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# Seismic Analysis of the Soil Behavior and Titling of the Building

S. M. Tahmidur Rahman[1*]

[1]B.Sc. in Civil Engineering (KUET), M.Sc. in Civil Engineering (UAP), Dhaka, Bangladesh

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***Corresponding author:** S. M. Tahmidur Rahman
B.Sc. in Civil Engineering (KUET), M.Sc. in Civil Engineering (UAP), Dhaka, Bangladesh

**Abstract** **Original Research Article**

The mechanism of this yielding and its behavior under seismic loading of soil are the primary focus of this investigation. Nonlinear analysis is taken into account to see the real behavior of soil. In order to analyze soil, we employ both its solid mass and its lumped mass. In this study, the Finite Element Model (FEM) forms the basis for the mathematical formulas. Soil analysis in the case of a lumped mass takes into account the soil's one DOF, two DOF, and multi DOF degrees of freedom. In order to determine soil characteristics for MDOF, a soil bore log must be employed. In the instance of MDOF, the soil is composed of 12 distinct layers. SAP 2000 is used to do linear and nonlinear analysis of time series for this research. According to the findings, solid and lumped soil mass displacements are almost identical. Therefore, it is possible to get insight into the behavior of soil mass during an earthquake by studying lumped soil mass. The soil's nonlinear behavior is investigated using a variety of linear completely plastic hysteretic loops. Soil characteristics are shown to be crucial in this regard. Inadequate soil stiffness may result in persistent deformation, which in turn can lead structures to lean out of alignment. It is also noted that near the soil's surface, amplification is greatest.

**Keywords:** Nonlinear analysis, The soil's nonlinear behavior, Finite Element Model (FEM).

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## INTRODUCTION

The population of Bangladesh is rather high. In Bangladesh, geologists have identified many active tectonic plate borders. Destructive active faults may be found in parts of Bangladesh such as the north and east of the country. In addition to this, it is the biggest river delta in the world and is located extremely near to sea level. Scientists believe that it is just a matter of time until a significant earthquake takes place [1]. It is regularly discovered that earthquakes influence the designs of structural elements, and the tilting of many structures may cause severe damage. During periods of ground shaking, the performance of foundations often deteriorates. Differential settlements are the primary factor responsible for the building's slanting appearance. The term "uneven load deformation behavior" refers to this phenomenon, which may also be described as "asymmetric behavior." It will take place when certain plastic yield scenarios have been shown by the structures. When aroused by seismic stress, the plastic deformation of the symmetric structures works to counterbalance each other, thus the buildings remain stable. When asymmetric yielding structures are aroused by seismic stress, plastic deformations emerge in the direction of tilting in the building. It is possible to express this idea more explicitly by stating that strong and weak routes will form as a result of tilting for symmetrical structures. In the actual world, symmetrical architectural designs like this one are not always feasible. Because of this, the majority of the structures have a distinct yield strength in each of the four orientations. When structures are exposed to seismic ground vibrations that last for an extended period of time, it causes considerable damage to the structure.

On April 25, 2015, Nepal was devastated by a magnitude 7.8 earthquake known as the Gorkha earthquake. This earthquake was caused by the Indian and Eurasian plates colliding at their plate borders, which caused a convergent collision. The capital city of Kathmandu is located around sixty kilometers to the north- west of the epicenter, and the focus of the earthquake was just eight kilometers deep. There were around 9000 fatalities and over 20,000 injuries, while more than 600,000 buildings in Kathmandu and other adjacent cities were either damaged or destroyed, which left more than 3.5 million people without a home [2]. Additionally, it caused damage to a number of buildings in Bangladesh.

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Almost all buildings built using civil engineering techniques include components that rest directly on the ground. When external forces, like earthquakes, impinge on such systems, the resulting structure and ground displacements are not separate. Soil-structure interaction (SSI) is the reciprocal process through which a structure's motion affects the soil's reaction (and vice versa) [3]. Traditional approaches of structural design don't account for SSI consequences. Light constructions on reasonably firm soil, including low-rise apartment complexes and basic inflexible retaining walls, may get away with ignoring SSI. But for big structures on relatively soft soils, including nuclear power stations, high-rise skyscrapers, and elevated-highways on soft soil [4], the influence of SSI becomes significant. Recent earthquakes like the 1995 Kobe Earthquake have shown that a building's seismic behavior is heavily influenced by the response of the foundation and the ground as well as the superstructure [5]. Accordingly, the response analysis must be carried out with the entire structural system in mind, including the superstructure, the foundation, and the ground Standard Specifications for Concrete Structures: Seismic Performance Verification [6].

The performance of foundations is a major concern in soil mechanics and foundation engineering since every building must rest on the ground eventually. Static, dynamic, or even combined stresses may cause problems for a building's underpinnings [7]. A dynamic load may be the result of an earthquake, the application of cyclic loads with varying cycle numbers, or any other sort of load that varies over time. Damage to geotechnical structures, such as liquefaction, slope instability, deformation of retaining walls, and damage to foundations by diminishing bearing capacity and increasing sinking, may be caused by a significant dynamic load. A foundation's stress state near the floor transitions from elastic to plastic as a load is applied; plastic flow initiates at a corner of the foundation and spreads outward along a curved surface as the load increases, eventually covering the soil beneath the structure entirely [8,9,10]. Due to the complexity of dynamic force and soil behavior under the impact of these forces, the dynamic bearing capacity of foundations has been researched less than its static counterpart [11].

This study focuses on how tilting happens and its behavior against seismic loading of soil. To observe the actual behavior of soil, nonlinear analysis is considered.

## OBJECTIVE OF THE STUDY

- The main objective of the work is to investigate the soil behavior and tilting of buildings due to seismic loading.

## SUB-STRUCTURE MODELS USED FOR ANALYSIS

Structural dynamics is needed to perform seismic analysis. Non-linear analysis is also needed to know the actual behavior of soil. This study also includes time history analysis for which data is produced from UAP experimental work. This chapter includes the numerical results obtained from using software SAP 2000.

This study includes three sub structure models for analysis. First one is one degree of freedom (1DOF), second one is two degree of freedom (2DOF) and third one is multi degree of freedom (MDOF).

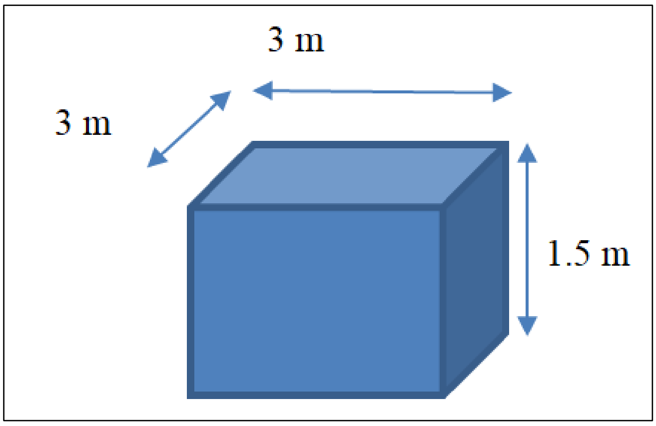


**Fig. 1: Soil layers for 1DOF**

An assumed soil mass is considered three meter by three meter (3×3) area and 1.5 m thickness layer as per assumed soil parameter for 1DOF as shown in Fig. 1.

Assumed soil mass is also considered three meter by three meter (3×3) area and 3 m thickness layer as per assumed soil parameter for 2DOF. Total 2 layers is used for 6 m in total depth. Each layer is as shown in Fig. 2.

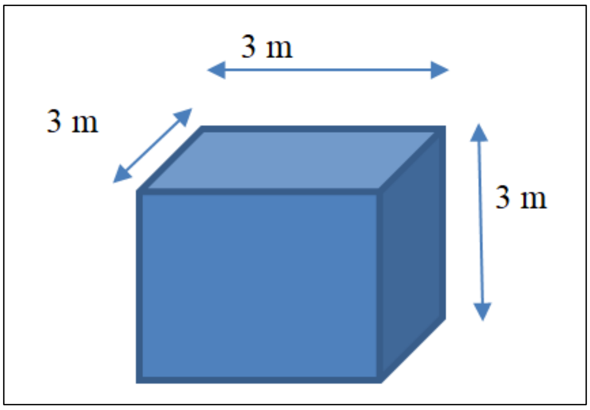


**Fig. 2: Soil layers for 2DOF**

Then for multi degree of freedom a bore log (appendix) is considered. All soil parameters are calculated from this bore log. Here also three meter by three meter (3×3) area and 1.5 m thickness each layer soil mass as per bore log is considered for analysis. 18 m in total depth is considered from existing ground level and total 12 layers are used. Each layer is as shown in Fig.3.

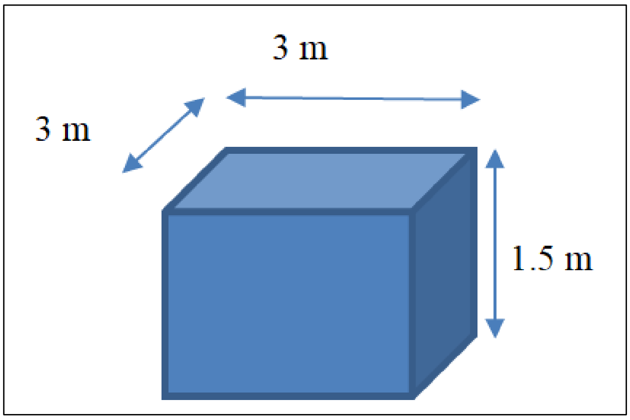


**Fig. 3: Soil layers for MDOF**

For linear analysis, solid mass analysis is performed along with lumped mass in three sub structure model analysis. Nonlinear analysis is performed for multi degree of freedom (MDOF) only.

In this study ground motion data are used from UAP laboratory test (Fig. 4) which was performed for 20-seconds for time history analysis.

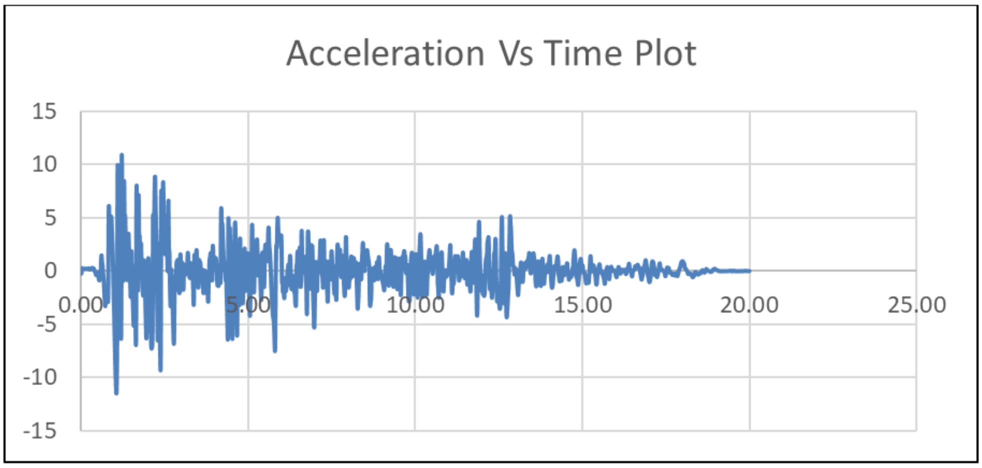


**Fig. 4: Time history data**

## RESULTS AND DISCUSSION

Table 1 and Table 2 show the Soil Parameters for Linear Analysis using 1-DOF and 2-DOF models.

