non-linear numerical model results to be obtained quickly within the capabilities of the computer employed.



*Figure 3. View of boundary conditions and parts of structure.*

In structure, walls and slabs of auxiliary building, and walls and dome of containment building were modelled via shell elements. Conversely, solid elements were used to model foundation (Sinha et al. 2017). The structural model was developed with 2.5 meshes of the same sizes to match the parts of the rest of the structure.



*Figure 4. Frequency Analysis of Containment Building*

Comparing auxiliary building to containment building, containment building is more flexible due to contribution of its height and structural shape. While frequency analysis run, fundamental frequency of containment building was validated frequency, which 4 Hz is also found by Sinha et al. (2017), at first mode as shown in *Figure 4*.

### 3.1.2 Soil Model

#### 3.1.2.1 Soil Assumptions

The depth of bedrock is 50 m below the under top of the surface of soil. The dimensions of the surface of the soil part are 200 m in width and 400 m in length. The earthquake is modelled by considering that it affects in the direction of the long side of the soil. The NPP structure is located on centre of the surface as shown in *Figure 5*.

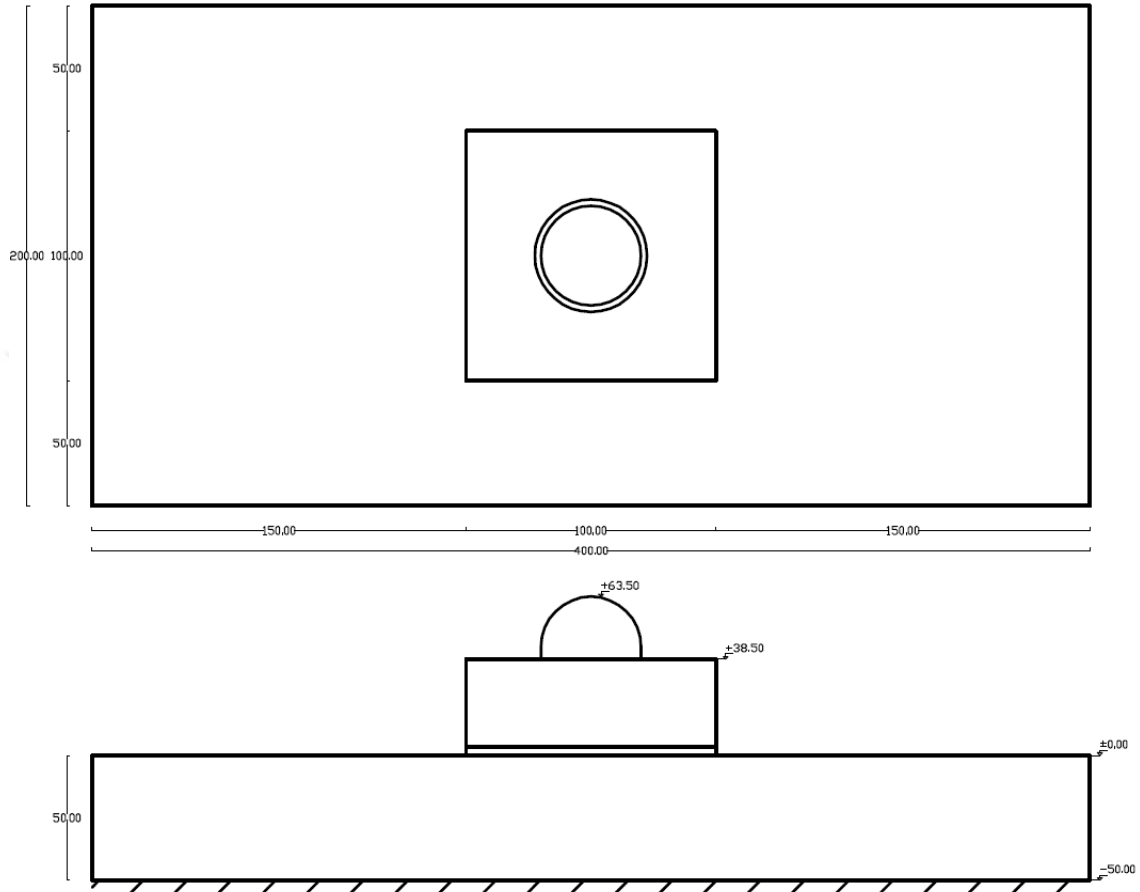


Figure 5. Plan of the soil (on the top) and longitudinal view (on the bottom).

While defining soil borders, distance between semi-infinite elements and foundation of structure was modelled same size with width of foundation of the structure (See *Figure 6*). This distance does not affect results of analysis (Li et al., 2023).

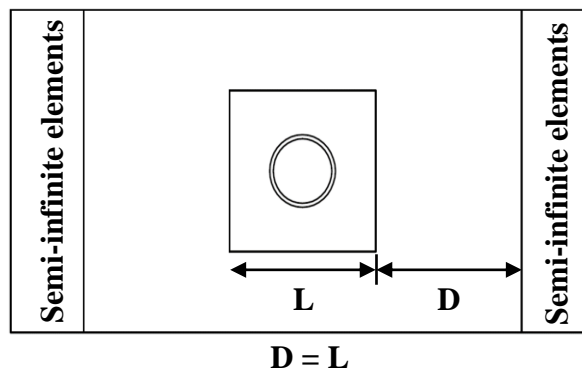


Figure 6. Distance between semi-infinite elements and the nearest structure border.

In this study, modelling was performed on soft soil, which has stiff clay behaviours, and medium soil which has dense sand behaviours. The material properties of soft and medium soil before flooding, and saturated soft and medium soil after flooding are given in *Table 2*. Soil Mechanics and Foundations principles established in Budhu M, (2010) have been taken as the main reference to parameterise the soil. To considering non-linear soil, Mohr Coulomb Plasticity parameters were used to define mechanical behaviour of the soils.

The parameters of the saturated soils were determined according to the undrained condition because the rate of earthquake loading is rapid, resulting in limited or no drainage. In addition, for this study, the surface water was withdrawn after the flooding, and it was assumed that the water table was at the same level with the soil surface.

*Table 2. The Mohr Coulomb Plasticity parameters for The Soil Conditions*

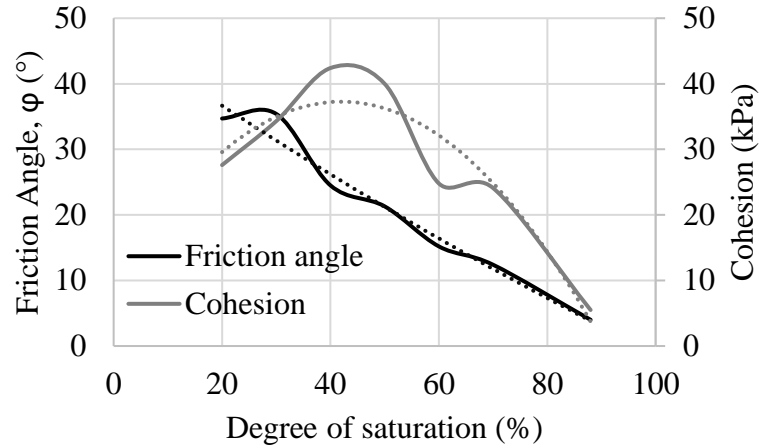
	Soft Soil	Saturated Soft Soil	Medium Soil	Saturated Medium Soil
Density, $\rho$ (kg/m <sup>3</sup> )	1800	2400	1700	2100
Young's Module, E (N/m <sup>2</sup> )	100e+06	25e+06	80e+06	60e+06
Poisson's Ratio, $\nu$	0.1	0.49	0.2	0.3
Friction Angle, $\phi$ (°)	23	12	38	14
Dilatancy Angle, $\psi$ (°)	0.1	0.1	8	0.1
Cohesion, c (N/m <sup>2</sup> )	90000	25000	100	0.1
Abs Plastic Strain	0	0	0	0