**Table 1: Soil Parameters for 1DOF (Linear Analysis)**

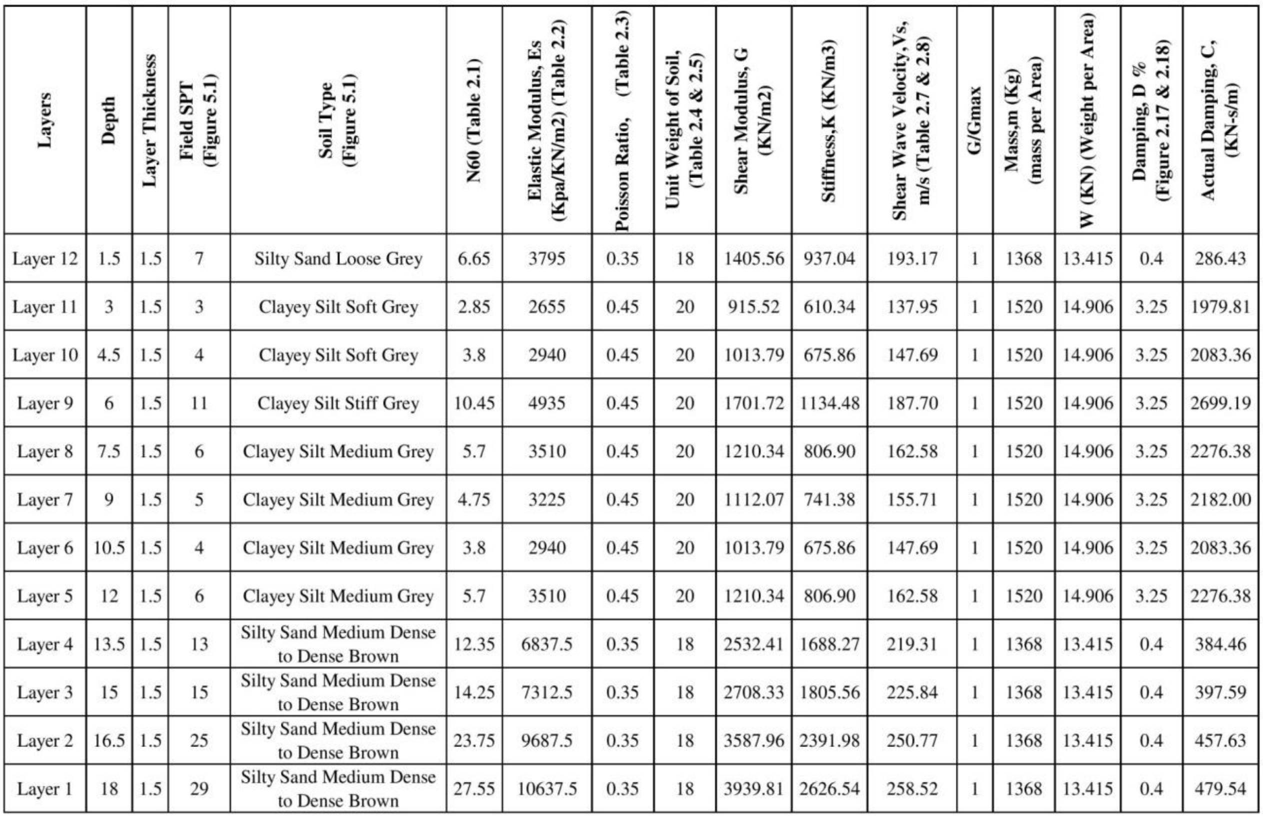
| Layers | 1 |
|---|---|
| Depth (m) | 1.5 |
| Layer Thickness (m) | 1.5 |
| Field SPT (Assumed) | 7 |
| Soil Type (Assumed) | Sandy Silt |
| N60 | 6.65 |
| Elastic Modulus, Es (kN/m2) | 3795 |
| Poisson Ratio, µ | 0.35 |
| Unit Weight of Soil, ϒ(kN/m3) | 18 |
| Shear Modulus, G (KN/m2) | 1405.56 |
| Stiffness, K (kN/m) per area | 937.04 |
| Shear Wave Velocity m/s | 193.17 |
| G/Gmax | 1 |
| m (Kg), mass per area | 1368 |
| W (kN) weight per area) | 13.415 |
| Damping Ratio, D % | 0.40 |
| Actual Damping, C(NS/m) | 286.43 |

**Table 2: Soil Parameters for 2DOF (Linear Analysis)**

| Layers | 1 | 2 |
|---|---|---|
| Depth (m) | 3 | 6 |
| Layer Thickness (m) | 3 | 3 |
| Field SPT (Assumed) | 8 | 2 |
| Soil Type (Assumed) | Sand | Clay |
| N60 | 7.6 | 1.9 |
| Elastic Modulus, Es (kN/m2) | 21550 | 10000 |
| Poisson Ratio, µ | 0.25 | 0.3 |
| Unit Weight of Soil, ϒ(kN/m3) | 18 | 16 |
| Shear Modulus, G (KN/m2) | 8620 | 3846.2 |
| Stiffness, K (kN/m) per area | 2873.333 | 1282.051 |
| Shear Wave Velocity m/s | 198.535 | 125.314 |
| G/Gmax | 1 | 1 |
| m (Kg), mass per area | 5198.78 | 2446.48 |
| W (kN) weight per area) | 50.98 | 23.99 |
| Damping Ratio, D % | 0.40 | 3.25 |
| Actual Damping, C(NS/m) | 977.8 | 3640.3 |

Table 3 and Table 4 show the Soil Parameters for MDOF (12 layer soil) using Linear and Nonlinear Analysis.

**Table 3: Soil Parameters for MDOF (Linear Analysis)**



| Layers | Depth | Layer Thickness | Field SPT (Figure 5.1) | Soil Type (Figure 5.1) | N60 (Table 2.1) | Elastic Modulus, Es (Kpa/KN/m2) (Table 2.2) | Poisson Ratio, (Table 2.3) | Unit Weight of Soil, (Table 2.4 & 2.5) | Shear Modulus, G (KN/m2) | Stiffness,K (KN/m3) | Shear Wave Velocity,Vs, m/s (Table 2.7 & 2.8) | G/Gmax | Mass,m (Kg) (mass per Area) | W (KN) (Weight per Area) | Damping, D % (Figure 2.17 & 2.18) | Actual Damping, C, (KN-s/m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 12 | 1.5 | 1.5 | 7 | Silty Sand Loose Grey | 6.65 | 3795 | 0.35 | 18 | 1405.56 | 937.04 | 193.17 | 1 | 1368 | 13.415 | 0.4 | 286.43 |
| Layer 11 | 3 | 1.5 | 3 | Clayey Silt Soft Grey | 2.85 | 2655 | 0.45 | 20 | 915.52 | 610.34 | 137.95 | 1 | 1520 | 14.906 | 3.25 | 1979.81 |
| Layer 10 | 4.5 | 1.5 | 4 | Clayey Silt Soft Grey | 3.8 | 2940 | 0.45 | 20 | 1013.79 | 675.86 | 147.69 | 1 | 1520 | 14.906 | 3.25 | 2083.36 |
| Layer 9 | 6 | 1.5 | 11 | Clayey Silt Stiff Grey | 10.45 | 4935 | 0.45 | 20 | 1701.72 | 1134.48 | 187.70 | 1 | 1520 | 14.906 | 3.25 | 2699.19 |
| Layer 8 | 7.5 | 1.5 | 6 | Clayey Silt Medium Grey | 5.7 | 3510 | 0.45 | 20 | 1210.34 | 806.90 | 162.58 | 1 | 1520 | 14.906 | 3.25 | 2276.38 |
| Layer 7 | 9 | 1.5 | 5 | Clayey Silt Medium Grey | 4.75 | 3225 | 0.45 | 20 | 1112.07 | 741.38 | 155.71 | 1 | 1520 | 14.906 | 3.25 | 2182.00 |
| Layer 6 | 10.5 | 1.5 | 4 | Clayey Silt Medium Grey | 3.8 | 2940 | 0.45 | 20 | 1013.79 | 675.86 | 147.69 | 1 | 1520 | 14.906 | 3.25 | 2083.36 |
| Layer 5 | 12 | 1.5 | 6 | Clayey Silt Medium Grey | 5.7 | 3510 | 0.45 | 20 | 1210.34 | 806.90 | 162.58 | 1 | 1520 | 14.906 | 3.25 | 2276.38 |
| Layer 4 | 13.5 | 1.5 | 13 | Silty Sand Medium Dense to Dense Brown | 12.35 | 6837.5 | 0.35 | 18 | 2532.41 | 1688.27 | 219.31 | 1 | 1368 | 13.415 | 0.4 | 384.46 |
| Layer 3 | 15 | 1.5 | 15 | Silty Sand Medium Dense to Dense Brown | 14.25 | 7312.5 | 0.35 | 18 | 2708.33 | 1805.56 | 225.84 | 1 | 1368 | 13.415 | 0.4 | 397.59 |
| Layer 2 | 16.5 | 1.5 | 25 | Silty Sand Medium Dense to Dense Brown | 23.75 | 9687.5 | 0.35 | 18 | 3587.96 | 2391.98 | 250.77 | 1 | 1368 | 13.415 | 0.4 | 457.63 |
| Layer 1 | 18 | 1.5 | 29 | Silty Sand Medium Dense to Dense Brown | 27.55 | 10637.5 | 0.35 | 18 | 3939.81 | 2626.54 | 258.52 | 1 | 1368 | 13.415 | 0.4 | 479.54 |

**Table 4: Soil Parameters for MDOF (Nonlinear Analysis)**

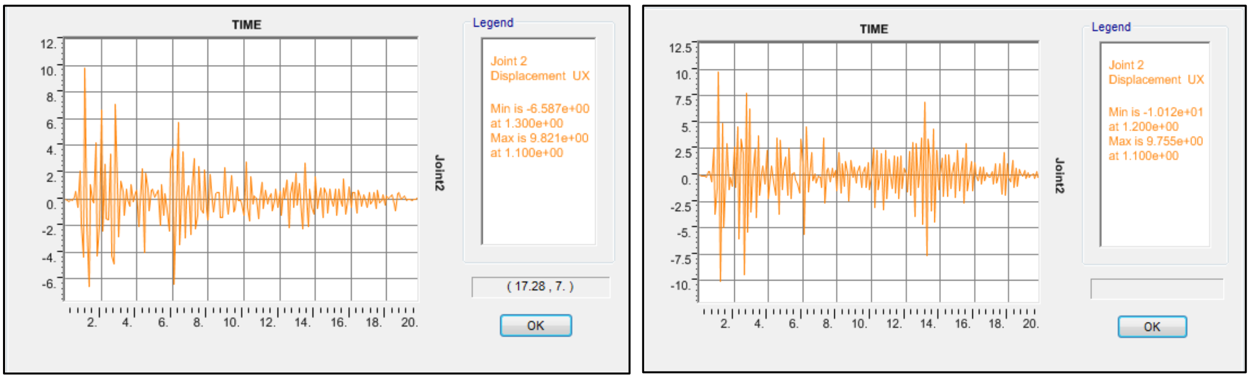
| Layers | Depth | Layer Thickness | Field SPT (Figure 5.1) | Soil Type (Figure 5.1) | N60 (Table 2.1) | Elastic Modulus, Es (Kpa/KN/m2) (Table 2.2) | Poisson Ratio, µ (Table 2.3) | Unit Weight of Soil, 2.4 & 2.5) | Shear Modulus, G (KN/m2) | Stiffness,K (KN/m3) | Shear Wave Velocity,Vs, m/s (Table 2.7 & 2.8) | Gmax (KN/m2) | G/Gmax | Mass,m (Kg) (mass per Area) | W (KN) (Weight per Area) | Damping, D % (Figure 2.17 & 2.18) | Actual Damping, C, (KN-s/m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 12 | 1.5 | 1.5 | 7 | Silty Sand Loose Grey | 6.65 | 3795 | 0.4 | 18 | 1405.56 | 937.04 | 193.17 | 68470.42 | 0.021 | 1368 | 13.42 | 32 | 22.91 |
| Layer 11 | 3 | 1.5 | 3 | Clayey Silt Soft Grey | 2.85 | 2655 | 0.5 | 20 | 915.52 | 610.34 | 137.95 | 38799.32 | 0.024 | 1520 | 14.91 | 17 | 10.36 |
| Layer 10 | 4.5 | 1.5 | 4 | Clayey Silt Soft Grey | 3.8 | 2940 | 0.5 | 20 | 1013.79 | 675.86 | 147.69 | 44467.74 | 0.023 | 1520 | 14.91 | 17 | 10.90 |
| Layer 9 | 6 | 1.5 | 11 | Clayey Silt Stiff Grey | 10.45 | 4935 | 0.5 | 20 | 1701.72 | 1134.48 | 187.70 | 71827.18 | 0.024 | 1520 | 14.91 | 17 | 14.12 |
| Layer 8 | 7.5 | 1.5 | 6 | Clayey Silt Medium Grey | 5.7 | 3510 | 0.5 | 20 | 1210.34 | 806.90 | 162.58 | 53890.52 | 0.022 | 1520 | 14.91 | 17 | 11.91 |
| Layer 7 | 9 | 1.5 | 5 | Clayey Silt Medium Grey | 4.75 | 3225 | 0.5 | 20 | 1112.07 | 741.38 | 155.71 | 49428.84 | 0.022 | 1520 | 14.91 | 17 | 11.41 |
| Layer 6 | 11 | 1.5 | 4 | Clayey Silt Medium Grey | 3.8 | 2940 | 0.5 | 20 | 1013.79 | 675.86 | 147.69 | 44467.74 | 0.023 | 1520 | 14.91 | 17 | 10.90 |
| Layer 5 | 12 | 1.5 | 6 | Clayey Silt Medium Grey | 5.7 | 3510 | 0.5 | 20 | 1210.34 | 806.90 | 162.58 | 53890.52 | 0.022 | 1520 | 14.91 | 17 | 11.91 |
| Layer 4 | 14 | 1.5 | 13 | Silty Sand Medium Dense to Dense Brown | 12.35 | 6837.5 | 0.4 | 18 | 2532.41 | 1688.27 | 219.31 | 88253.01 | 0.029 | 1368 | 13.42 | 31 | 29.80 |
| Layer 3 | 15 | 1.5 | 15 | Silty Sand Medium Dense to Dense Brown | 14.25 | 7312.5 | 0.4 | 18 | 2708.33 | 1805.56 | 225.84 | 93585.85 | 0.029 | 1368 | 13.42 | 31 | 30.81 |
| Layer 2 | 17 | 1.5 | 25 | Silty Sand Medium Dense to Dense Brown | 23.75 | 9687.5 | 0.4 | 18 | 3587.96 | 2391.98 | 250.77 | 115390.00 | 0.031 | 1368 | 13.42 | 31 | 35.47 |
| Layer 1 | 18 | 1.5 | 29 | Silty Sand Medium Dense to Dense Brown | 27.55 | 10637.5 | 0.4 | 18 | 3939.81 | 2626.54 | 258.52 | 122629.78 | 0.032 | 1368 | 13.42 | 31 | 37.16 |

## Results for Sub-Structure Model for Solid Mass vs. Lumped Linear Model (Linear Analysis)

## Results for 1DOF

**Table 5: Displacement results for 1DOF (Linear Analysis)**

| Layer | Depth (m) | Max/Min | Model Type | | | |
|---|---|---|---|---|---|---|
| | | | Solid Mass | | Lumped Mass | |
| | | | Joint No | Displacement (mm) | Joint No | Displacement (mm) |
| 1 | 1.5 | Min | 2 | -6.587 | 2 | -10.12 |
| | | Max | | 9.821 | | 9.755 |



Joint 2
Displacement UX

Min is -6.587e+00
at 1.300e+00
Max is 9.821e+00
at 1.100e+00

Joint 2
Displacement UX

Min is -1.012e+01
at 1.200e+00
Max is 9.755e+00
at 1.100e+00

Fig. 5: Displacement results for Solid Mass (Joint2) and Lumped Mass (Joint 2) (Linear analysis)

**Table 6: Time Periods for 1DOF**

| (a)Time Periods for 1DOF (Solid Mass) | | |
|---|---|---|
| **Step Type** | **Step Number** | **Period (Sec)** |
| Mode | 1 | 0.41713 |
| Mode | 2 | 0.36522 |
| Mode | 3 | 0.36522 |
| Mode | 4 | 0.31802 |

| **(a)Time Periods for 1DOF (Solid Mass)** | | |
|---|---|---|
| **Step Type** | **Step Number** | **Period (Sec)** |
| Mode | 5 | 0.29495 |
| Mode | 6 | 0.29157 |
| Mode | 7 | 0.29157 |
| Mode | 8 | 0.22653 |
| Mode | 9 | 0.22399 |
| Mode | 10 | 0.18612 |
| Mode | 11 | 0.18612 |
| Mode | 12 | 0.10571 |
| **(b) Time Periods for 1DOF (Lumped Mass)** | | |
| **Step Type** | **Step Number** | **Period** |
| | | **Sec** |
| Mode | 1 | 0.240074 |

**Results for 2DOF**

**Table 7: Displacement results for 2DOF (Linear Analysis)**

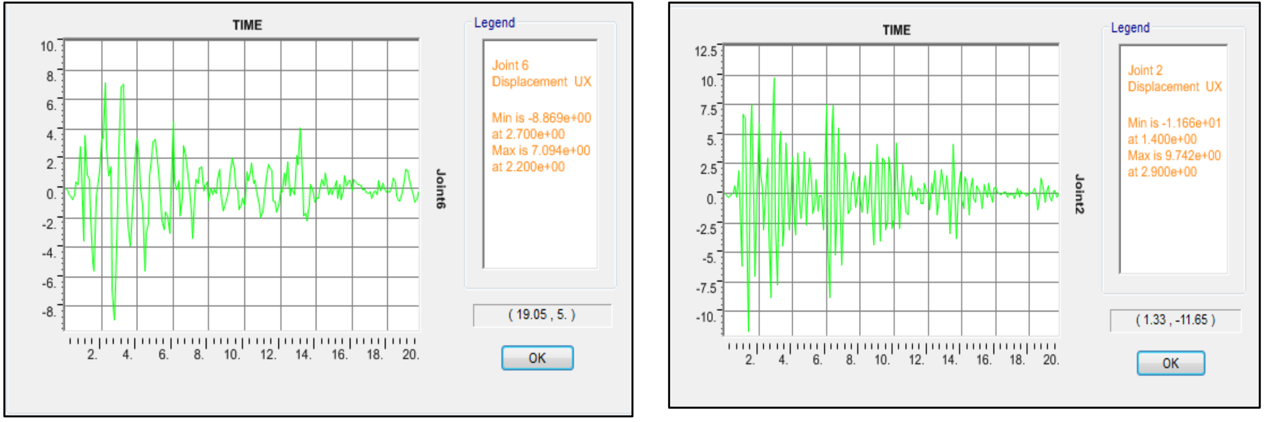
| **Layer** | **Depth (m)** | **Max/Min** | **Model Type** | | | |
|---|---|---|---|---|---|---|
| | | | **Solid Mass** | | **Lumped mass** | |
| | | | **Joint No** | **Displacement (mm)** | **Joint No** | **Displacement (mm)** |
| 1 | 3 | Min | 6 | -8.869 | 2 | -11.66 |
| | | Max | | 7.094 | | 9.742 |
| 2 | 6 | Min | 2 | -27.78 | 3 | -21.33 |
| | | Max | | 23.15 | | 21.26 |

Solid Mass Nodes No

Lumped Mass Nodes No

**Solid Mass (Joint 6)**

**Lump (Joint 2)**

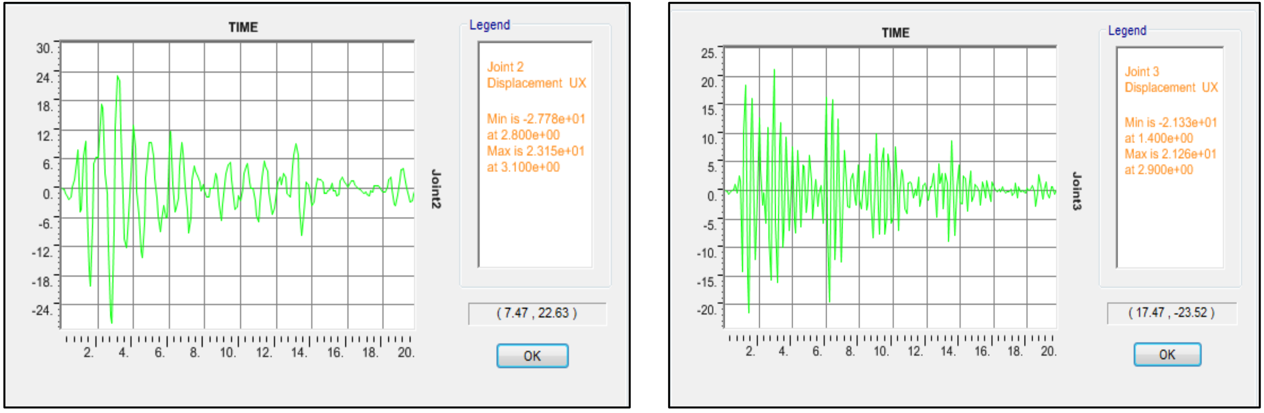


Joint 6
Displacement UX
Min is -8.869e+00
at 2.700e+00
Max is 7.094e+00
at 2.200e+00

Joint 2
Displacement UX
Min is -1.166e+01
at 1.400e+00
Max is 9.742e+00
at 2.900e+00

**Solid Mass (Joint 2)**

**Lump (Joint 3)**



Joint 2
Displacement UX
Min is -2.778e+01
at 2.800e+00
Max is 2.315e+01
at 3.100e+00

Joint 3
Displacement UX
Min is -2.133e+01
at 1.400e+00
Max is 2.126e+01
at 2.900e+00

**Fig. 6: Displacement results for Solid Mass (Joint6&2) and Lumped Mass (Joint 2&3) (Linear Analysis)**

**Table 8: Time Period for 2DOF (Linear Analysis)**

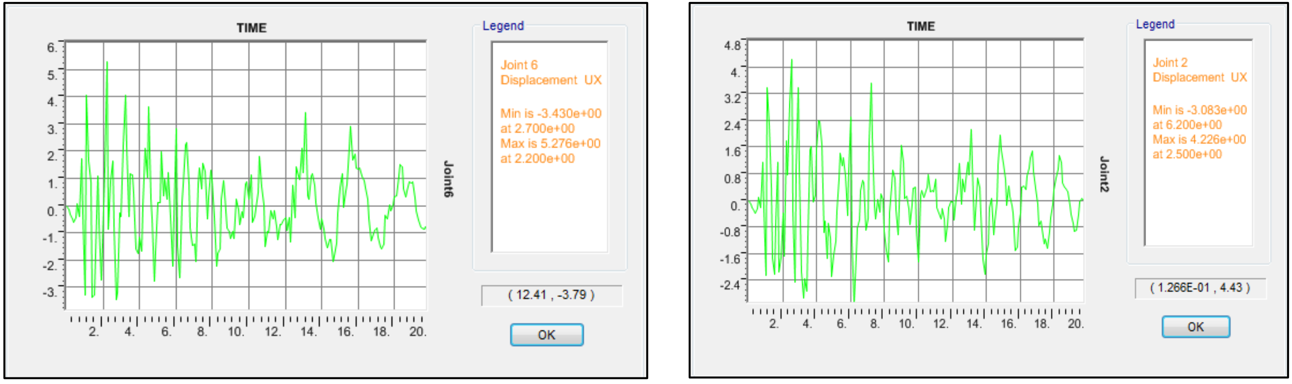
| **Time Periods for 2DOF (Solid Mass)** | | | | | |
|---|---|---|---|---|---|
| **Step Type** | **Step Number** | **Period (Sec)** | **Step Type** | **Step Number** | **Period (Sec)** |
| Mode | 1 | 0.883768 | Mode | 13 | 0.180628 |
| Mode | 2 | 0.883768 | Mode | 14 | 0.180628 |
| Mode | 3 | 0.654307 | Mode | 15 | 0.159313 |
| Mode | 4 | 0.336453 | Mode | 16 | 0.154248 |
| Mode | 5 | 0.296909 | Mode | 17 | 0.154248 |
| Mode | 6 | 0.296909 | Mode | 18 | 0.151640 |
| Mode | 7 | 0.263366 | Mode | 19 | 0.151640 |
| Mode | 8 | 0.238071 | Mode | 20 | 0.148895 |
| Mode | 9 | 0.223742 | Mode | 21 | 0.129137 |
| Mode | 10 | 0.223742 | Mode | 22 | 0.124224 |
| Mode | 11 | 0.204348 | Mode | 23 | 0.103646 |
| Mode | 12 | 0.184452 | Mode | 24 | 0.082281 |

**Table 9: Time Periods for 2DOF**

| **Time Periods for 2DOF (Solid Mass)** | | |
|---|---|---|
| **Step Type** | Mode | Mode |
| **Step Number** | 1 | 2 |
| **Period (Sec)** | 0.37769 | 0.19421 |