The density of the soil that has a particular volume, which becomes saturated due to a flood hazard, increases as water fills the pores within the soil (Nicholson, 2014). This increase in density occurs because of the water occupying the previously voids in the soil. On the other hand, increasing soil saturation after a hazard such as a flood causes water to fill the pores. The water layer covering soil particles lubricates contact of interparticle. That is, allows easier sliding between soil particles and results in a decrease on the Young's modulus of the soil. This decrease in young's modulus is significantly in clayey soils, but slightly decreases the sandy soil's elastic modulus (Zhang et al., 2022). When a soil is saturated, Poisson's ratio increases. The voids are filled with water, which leads to an increase in the effective stress. This causes in a reduction in the compressibility of the soil mass. As a result, the soil becomes more resistant to deformation and more prone to volumetric expansion under applied loads (Oh and Vanapalli, 2011; Thota et al., 2021; Yan et al., 2023).

The shear strength of soil dependences on saturation, and increasing saturation ratio, which leads to a significant decrease in both the angle of internal friction and cohesion in the tested soil samples, regardless of soil type and density, is observed by Yoshida et al., (1991) and Brakorenko et al., (2019).

Moreover, the angle of internal friction plays a significant role in controlling the shear strength especially silty-clay soil and tests showed mechanical behaviours of soil

such as inertial friction angle and cohesion force significantly decrease after over of the optimal saturation degree of the soil (Chen et al., 2022; Kumar et al., 2020; Li et al., 2022). As demonstrated following *Figure 7*, this change can be clearly observed (Farooq et al., 2015). The graphic illustrates how soft and medium soils generally respond to saturation.



*Figure 7. Graph for relationship between friction angle, cohesion, and degree of saturation, based on tabulated data from Farooq et al., 2015.*

Considering these changes, saturated parameters especially to easily observe the differences of the conditions, are defined with remarkable numerical range for analysis.

### 3.1.2.2 Soil Modelling

While modelling the soil, it was modelled as a half-section like the rest of the model, with the correct boundary conditions (*See Figure 8*). Semi-infinite elements are located on both end of the long side direction to not reflect earthquake waves back to model. Before running analysis, for converting these standard elements to semi-infinite element, name of the elements was changed from DC3D8, which element type was defined in meshing section, to CIN3D8 in “inp” file.

For calculation sensitivity, the location that structure is placed was developed 2.5 mesh size and these sizes were increased when going far from the location of the structure.

Interaction property of between structure and soil was defined contact and friction coefficient as shown *Table 3* between structure and soil was calculated by using formula (1), which is an empirical relationship used in geotechnical engineering to estimate the frictional resistance at their interface, for different type and condition soils. The formula assumes a linear relationship between the two, based on Coulomb's friction law.

$$\mu = (2/3) \times \tan(\phi) \quad (1)$$

Table 3. Friction Coefficients Between Foundation and Soil Conditions.

	Soft Soil	Saturated Soft Soil	Medium Soil	Saturated Medium Soil
Friction Coefficient	0.283	0.142	0.521	0.166

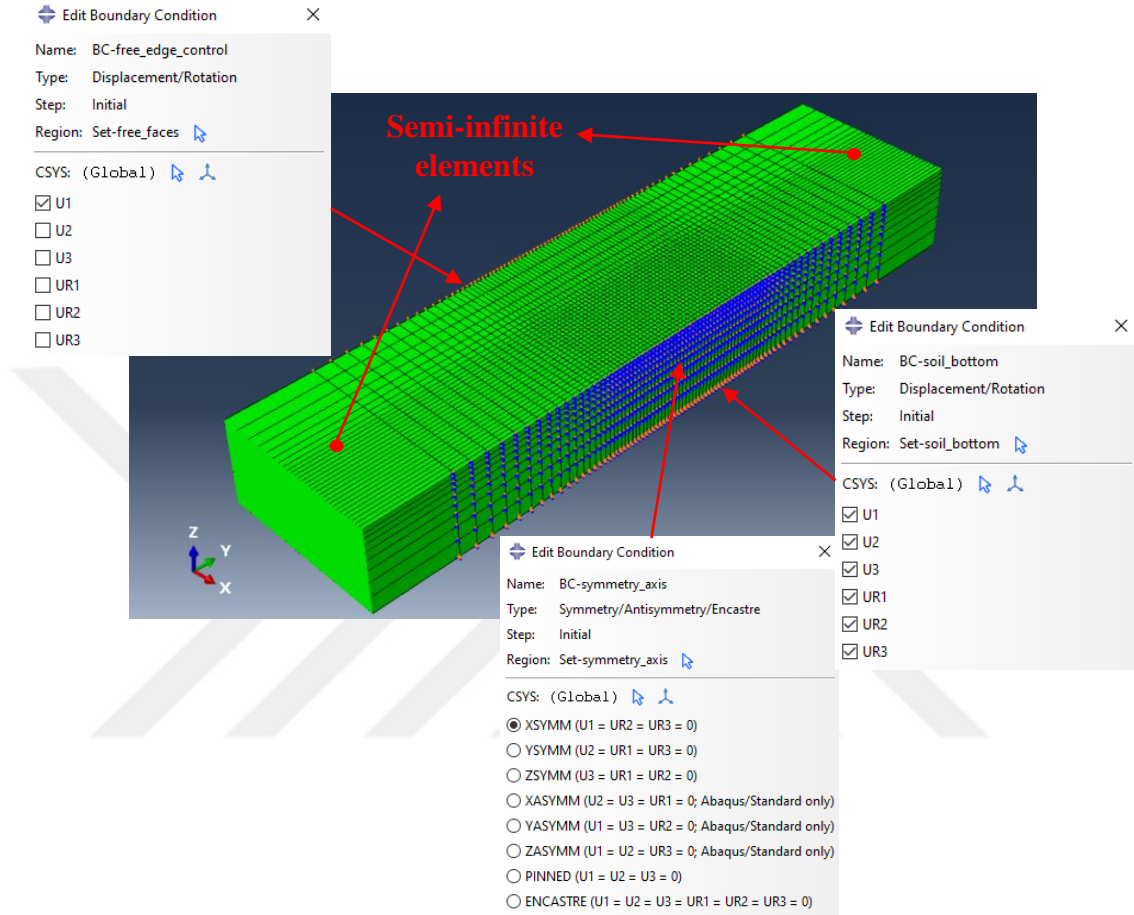


Figure 8. View of boundary conditions of soil.