## Results for MDOF

### Solid Mass (Joint 6) vs. Lumped Mass (Joint 2)



### Solid Mass (Joint 10) vs. Lumped Mass (Joint 3)

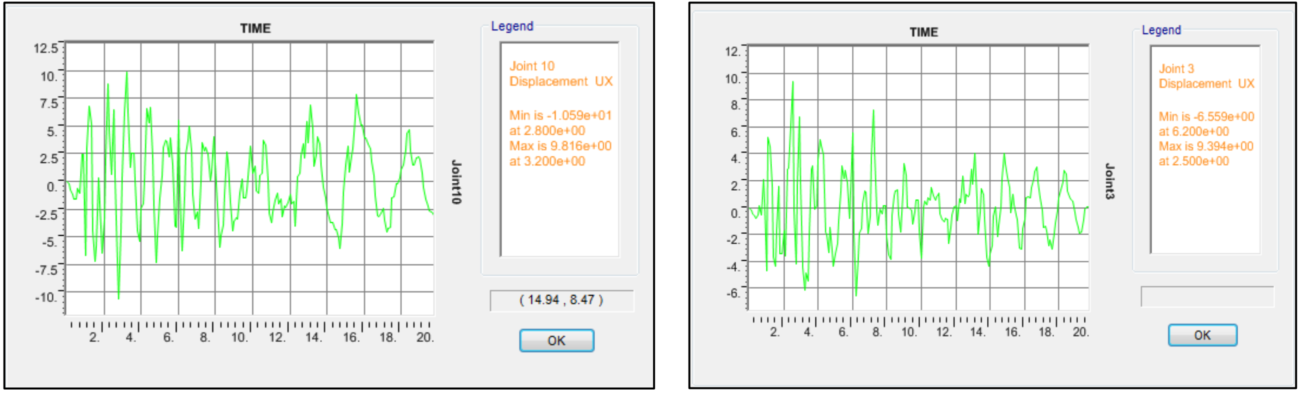
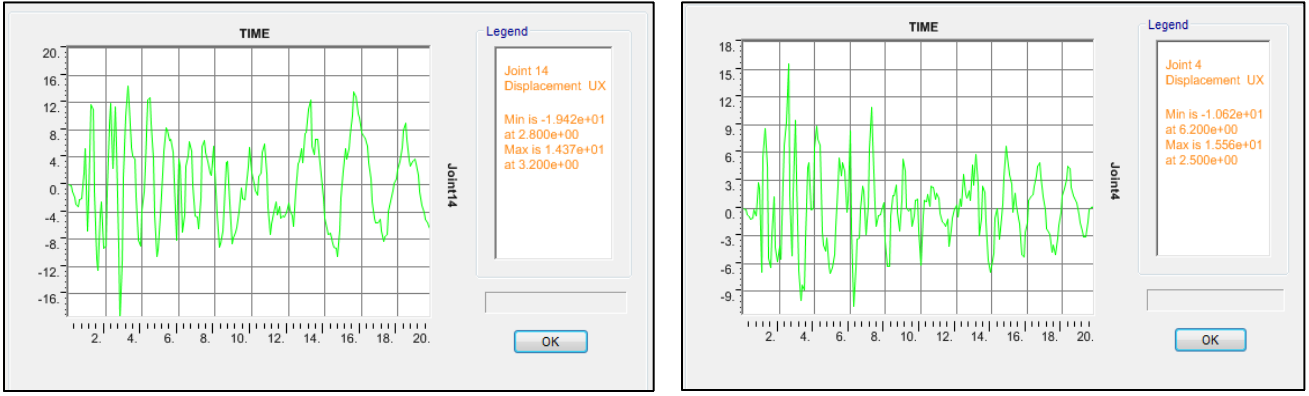


**Fig. 7: Displacement results for Solid Mass (Joint 6 & 10) and Lumped Mass (Joint 2 & 3) (Linear Analysis)**

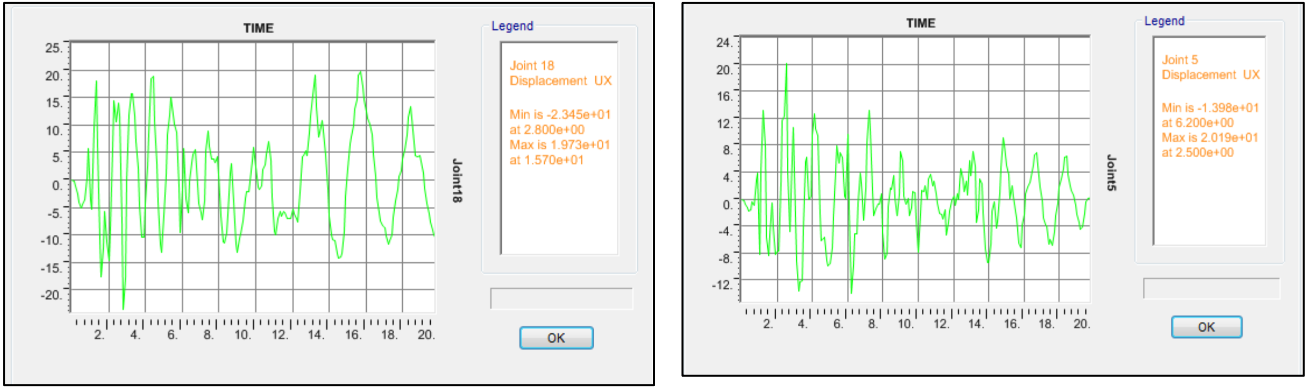
**Solid Mass (Joint 14) vs. Lumped Mass(Joint 4)**



Joint 14
Displacement UX
Min is -1.942e+01
at 2.800e+00
Max is 1.437e+01
at 3.200e+00

Joint 4
Displacement UX
Min is -1.062e+01
at 6.200e+00
Max is 1.556e+01
at 2.500e+00

**Solid Mass (Joint 18) vs. Lumped Mass (Joint 5)**

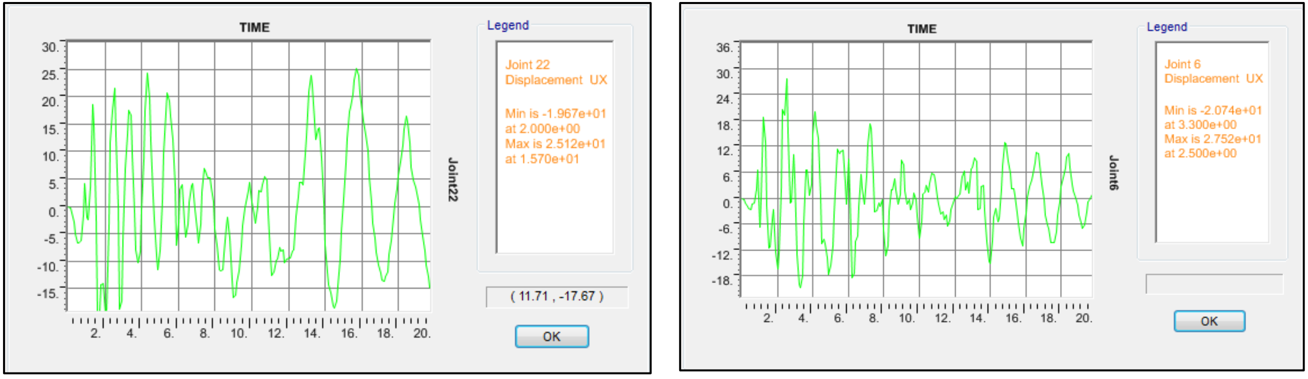


Joint 18
Displacement UX
Min is -2.345e+01
at 2.800e+00
Max is 1.973e+01
at 1.570e+01

Joint 5
Displacement UX
Min is -1.398e+01
at 6.200e+00
Max is 2.019e+01
at 2.500e+00

**Fig. 8: Displacement results for Solid Mass (Joint 14 & 18) and Lumped Mass (Joint 4 & 5) (Linear Analysis)**

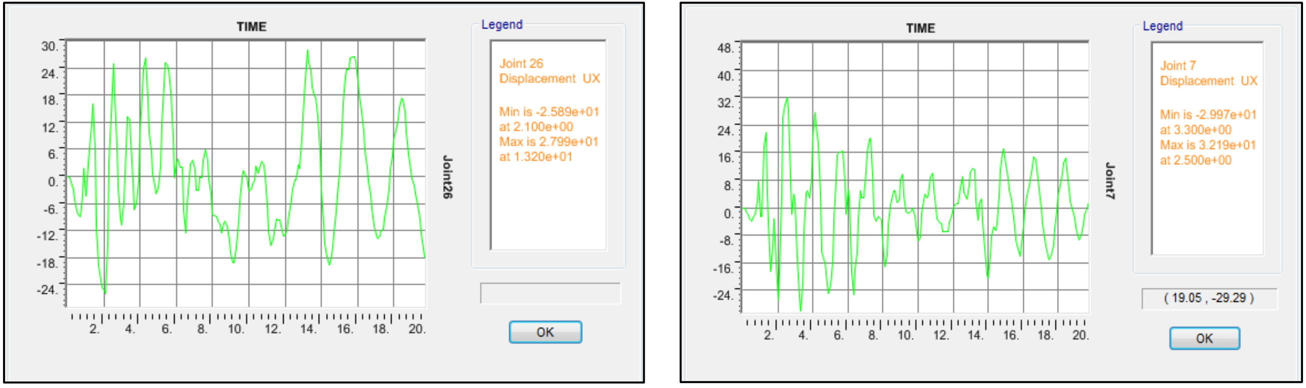
**Solid Mass (Joint 22) vs. Lumped Mass (Joint 6)**



Joint 22
Displacement UX
Min is -1.967e+01
at 2.000e+00
Max is 2.512e+01
at 1.570e+01

Joint 6
Displacement UX
Min is -2.074e+01
at 3.300e+00
Max is 2.752e+01
at 2.500e+00

**Solid Mass (Joint 26) vs. Lumped Mass(Joint 7)**

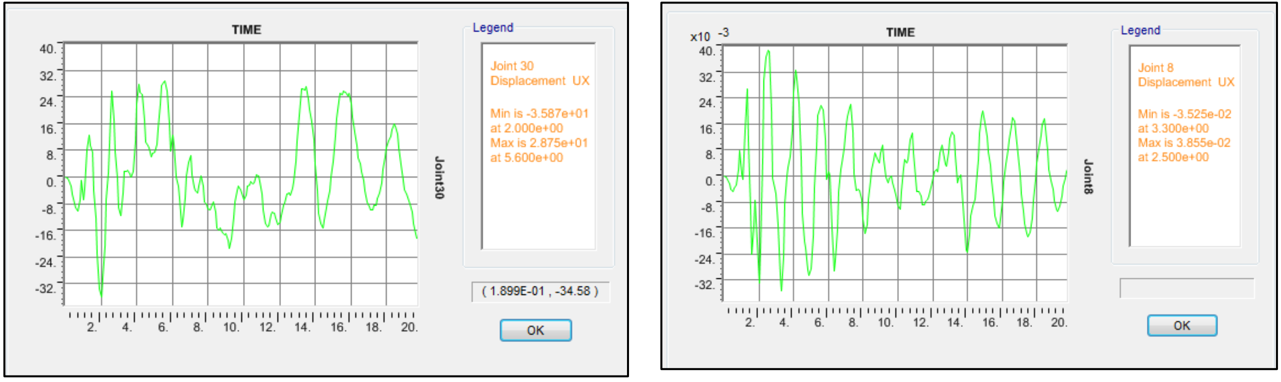


Joint 26
Displacement UX
Min is -2.589e+01
at 2.100e+00
Max is 2.799e+01
at 1.320e+01

Joint 7
Displacement UX
Min is -2.997e+01
at 3.300e+00
Max is 3.219e+01
at 2.500e+00

**Fig. 9: Displacement results for Solid Mass (Joint 22 & 26) and Lumped Mass (Joint 6 & 7) (Linear Analysis)**

**Solid Mass (Joint 30) vs. Lumped Mass (Joint 8)**

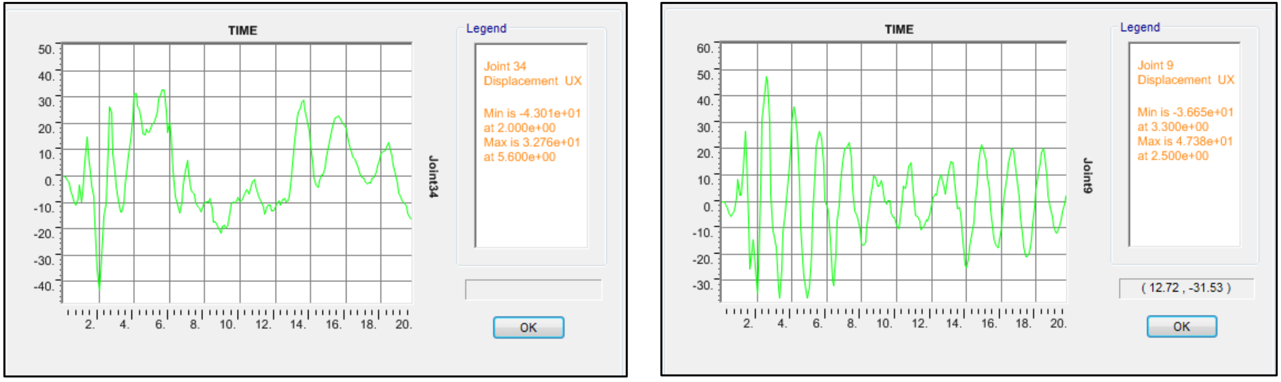


Joint 30
Displacement UX
Min is -3.587e+01
at 2.000e+00
Max is 2.875e+01
at 5.600e+00

( 1.899E-01 , -34.58 )

Joint 8
Displacement UX
Min is -3.525e-02
at 3.300e+00
Max is 3.855e-02
at 2.500e+00