According to the soil type, whether it was saturated or not, the internal stresses of the soil at model were defined. Moreover, the coefficients of lateral earth pressure at rest ( $K_0$ ), which represents the ratio of horizontal to vertical effective stress in a soil mass that is not deformed by external forces, were calculated by formula (2) (See Table 4). The coefficient, which equation is defined by Jaky, J. (1944), is based on the assumption that the soil mass is homogeneous, isotropic, and normally consolidated, and that the internal friction angle ( $\phi$ ) is the critical-state friction angle.

$$K_0 = 1 - \sin(\phi) \quad (2)$$

Table 4. Lateral Coefficients of Soil Conditions

	Soft Soil	Saturated Soft Soil	Medium Soil	Saturated Medium Soil
Lateral Coefficient	0.609	0.792	0.384	0.758

### 3.1.3 Model Setup for Analysis

To conduct the non-linear analysis for SSI, the Kobe 1995 earthquake, which is a critical case study that leading to advancements and one of turning point in earthquake engineering practices and understanding of ground motion effects on structures, was applied to base of soil. The magnitude ( $M_w$ ) of earthquake, which seismic record is 40 sec, is 6.9 and has 0.3447g peak ground acceleration. In addition, gravitational acceleration was defined at vertical direction, and model was run (See Figure 9).

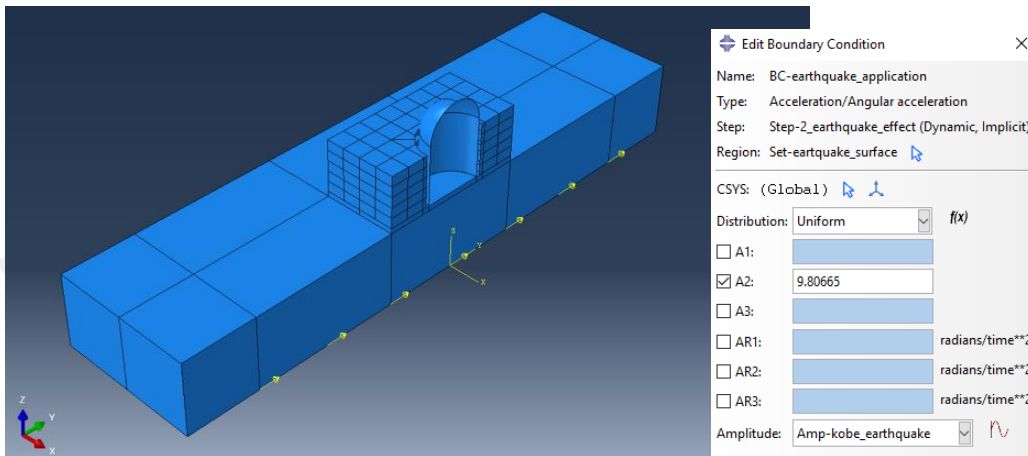


Figure 9. View of earthquake direction and model.

The seismic excitation acting on the soil base is shown in Figure 10 below.

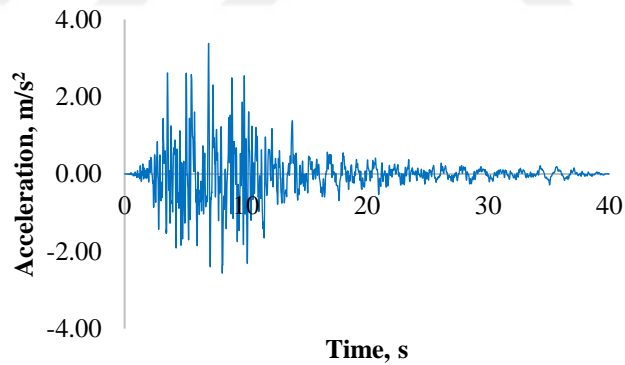


Figure 10. The acceleration time history of the Kobe earthquake.

## 4 Results and Discussions

This section presents the results of the SSI conducted using Abaqus and evaluation of them on four different scenarios. The peak values obtained from the analysis results of the nodes whose locations are defined are presented below (See Figures 11 to 13 and Tables 5 to 7).

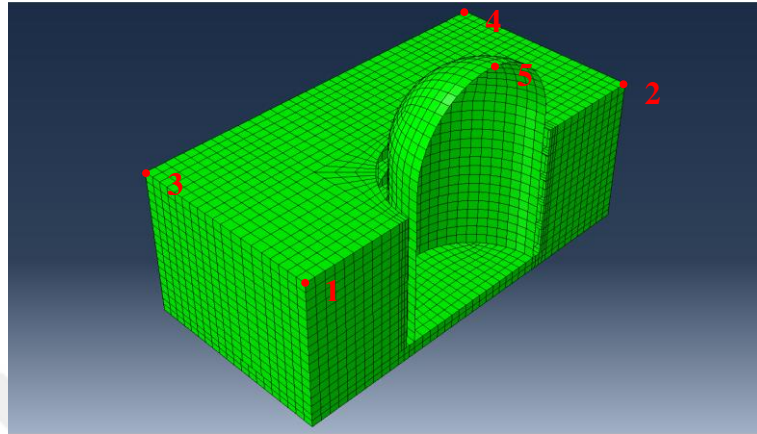


Figure 11. View of nodes on top of the superstructure

Table 5. The peak values of nodes on top of the superstructure

	Node No	Soft Soil		Medium Soil	
		Unsaturated	Saturated	Unsaturated	Saturated
Peak Acceleration, $m/s^2$	1	3.914	1.119	6.299	2.044
	2	4.152	1.120	6.263	2.019
	3	3.899	1.100	6.229	1.971
	4	4.110	1.102	6.308	1.974
	5	8.151	1.229	8.868	0.242
Peak Relative Lateral Displacement, m	1	0.073	0.031	0.131	0.071
	2	0.074	0.031	0.126	0.067
	3	0.073	0.031	0.129	0.070
	4	0.075	0.031	0.123	0.066
	5	1.057	0.057	3.913	0.134

The unsaturated state represents before the flooding, and the saturated state after the flooding.

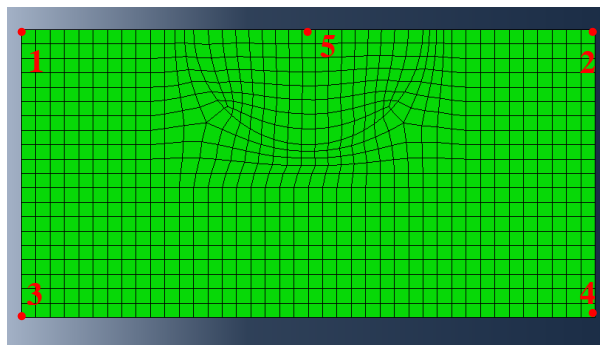


Figure 12. View of the nodes on bottom of the foundation

Table 6. The peak values of nodes on bottom of the foundation

	Node No	Soft Soil		Medium Soil	
		Unsaturated	Saturated	Unsaturated	Saturated
Peak Acceleration, $m/s^2$	1	3.236	1.095	4.828	1.477
	2	2.988	1.097	5.330	1.418
	3	3.481	0.994	4.694	1.447
	4	3.494	1.028	5.119	1.421
	5	2.906	1.056	4.623	1.411
Peak Settlement, m	1	0.203	0.196	0.342	0.657
	2	0.216	0.195	0.320	0.633
	3	0.203	0.196	0.345	0.660
	4	0.216	0.195	0.321	0.636
	5	0.110	0.134	0.153	0.534

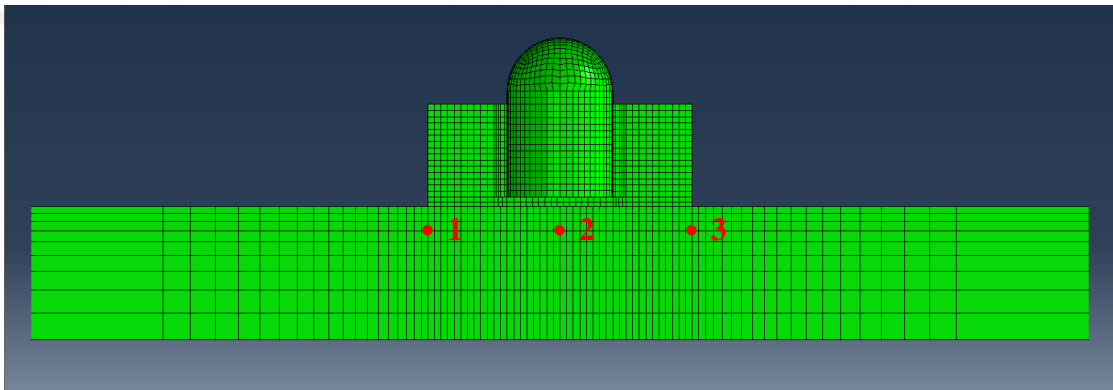


Figure 13. View of the nodes in soil

Table 7. The peak values of the nodes in soil

	Node No	Soft Soil		Medium Soil	
		Unsaturated	Saturated	Unsaturated	Saturated
Peak Acceleration, $m/s^2$	1	4.135	0.879	5.420	2.159
	2	4.318	1.227	5.353	1.879
	3	3.979	0.898	5.428	2.247
Peak Lateral Displacement, m	1	0.157	0.207	0.308	0.695
	2	0.174	0.131	0.326	0.146
	3	0.160	0.227	0.261	0.568
Peak Settlement, m	1	0.122	0.076	0.249	0.222
	2	0.094	0.110	0.130	0.447
	3	0.137	0.082	0.217	0.219

The nodes, which are located at the top of the superstructure, are important to understand the response of the structure. Especially the top node of the containment

building because it is more flexible. Moreover, the chosen bottom nodes of foundation are allowed to see settlement of structure. The nodes located 9 m below the soil surface allow us to observe the behaviour of the soil. Below is a graphical presentation of the analysis results of the nodes whose locations are defined above. (See figure 14 to 21)

Results for top nodes of superstructure:

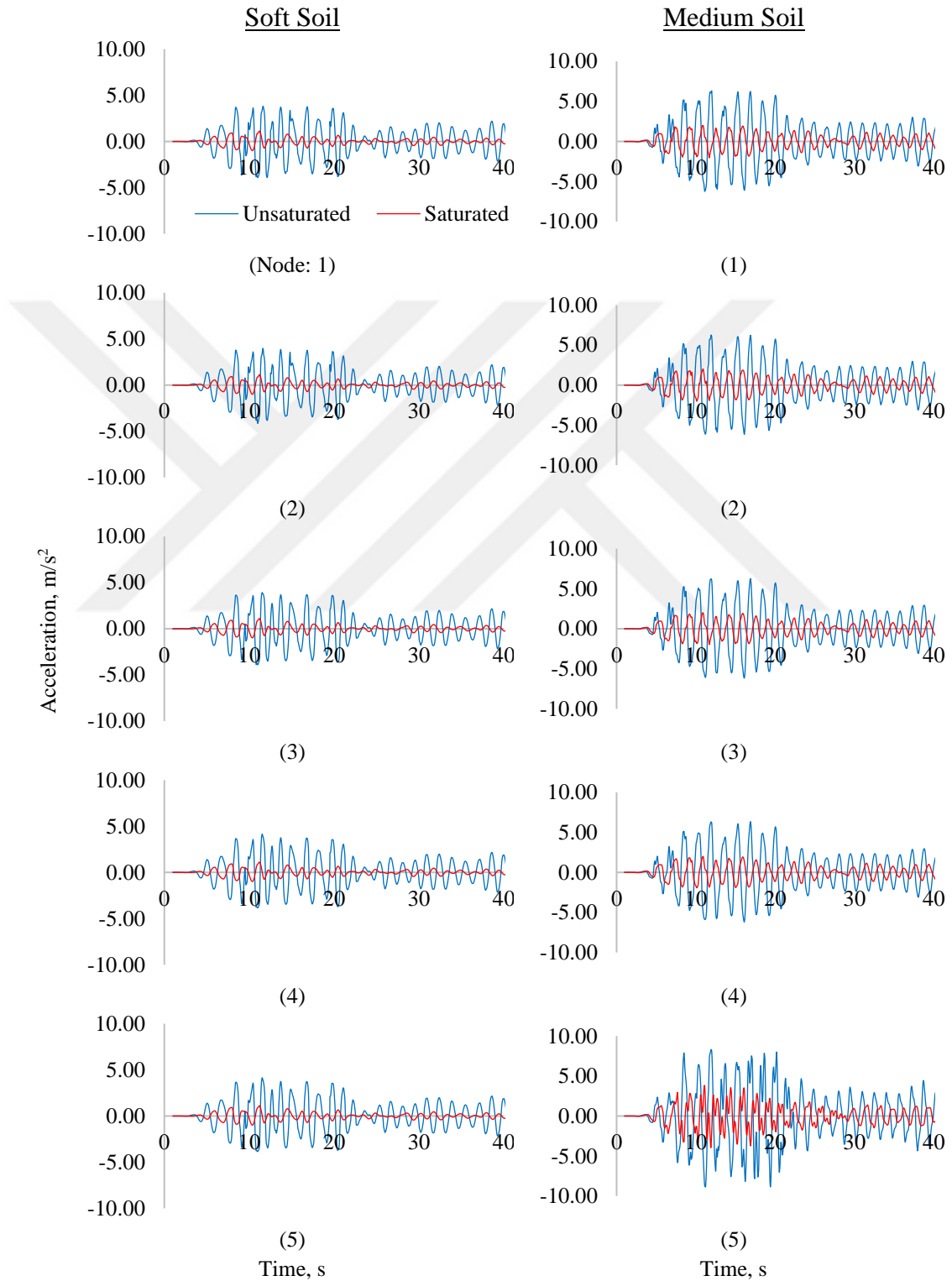
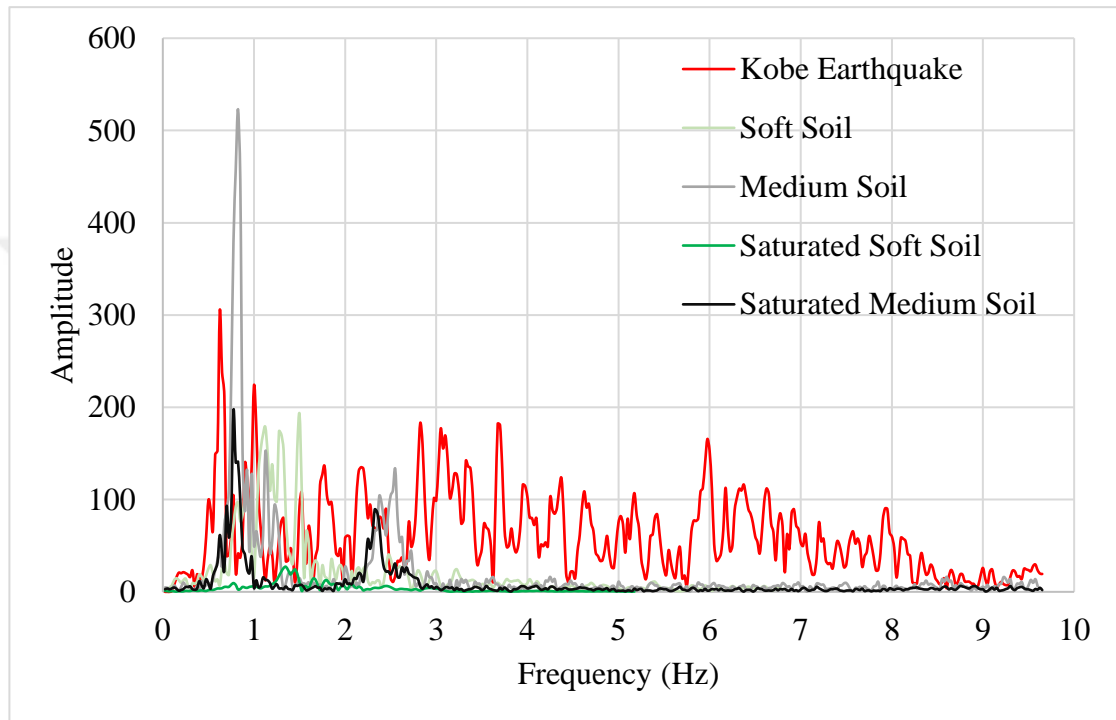