**Solid Mass (Joint 34) vs. Lumped Mass (Joint 9)**



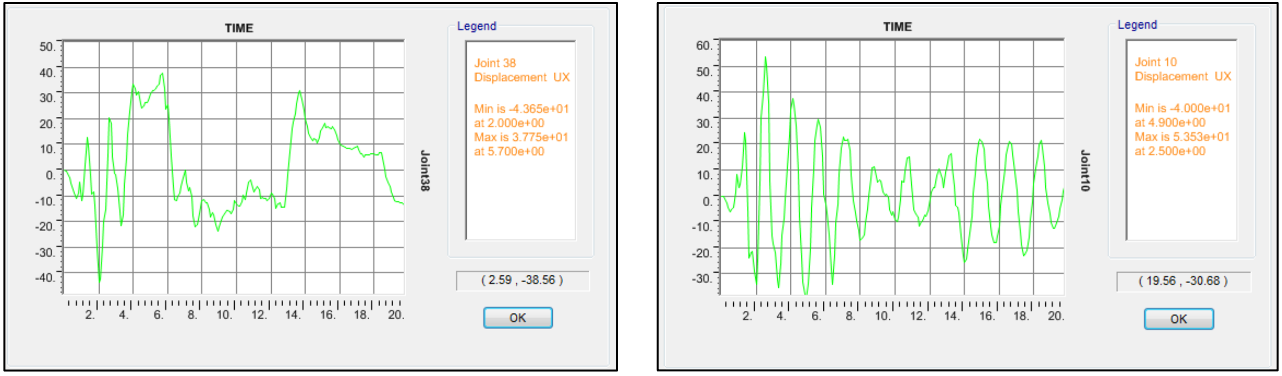
Joint 34
Displacement UX
Min is -4.301e+01
at 2.000e+00
Max is 3.276e+01
at 5.600e+00

Joint 9
Displacement UX
Min is -3.665e+01
at 3.300e+00
Max is 4.738e+01
at 2.500e+00

( 12.72 , -31.53 )

Fig. 10: Displacement results for Solid Mass (Joint 30 & 34) and Lumped Mass (Joint 8 & 9) (Linear Analysis)

**Solid Mass (Joint 38) vs. Lumped Mass(Joint 10)**



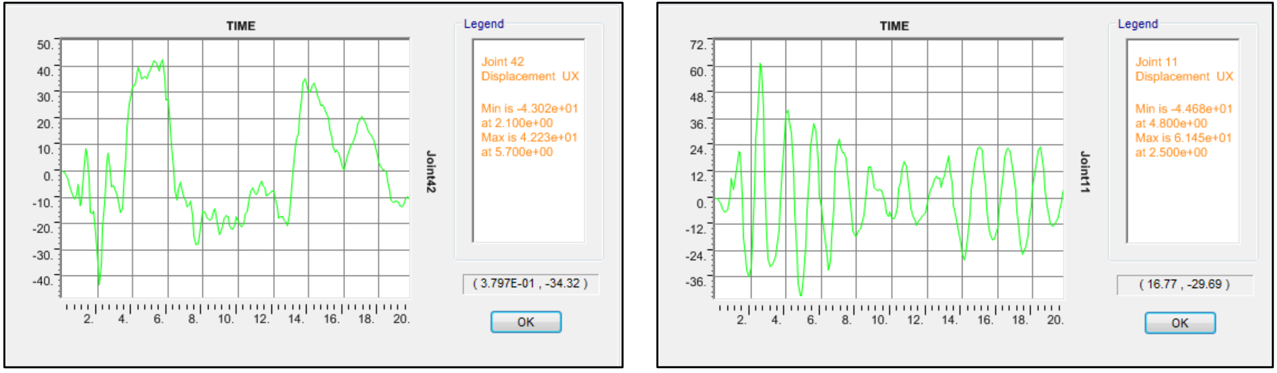
Joint 38
Displacement UX
Min is -4.365e+01
at 2.000e+00
Max is 3.775e+01
at 5.700e+00

( 2.59 , -38.56 )

Joint 10
Displacement UX
Min is -4.000e+01
at 4.900e+00
Max is 5.353e+01
at 2.500e+00

( 19.56 , -30.68 )

**Solid Mass (Joint 42) vs. Lumped Mass(Joint 11)**



Joint 42
Displacement UX
Min is -4.302e+01
at 2.100e+00
Max is 4.223e+01
at 5.700e+00

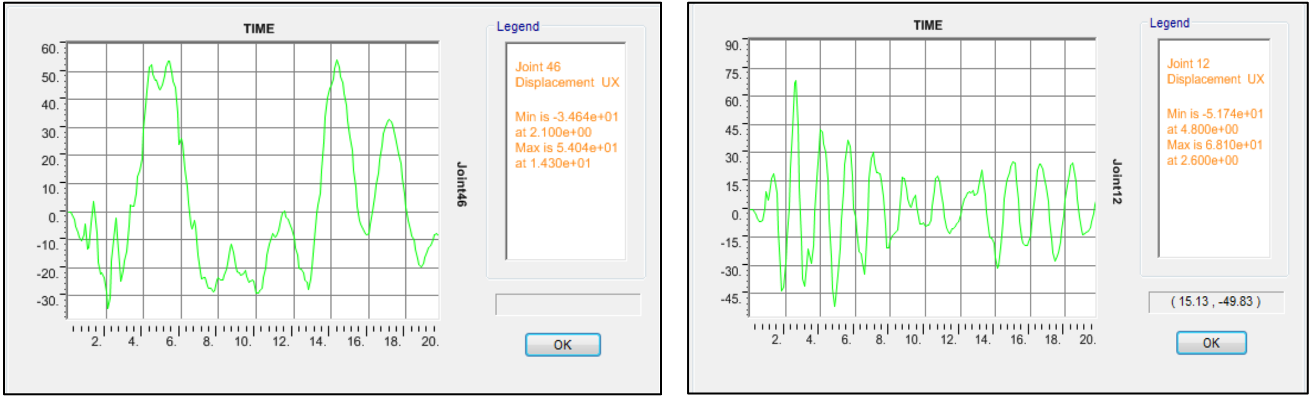
( 3.797E-01 , -34.32 )

Joint 11
Displacement UX
Min is -4.468e+01
at 4.800e+00
Max is 6.145e+01
at 2.500e+00

( 16.77 , -29.69 )

Fig. 11: Displacement results for Solid Mass (Joint 38 & 42) and Lumped Mass (Joint 10 & 11) (Linear Analysis)

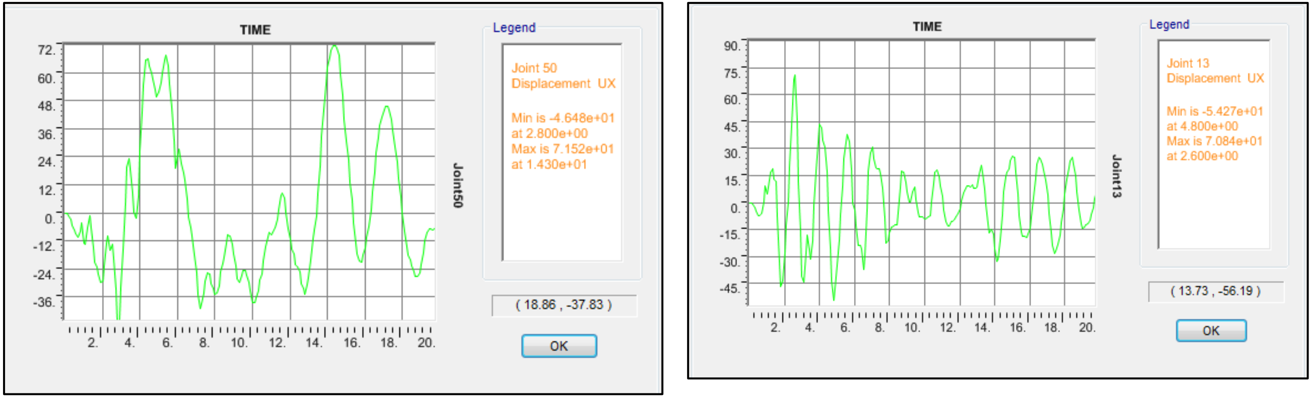
**Solid Mass (Joint 46) vs. Lumped Mass(Joint 12)**



Joint 46
Displacement UX
Min is -3.464e+01
at 2.100e+00
Max is 5.404e+01
at 1.430e+01

Joint 12
Displacement UX
Min is -5.174e+01
at 4.800e+00
Max is 6.810e+01
at 2.600e+00

**Solid Mass (Joint 50) vs. Lumped Mass (Joint 13)**



Joint 50
Displacement UX
Min is -4.648e+01
at 2.800e+00
Max is 7.152e+01
at 1.430e+01

Joint 13
Displacement UX
Min is -5.427e+01
at 4.800e+00
Max is 7.084e+01
at 2.600e+00

**Fig. 12: Displacement results for Solid Mass (Joint 46&50) and Lumped Mass (Joint 12&13) (Linear Analysis)**

**Table 10: Displacement Results vs. Time (Linear Analysis)**

| Layer | Depth m | Layer Thickness m | Maximum/ Minimum value in m | Model Type | | | |
|---|---|---|---|---|---|---|---|
| | | | | Solid Mass Linear Model | | Lump Mass Linear Model | |
| | | | | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) |
| 1 | 18 | 1.5 | Minimum | 6 | -3.43 | 2 | -3.083 |
| | | | Maximum | | 5.276 | | 4.226 |
| 2 | 16.5 | 2.5 | Minimum | 10 | -10.59 | 3 | -6.559 |
| | | | Maximum | | 9.816 | | 9.394 |
| 3 | 15 | 3.5 | Minimum | 14 | -19.42 | 4 | -10.62 |
| | | | Maximum | | 14.37 | | 15.56 |
| 4 | 13.5 | 4.5 | Minimum | 18 | -23.45 | 5 | -13.98 |
| | | | Maximum | | 19.73 | | 20.19 |
| 5 | 12 | 5.5 | Minimum | 22 | -19.67 | 6 | -20.74 |
| | | | Maximum | | 25.12 | | 27.52 |
| 6 | 10.5 | 6.5 | Minimum | 26 | -25.89 | 7 | -29.97 |
| | | | Maximum | | 27.99 | | 32.19 |
| 7 | 9 | 7.5 | Minimum | 30 | -35.87 | 8 | -35.25 |
| | | | Maximum | | 28.75 | | 38.55 |
| 8 | 7.5 | 8.5 | Minimum | 34 | -43.01 | 9 | -36.65 |
| | | | Maximum | | 32.76 | | 47.38 |
| 9 | 6 | 9.5 | Minimum | 38 | -43.65 | 10 | -40 |
| | | | Maximum | | 37.75 | | 53.53 |
| 10 | 4.5 | 10.5 | Minimum | 42 | -43.02 | 11 | -44.68 |
| | | | Maximum | | 42.23 | | 61.45 |
| 11 | 3 | 11.5 | Minimum | 46 | -34.64 | 12 | -51.74 |
| | | | Maximum | | 54.04 | | 68.1 |
| 12 | 1.5 | 12.5 | Minimum | 50 | -46.48 | 13 | -54.27 |
| | | | Maximum | | 71.52 | | 70.84 |

### Table 11: Time Period and Frequency results for MDOF (Linear Analysis)

| Time Period for MDOF (Solid Mass) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Step Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **Period (Sec)** | 11.822 | 11.822 | 4.127 | 2.556 | 2.556 | 1.408 | 1.408 | 1.100 | 1.100 | 0.939 | 0.679 | 0.679 | 0.678 | 0.528 | 0.505 | 0.494 | 0.488 | 0.488 | 0.470 |
| **Step Number** | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
| **Period (Sec)** | 0.460 | 0.448 | 0.428 | 0.397 | 0.397 | 0.396 | 0.396 | 0.381 | 0.381 | 0.367 | 0.365 | 0.364 | 0.364 | 0.358 | 0.357 | 0.357 | 0.354 | 0.354 | 0.348 |
| **Step Number** | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 |
| **Period (Sec)** | 0.347 | 0.347 | 0.339 | 0.339 | 0.336 | 0.332 | 0.324 | 0.320 | 0.319 | 0.319 | 0.312 | 0.312 | 0.310 | 0.307 | 0.303 | 0.303 | 0.300 | 0.297 | 0.292 |
| **Step Number** | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 |
| **Period (Sec)** | 0.287 | 0.287 | 0.286 | 0.286 | 0.279 | 0.279 | 0.278 | 0.278 | 0.271 | 0.265 | 0.263 | 0.263 | 0.262 | 0.262 | 0.261 | 0.259 | 0.259 | 0.256 | 0.253 |
| **Step Number** | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 |
| **Period (Sec)** | 0.253 | 0.252 | 0.250 | 0.242 | 0.237 | 0.237 | 0.236 | 0.235 | 0.235 | 0.233 | 0.226 | 0.225 | 0.225 | 0.224 | 0.224 | 0.214 | 0.212 | 0.212 | 0.211 |
| **Step Number** | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 | 114 |
| **Period (Sec)** | 0.209 | 0.209 | 0.209 | 0.202 | 0.202 | 0.201 | 0.195 | 0.195 | 0.188 | 0.188 | 0.186 | 0.186 | 0.186 | 0.181 | 0.180 | 0.180 | 0.177 | 0.177 | 0.171 |
| **Step Number** | 115 | 116 | 117 | 118 | 119 | 120 | 121 | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | 130 | 131 | 132 | 133 |
| **Period (Sec)** | 0.169 | 0.169 | 0.167 | 0.166 | 0.166 | 0.165 | 0.165 | 0.163 | 0.154 | 0.144 | 0.143 | 0.143 | 0.140 | 0.140 | 0.116 | 0.116 | 0.114 | 0.114 | 0.096 |

| **Step Number** | 134 | 135 | 136 | 137 | 138 | 139 | 140 | 141 | 142 | 143 | 144 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Period (Sec)** | 0.093 | 0.092 | 0.087 | 0.083 | 0.078 | 0.073 | 0.071 | 0.066 | 0.062 | 0.057 | 0.055 |

| Time Period for MDOF (Lumped Mass) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Step Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Period (Sec)** | 1.767 | 0.602 | 0.395 | 0.282 | 0.222 | 0.191 | 0.163 | 0.154 | 0.144 | 0.134 | 0.105 | 0.085 |