Figure 14. Acceleration and time relationship

Acceleration is higher at medium soil than soft soil as it can be seen from *Figure 14* because the soft soil comparing to medium soil has cohesion, which is adhesive effect, in addition to friction angle. This phenomenon, which is making amplitude bigger than Kobe Earthquake, calls amplification of seismic waves.

By considering top node (No:5) of containment building, which is flexible part of NPP, power spectrums of acceleration of these nodes, which is defined via Fast Fourier Transform (FFT), were investigated for four different scenarios as it can be seen at *Figure 15*.



*Figure 15. The power spectrum of four different scenarios*

The soft soil compared to medium soil amplifies the vibration of the seismic waves that occur due to earthquakes between 1 and 1.5 Hz frequencies but reduces it at after 1.5 Hz frequencies. Medium soil tends to increase between 0.5-1 Hz, fundamental mode, and 2-3 Hz, second mode, frequencies. Therefore, the structure is more susceptible to damage at these spacings which are defined depending on soil types.

In same spacings, saturated conditions for both types of soil show similar effects, which increase vibration of seismic waves, like unsaturated conditions but less effective than them. Moreover, these effects can be seen results from *Tables 5* and *Figures 14 and 15* that presence of water due to flooding in soil provides to decrease response acceleration and lateral displacement of structure. In other words, presence of water causes damping effect on seismic waves (Chen & Ho, 2000). Comparing medium soil, it can be observed clearly on soft soil.

In addition, when the acceleration values are carefully looked at *Table 5* and *Figure 14*, it will be seen that the acceleration values of the corner nodes are different, which is a potential risk that will cause the structure to rotate. If it had been studied with

an asymmetrical structure as opposed to the symmetrical structure used in this study, it would have been inevitable to encounter different settlements, which is another vital issue, in addition to its rotation around its axis. This is an undesirable situation in highly important structures such as NPPs.

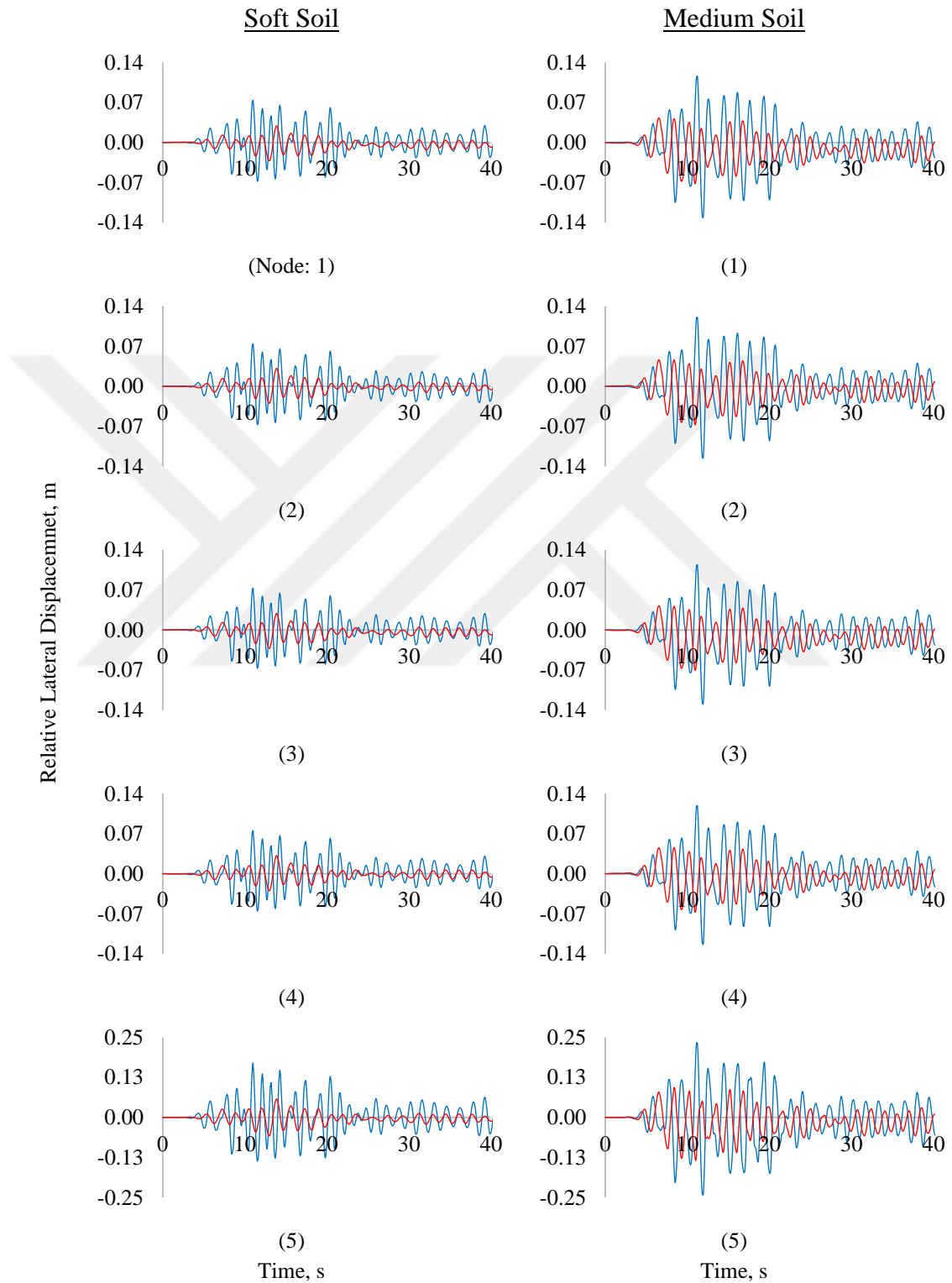


Figure 16. Relative Lateral Displacement and time relationship

Results for bottom nodes of foundation:

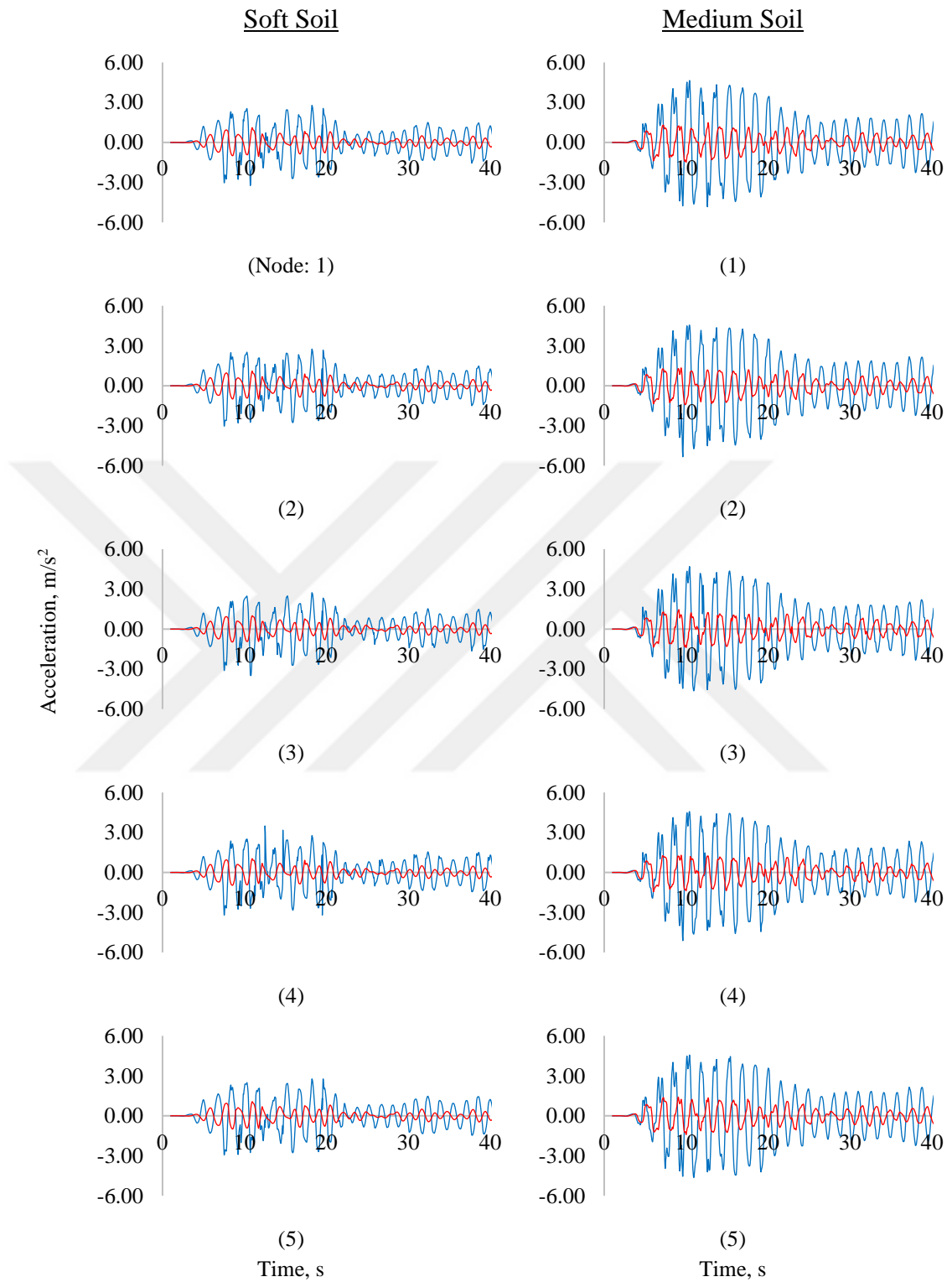


Figure 17. Acceleration and time relationship

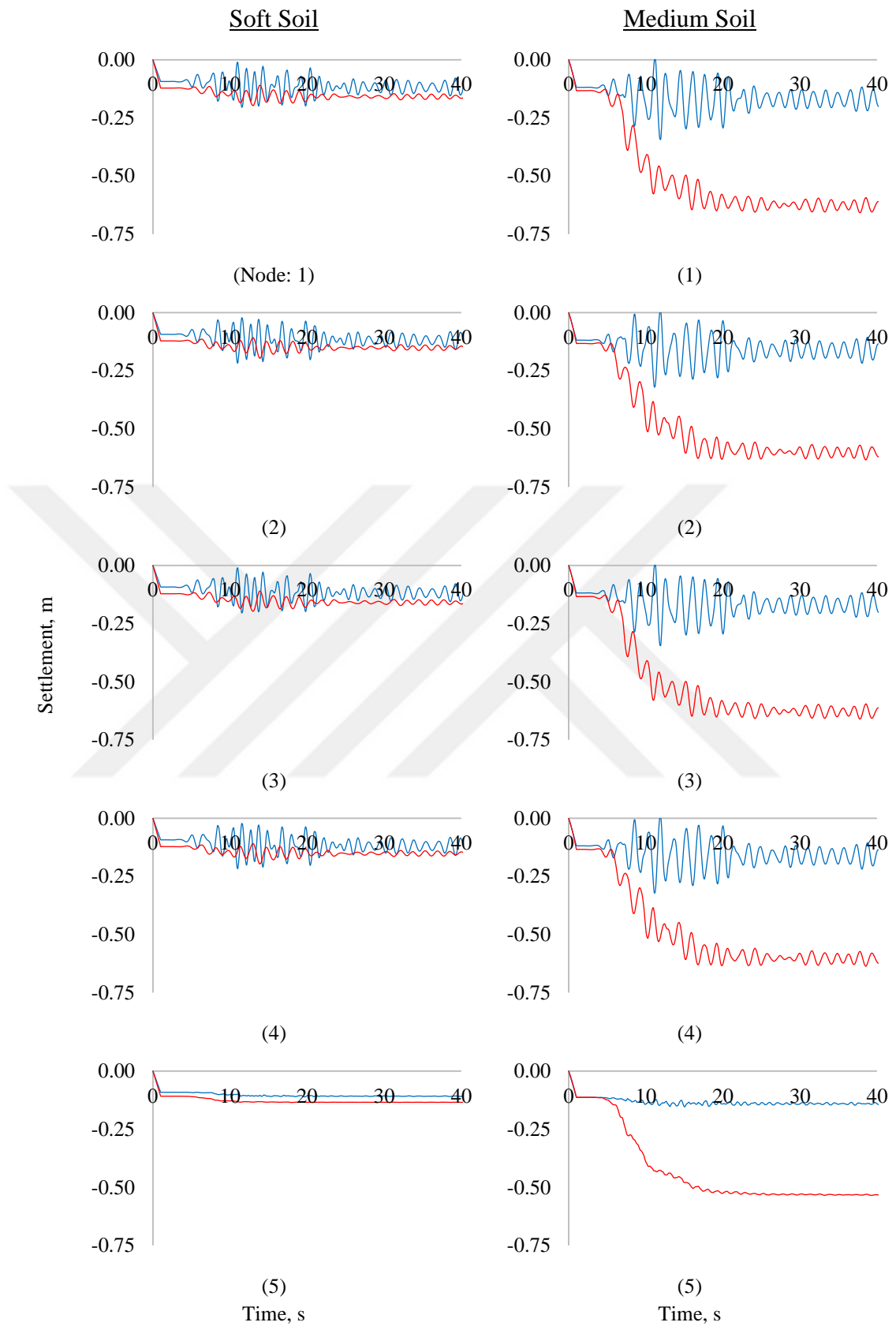


Figure 18. Settlement and time relationship

Moreover, settlement of the structure has been increased by saturation as seen Table 6 and Figure 17. Observed this response, known as liquefaction, which observe