**Results for Sub-Structure Lumped Mass (Nonlinear Analysis):**

**Table 12: Load vs. Displacement for Series 1 & 2**

| **Series 1** | | | **Series 2** | | |
|---|---|---|---|---|---|
| **Displacement, mm** | **Force, kN** | **Stiffness, kN/m** | **Displacement, mm** | **Force, kN** | **Stiffness, kN/m** |
| -70 | -10 | 142.86 | -70 | -20 | 285.71 |
| -68 | -10 | 147.06 | -68 | -20 | 294.12 |
| -61 | -10 | 163.93 | -61 | -20 | 327.87 |
| -53 | -10 | 188.68 | -53 | -20 | 377.36 |
| -47 | -10 | 212.77 | -47 | -20 | 425.53 |
| -38 | -10 | 263.16 | -38 | -20 | 526.32 |
| -32 | -10 | 312.50 | -32 | -20 | 625.00 |
| -27 | -10 | 370.37 | -27 | -20 | 740.74 |
| -20 | -10 | 500.00 | -20 | -20 | 1000.00 |
| -15 | -10 | 666.67 | -15 | -20 | 1333.33 |
| -10 | -10 | 1000.00 | -12 | -20 | 1666.67 |
| -5 | -10 | 2000.00 | -10 | -20 | 2000.00 |
| 0 | 0 | 0.00 | 0 | 0 | 0.00 |
| 5 | 10 | 2000.00 | 10 | 20 | 2000.00 |
| 10 | 10 | 1000.00 | 12 | 20 | 1666.67 |
| 15 | 10 | 666.67 | 15 | 20 | 1333.33 |
| 20 | 10 | 500.00 | 20 | 20 | 1000.00 |
| 27 | 10 | 370.37 | 27 | 20 | 740.74 |
| 32 | 10 | 312.50 | 32 | 20 | 625.00 |
| 38 | 10 | 263.16 | 38 | 20 | 526.32 |
| 47 | 10 | 212.77 | 47 | 20 | 425.53 |
| 53 | 10 | 188.68 | 53 | 20 | 377.36 |
| 61 | 10 | 163.93 | 61 | 20 | 327.87 |
| 68 | 10 | 147.06 | 68 | 20 | 294.12 |
| 70 | 10 | 142.86 | 70 | 20 | 285.71 |

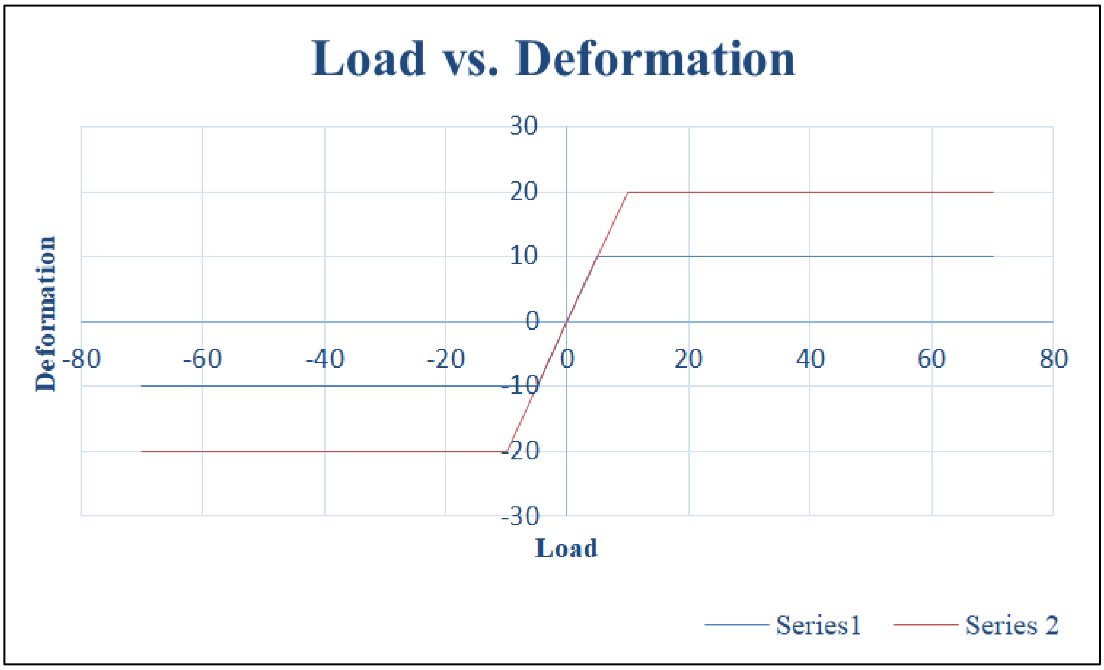
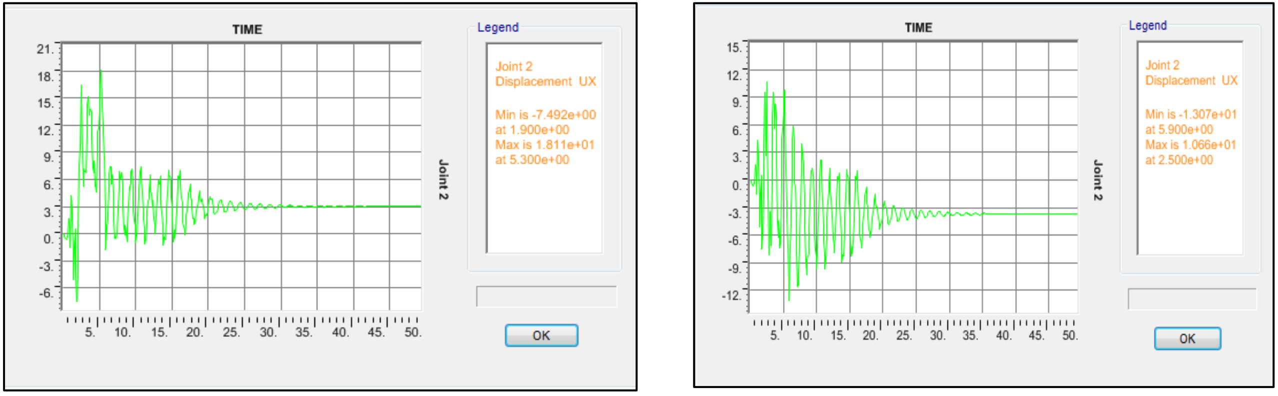


**Fig. 13: Load vs. Deformation curve for Series 1 & 2**

Series 1 (Joint 2) Series 2 (Joint 2)



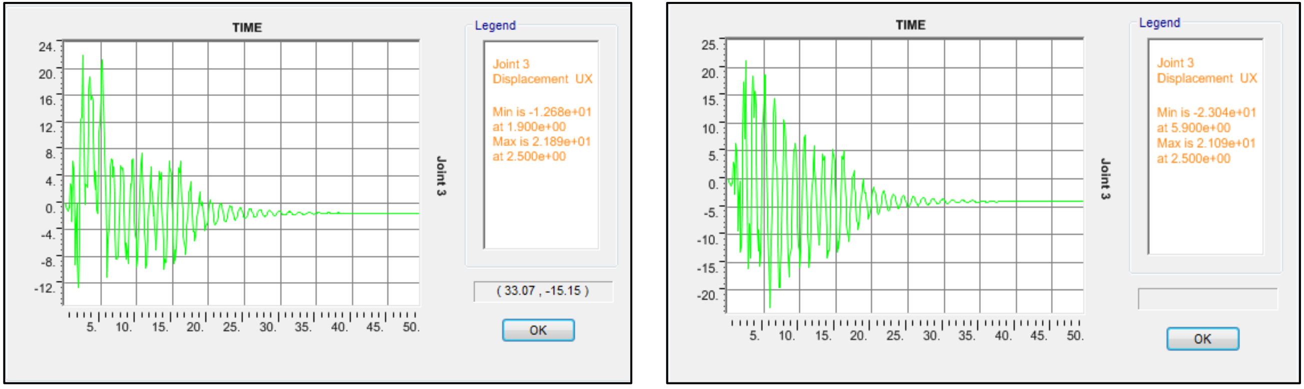
Joint 2
Displacement UX

Min is -7.492e+00
at 1.900e+00
Max is 1.811e+01
at 5.300e+00

Joint 2
Displacement UX

Min is -1.307e+01
at 5.900e+00
Max is 1.066e+01
at 2.500e+00

Series 1 (Joint 3) Series 2 (Joint 3)



Joint 3
Displacement UX

Min is -1.268e+01
at 1.900e+00
Max is 2.189e+01
at 2.500e+00

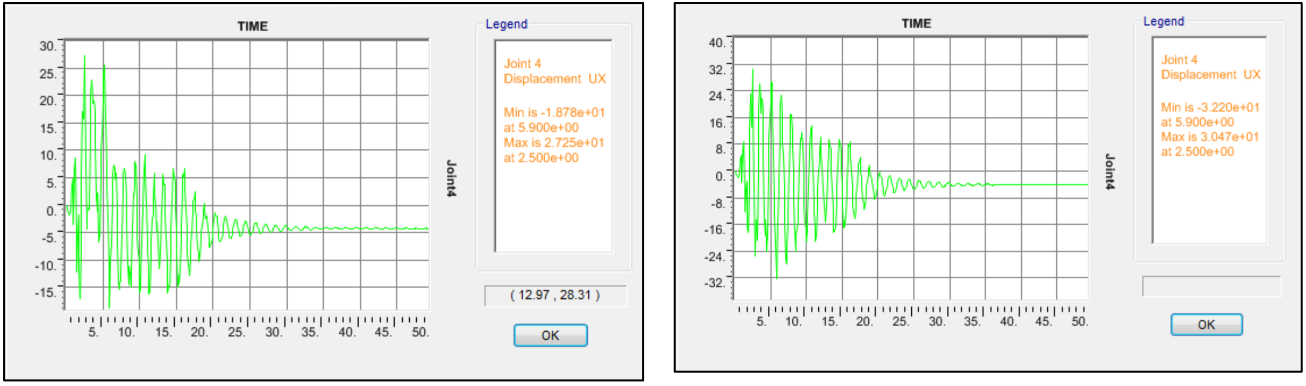
( 33.07 , -15.15 )

Joint 3
Displacement UX

Min is -2.304e+01
at 5.900e+00
Max is 2.109e+01
at 2.500e+00

Fig. 14: Displacement vs. Time for Joint 1 & 2 (Nonlinear Analysis - Series 1 & 2)

Series 1 (Joint 4) Series 2 (Joint 4)



Joint 4
Displacement UX

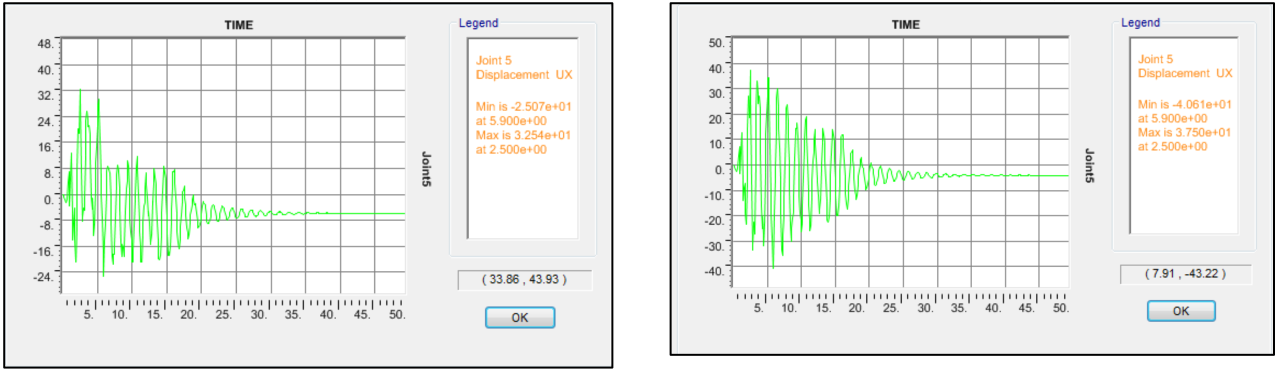
Min is -1.878e+01
at 5.900e+00
Max is 2.725e+01
at 2.500e+00