at soil that has cohesionless stiff sandy behaviours in saturated condition, can be seen expressly at medium soil.

Results for nodes in soil (9 m below from surface of soil):

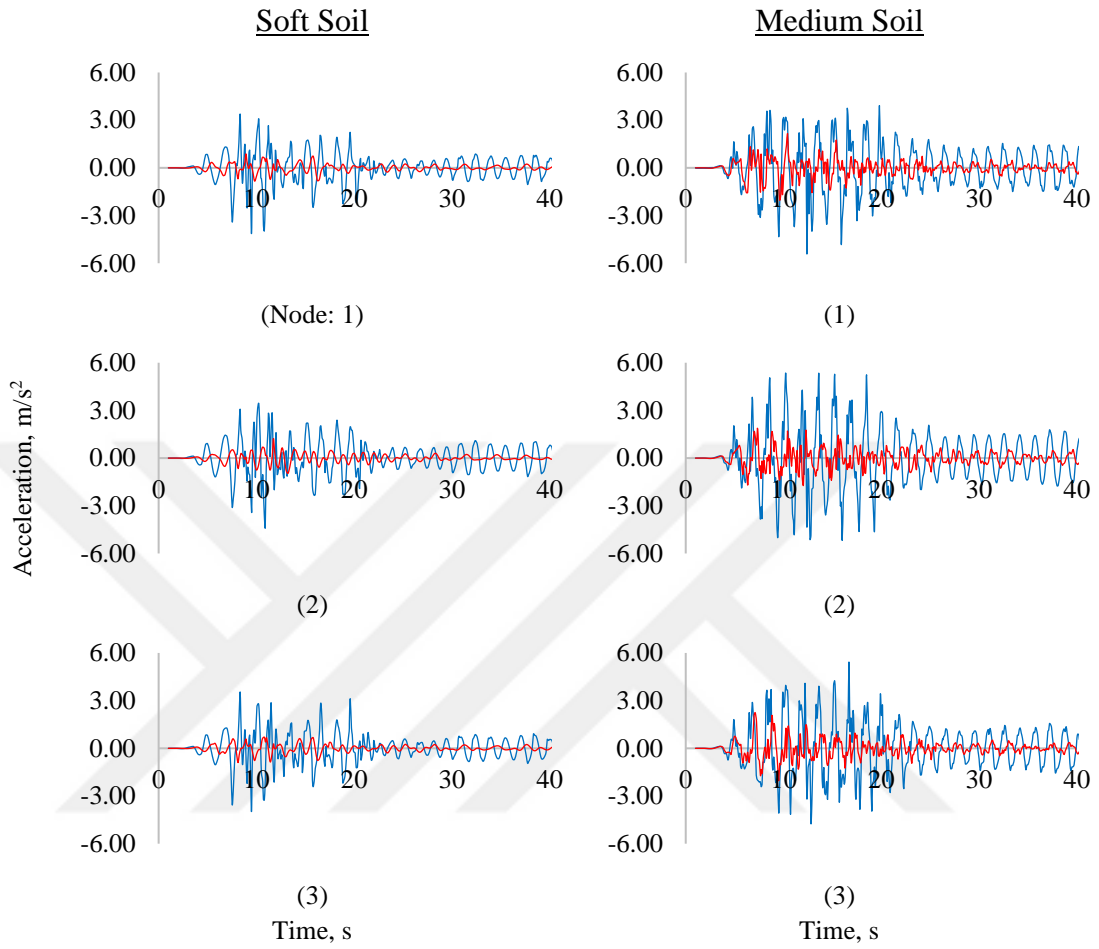
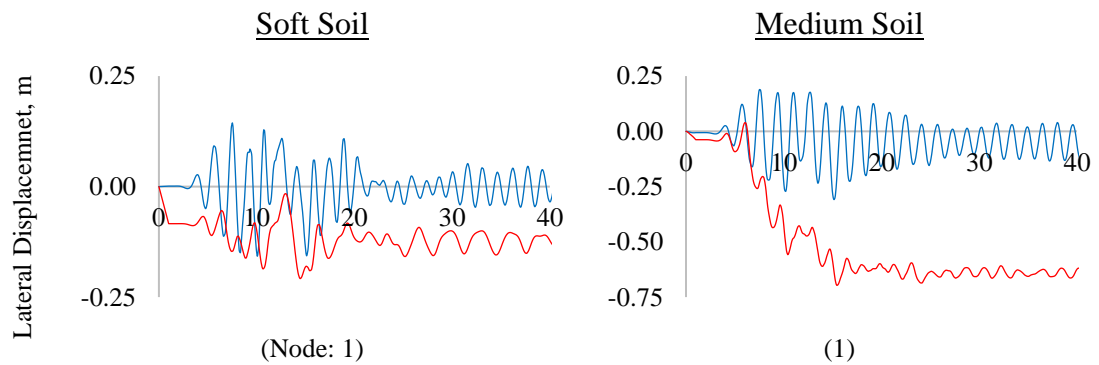