( 12.97 , 28.31 )

Joint 4
Displacement UX

Min is -3.220e+01
at 5.900e+00
Max is 3.047e+01
at 2.500e+00

Series 1 (Joint 5) Series 2 (Joint 5)



Joint 5
Displacement UX

Min is -2.507e+01
at 5.900e+00
Max is 3.254e+01
at 2.500e+00

( 33.86 , 43.93 )

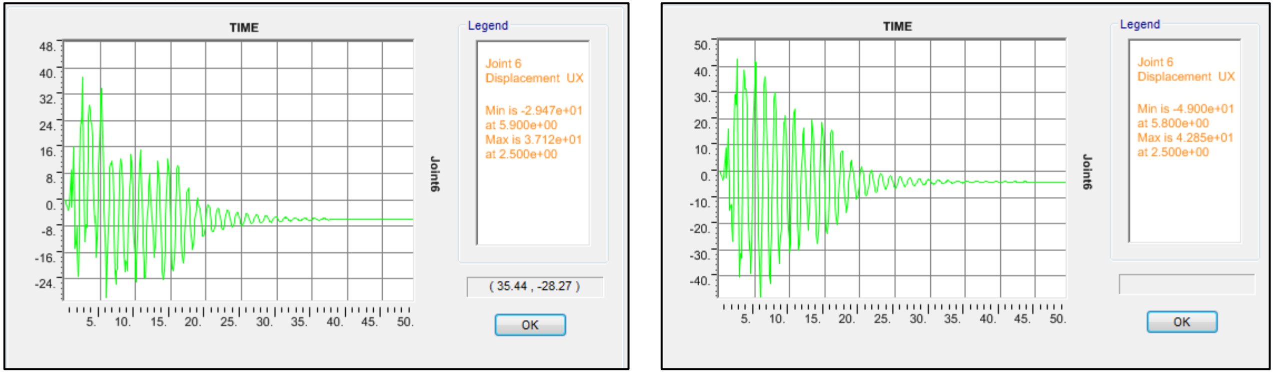
Joint 5
Displacement UX

Min is -4.061e+01
at 5.900e+00
Max is 3.750e+01
at 2.500e+00

( 7.91 , -43.22 )

Fig. 15: Displacement vs. Time for Joint 4 & 5 (Nonlinear Analysis - Series 1 & 2)

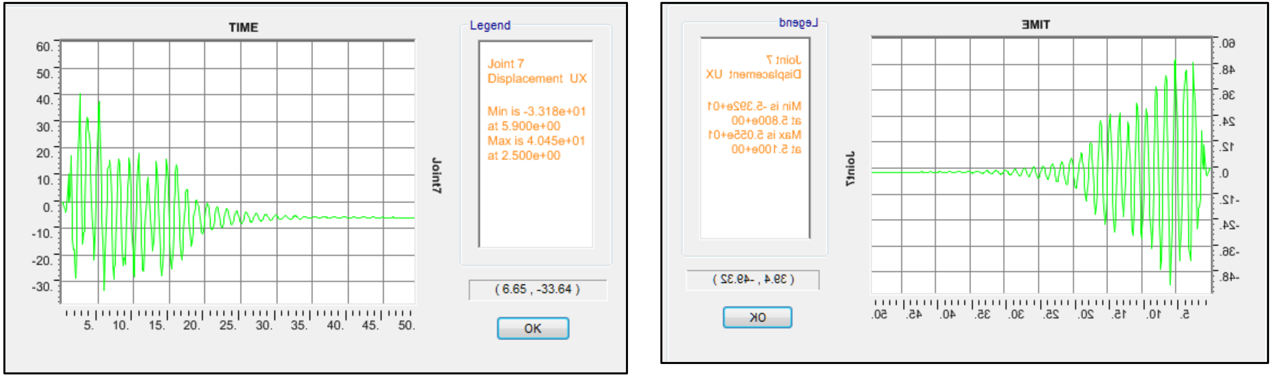
Series 1 (Joint 6) Series 2 (Joint 6)



Joint 6
Displacement UX
Min is -2.947e+01
at 5.900e+00
Max is 3.712e+01
at 2.500e+00
( 35.44 , -28.27 )

Joint 6
Displacement UX
Min is -4.900e+01
at 5.800e+00
Max is 4.285e+01
at 2.500e+00

Series 1 (Joint 7) Series 2 (Joint 7)

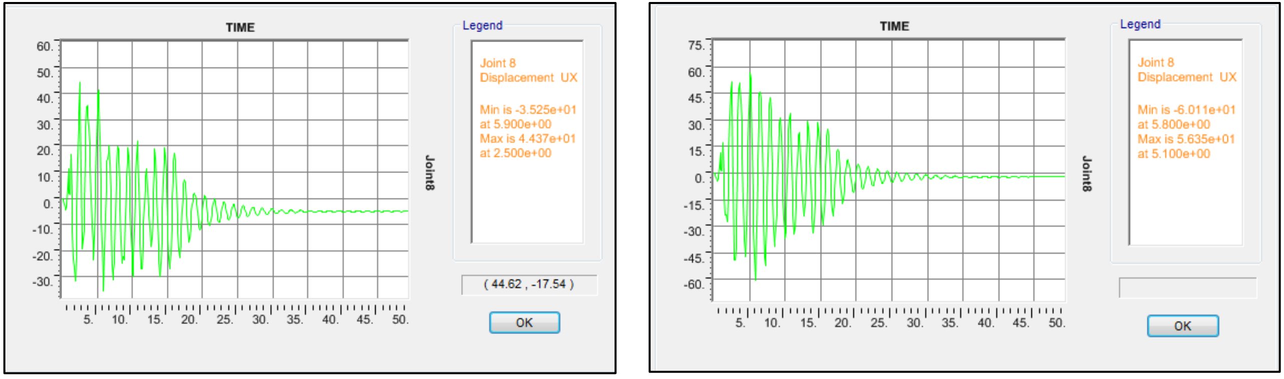


Joint 7
Displacement UX
Min is -3.318e+01
at 5.900e+00
Max is 4.045e+01
at 2.500e+00
( 6.65 , -33.64 )

Joint 7
Displacement UX
Min is -5.392e+01
at 5.800e+00
Max is 5.055e+01
at 5.100e+00
( 39.4 , -49.32 )

Fig. 16: Displacement vs. time for joint 6 & 7 (Nonlinear Analysis - Series 1 & 2)

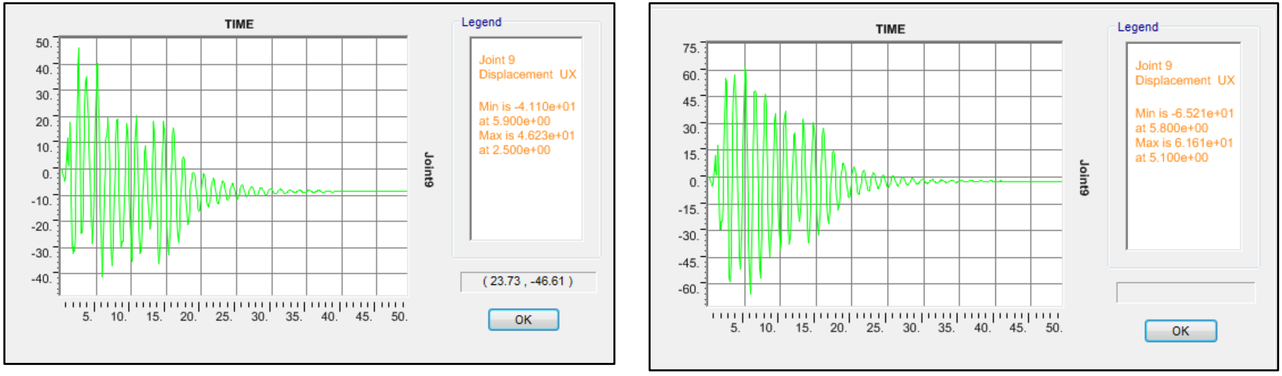
Series 1 (Joint 8) Series 2 (Joint 8)



Joint 8
Displacement UX
Min is -3.525e+01
at 5.900e+00
Max is 4.437e+01
at 2.500e+00
( 44.62 , -17.54 )

Joint 8
Displacement UX
Min is -6.011e+01
at 5.800e+00
Max is 5.635e+01
at 5.100e+00

Series 1 (Joint 9) Series 2 (Joint 9)

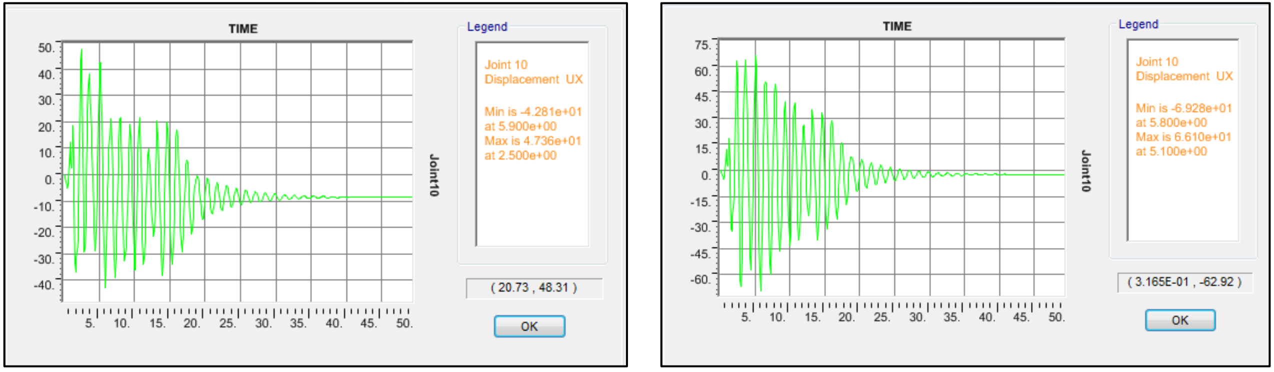


Joint 9
Displacement UX
Min is -4.110e+01
at 5.900e+00
Max is 4.623e+01
at 2.500e+00
( 23.73 , -46.61 )

Joint 9
Displacement UX
Min is -6.521e+01
at 5.800e+00
Max is 6.161e+01
at 5.100e+00

Fig. 17: Displacement vs. Time for Joint 8 & 9 (Nonlinear Analysis - Series 1 & 2)

Series 1 (Joint 10) Series 2 (Joint 10)



Series 1 (Joint 11) Series 2 (Joint 11)

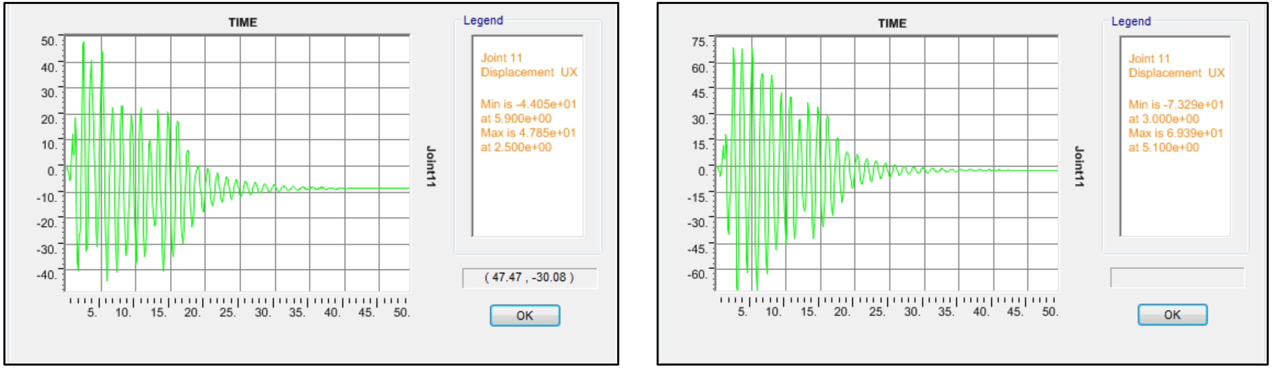
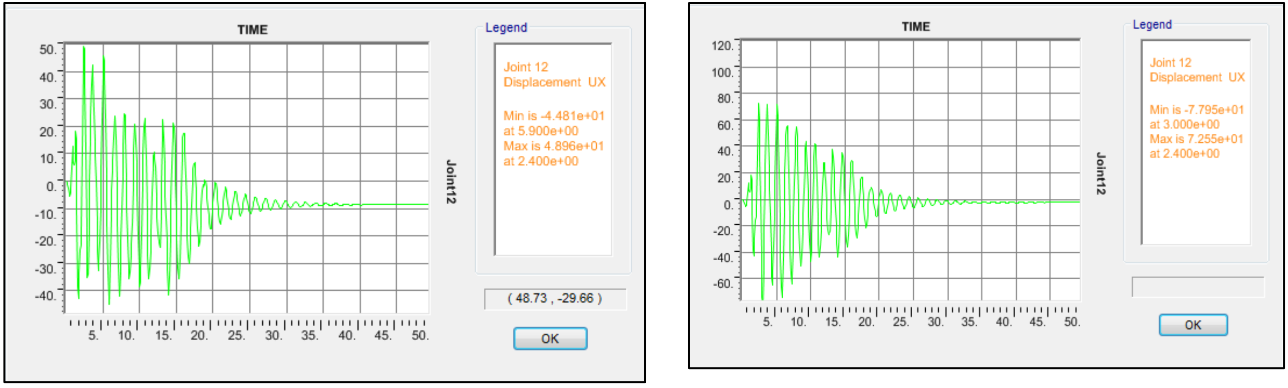