Figure 19. Acceleration and time relationship



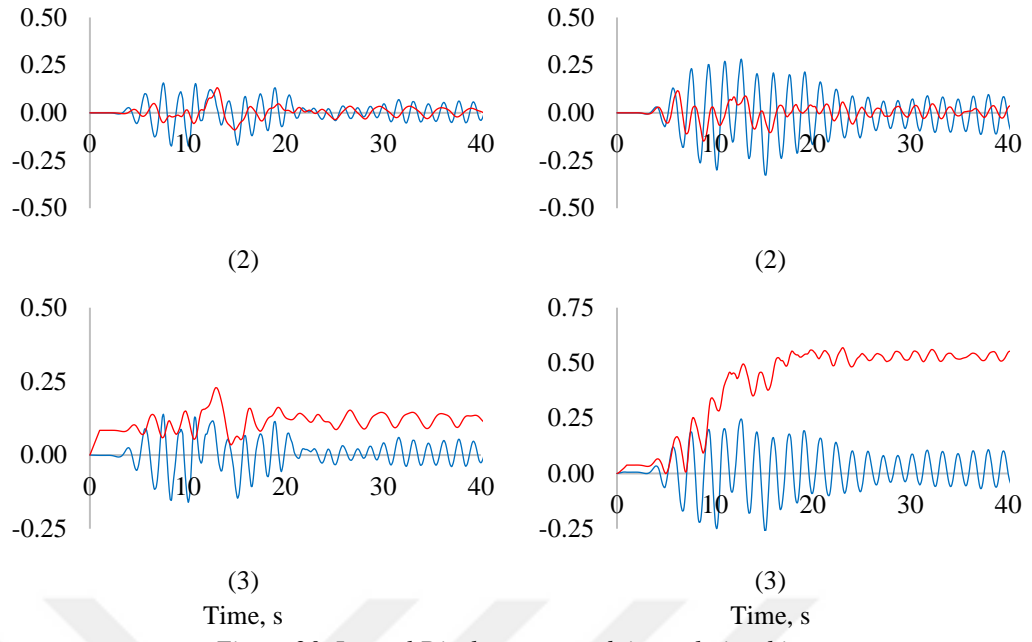


Figure 20. Lateral Displacement and time relationship

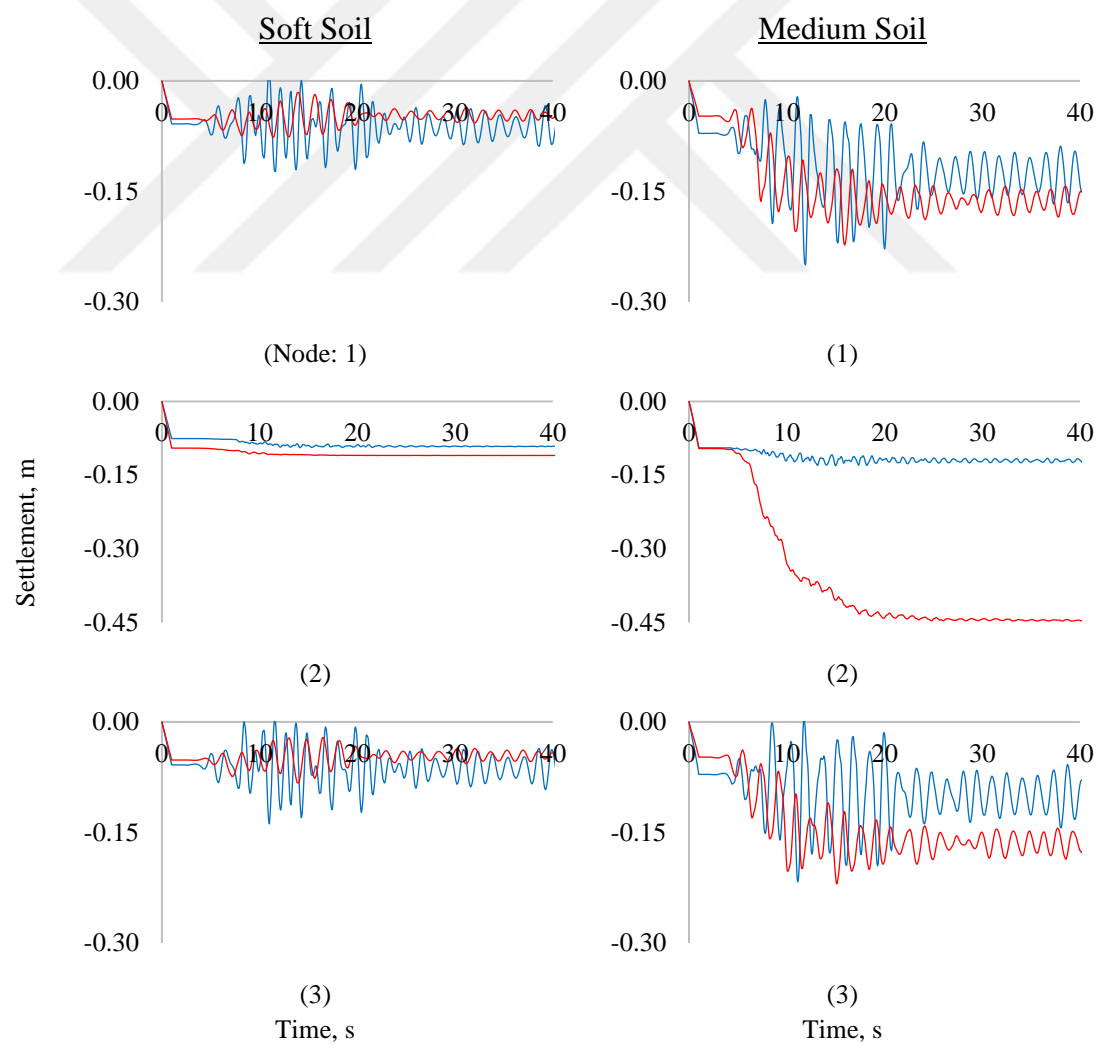


Figure 21. Settlement and time relationship

When observing inside the soil from *Table 7* and *Figures 18 to 20*, it is seen that the soil moves from under the structure to the right and left (On Y axis direction) with the effect of the seismic waves of earthquake, emptying its bottom and allowing settlement. It is possible to say that the decrease in friction between the structure and the ground interface with the lubrication effect brought by saturation, prevents the high horizontal displacements seen in the ground from affecting the structure.

The parameters used in this study have been determined independently. Different parameters for properties of soil and structure, and their dimensions will allow to obtain different results. However, the parameters in this scale will give result in this scope. The response will be different when SSI analysis is done by using different earthquakes. This kind of studies allows us to understand the response of structure to seismic waves better.



## **5 Conclusion and Recommendations for Future Studies**

Considering the potential multi-hazard situation, SSI analysis of a NPP was modelled in Abaqus finite element software, and the results were evaluated. A NPP structure is modelled on two different types of soil to observe its earthquake response comparing before and after flooding hazard. As seen from the results, the presence of water in the soil after the flood significantly affects the response of the structure to seismic effects.

These results, obtained by using finite element software, which draw attention to the issues that are frequently emphasized in engineering studies and solutions, once again show the importance of SSI analysis by considering all possibilities, especially in important structures such as NPPs. Because seismic excitation during shaking can be dangerous for nuclear equipment, it is vital to foresee it. As a result, it is crucial to monitor and forecast these seismic excitations during earthquakes to assure proper nuclear building design. With this study, it has been shown that critical information can be provided for designs by considering multi-hazard situations such as flood and earthquake at the same time by using finite element software.

On the other hand, this numerical study can be experimentally performed again by determining the soil parameters for non-flooding and flooding situation at laboratory experiments, and using appropriately scaled the lumped mass-spring model of the structure and representing the effect of earthquake by shaking table in further studies. The experimental study defines various soils, their saturation states, response of structure properly, and supports more using effectively of numeric studying.

In addition, the seismic waves that affected on the bottom of the soil are the values measured from the station nearest to the epicentre on the surface. The seismic excitation is not fully reflected this way. It would be a more realistic reflection to enter the deep seismic records taken from the borehole into the bottom of the modelled soil. This would let to fully observe SSI and to accurately simulate seismic excitations (Wang et al., 2022).

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