Fig. 19: Displacement vs. Time for Joint 10 & 11 (Nonlinear Analysis - Series 1 & 2)

Series 1 (Joint 12) Series 2 (Joint 12)



Series 1 (Joint 13) Series 2 (Joint 13)

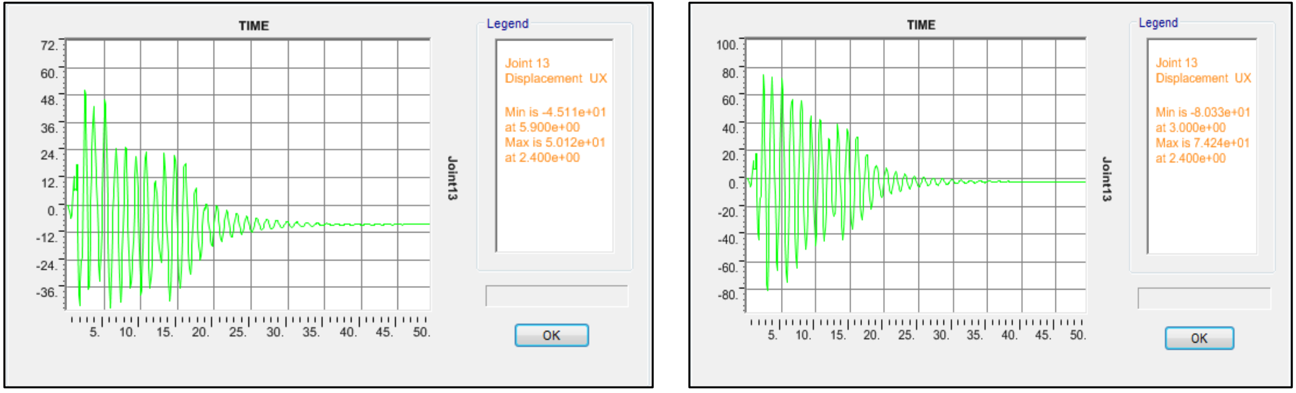
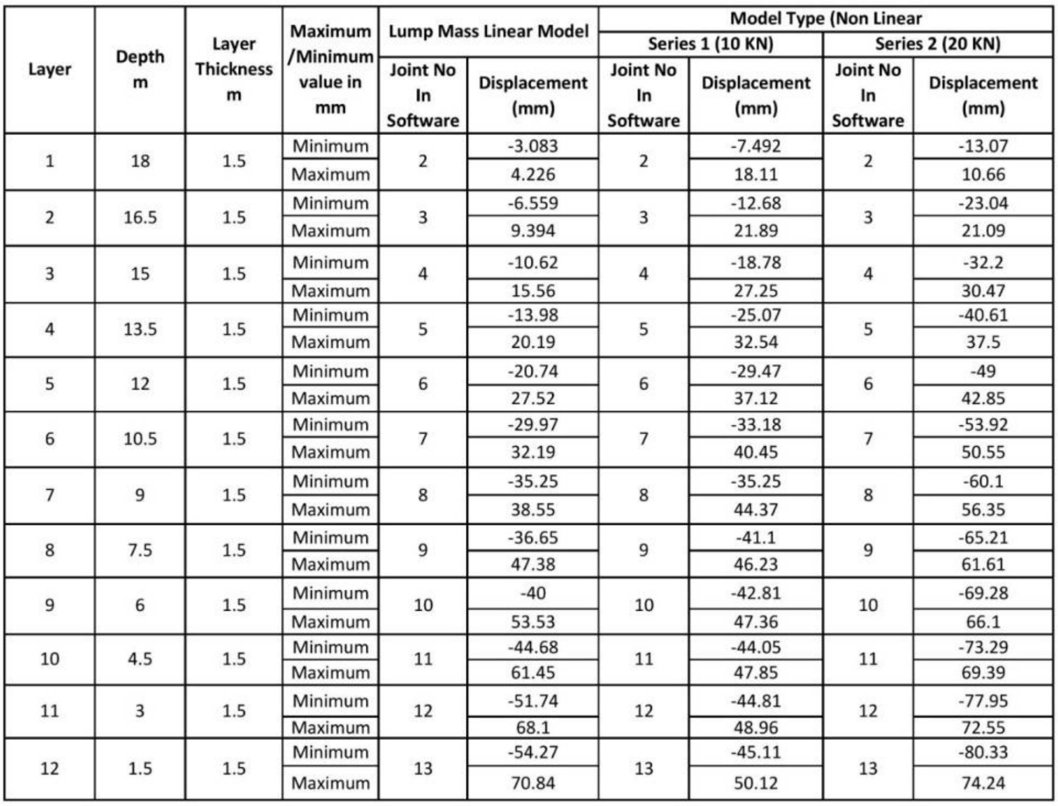


Fig. 20: Displacement vs. Time for Joint 12 & 13 (Nonlinear Analysis - Series 1 & 2)

**Table 13: Displacement Results vs. Time for Series 1 & 2 (Nonlinear Analysis)**



| Layer | Depth m | Layer Thickness m | Maximum /Minimum value in mm | Lump Mass Linear Model | | Model Type (Non Linear | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Series 1 (10 KN) | | Series 2 (20 KN) | |
| | | | | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) |
| 1 | 18 | 1.5 | Minimum | 2 | -3.083 | 2 | -7.492 | 2 | -13.07 |
| | | | Maximum | | 4.226 | | 18.11 | | 10.66 |
| 2 | 16.5 | 1.5 | Minimum | 3 | -6.559 | 3 | -12.68 | 3 | -23.04 |
| | | | Maximum | | 9.394 | | 21.89 | | 21.09 |
| 3 | 15 | 1.5 | Minimum | 4 | -10.62 | 4 | -18.78 | 4 | -32.2 |
| | | | Maximum | | 15.56 | | 27.25 | | 30.47 |
| 4 | 13.5 | 1.5 | Minimum | 5 | -13.98 | 5 | -25.07 | 5 | -40.61 |
| | | | Maximum | | 20.19 | | 32.54 | | 37.5 |
| 5 | 12 | 1.5 | Minimum | 6 | -20.74 | 6 | -29.47 | 6 | -49 |
| | | | Maximum | | 27.52 | | 37.12 | | 42.85 |
| 6 | 10.5 | 1.5 | Minimum | 7 | -29.97 | 7 | -33.18 | 7 | -53.92 |
| | | | Maximum | | 32.19 | | 40.45 | | 50.55 |
| 7 | 9 | 1.5 | Minimum | 8 | -35.25 | 8 | -35.25 | 8 | -60.1 |
| | | | Maximum | | 38.55 | | 44.37 | | 56.35 |
| 8 | 7.5 | 1.5 | Minimum | 9 | -36.65 | 9 | -41.1 | 9 | -65.21 |
| | | | Maximum | | 47.38 | | 46.23 | | 61.61 |
| 9 | 6 | 1.5 | Minimum | 10 | -40 | 10 | -42.81 | 10 | -69.28 |
| | | | Maximum | | 53.53 | | 47.36 | | 66.1 |
| 10 | 4.5 | 1.5 | Minimum | 11 | -44.68 | 11 | -44.05 | 11 | -73.29 |
| | | | Maximum | | 61.45 | | 47.85 | | 69.39 |
| 11 | 3 | 1.5 | Minimum | 12 | -51.74 | 12 | -44.81 | 12 | -77.95 |
| | | | Maximum | | 68.1 | | 48.96 | | 72.55 |
| 12 | 1.5 | 1.5 | Minimum | 13 | -54.27 | 13 | -45.11 | 13 | -80.33 |
| | | | Maximum | | 70.84 | | 50.12 | | 74.24 |

**Table 14: Load vs. Displacement for Series 3 and 4**

| Series 3 | | |
|---|---|---|
| Displacement, mm | Force, kN | Stiffness, kN/m |
| -70 | -30 | 428.57 |
| -68 | -30 | 441.18 |
| -61 | -30 | 491.80 |
| -53 | -30 | 566.04 |
| -47 | -30 | 638.30 |
| -38 | -30 | 789.47 |
| -32 | -30 | 937.50 |
| -27 | -30 | 1111.11 |
| -20 | -30 | 1500.00 |
| -15 | -30 | 2000.00 |
| -12 | -30 | 2500.00 |
| -10 | -30 | 3000.00 |
| 0 | 0 | 0.00 |
| 10 | 30 | 3000.00 |
| 12 | 30 | 2500.00 |
| 15 | 30 | 2000.00 |
| 20 | 30 | 1500.00 |
| 27 | 30 | 1111.11 |
| 32 | 30 | 937.50 |
| 38 | 30 | 789.47 |
| 47 | 30 | 638.30 |
| 53 | 30 | 566.04 |
| 61 | 30 | 491.80 |
| 68 | 30 | 441.18 |
| 70 | 30 | 428.57 |

| Series 4 | | |
|---|---|---|
| Displacement, mm | Force, kN | Stiffness, kN/m |
| -70 | -40 | 571.43 |
| -68 | -40 | 588.24 |
| -61 | -40 | 655.74 |
| -53 | -40 | 754.72 |
| -47 | -40 | 851.06 |
| -38 | -40 | 1052.63 |
| -32 | -40 | 1250.00 |
| -27 | -40 | 1481.48 |
| -20 | -40 | 2000.00 |
| -15 | -40 | 2666.67 |
| -12 | -40 | 3333.33 |
| -10 | -40 | 4000.00 |
| 0 | 0 | 0.00 |
| 10 | 40 | 4000.00 |
| 12 | 40 | 3333.33 |
| 15 | 40 | 2666.67 |
| 20 | 40 | 2000.00 |
| 27 | 40 | 1481.48 |
| 32 | 40 | 1250.00 |
| 38 | 40 | 1052.63 |
| 47 | 40 | 851.06 |
| 53 | 40 | 754.72 |
| 61 | 40 | 655.74 |
| 68 | 40 | 588.24 |
| 70 | 40 | 571.43 |

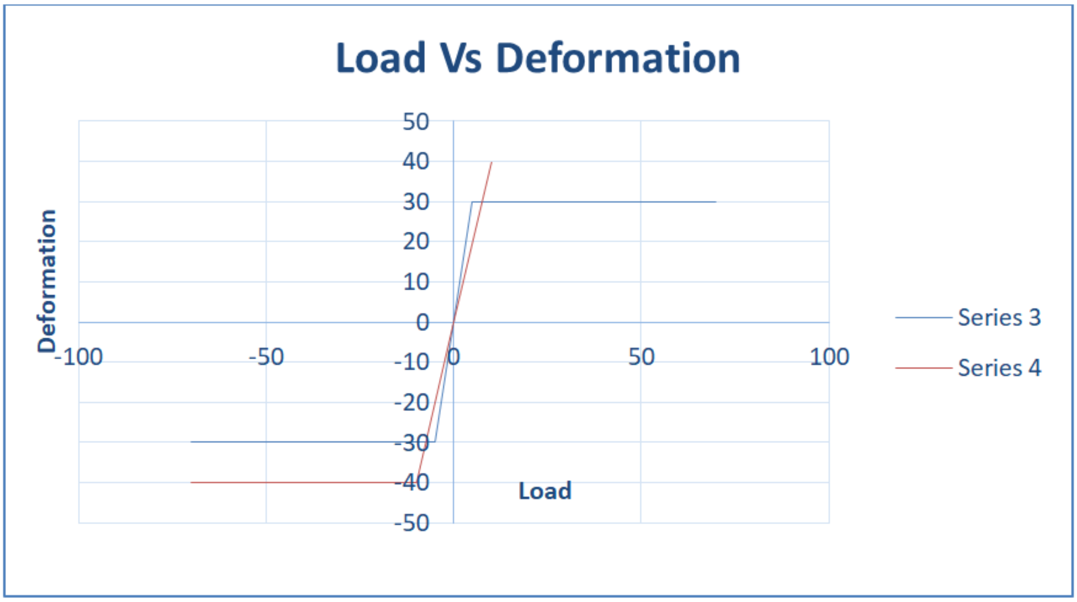
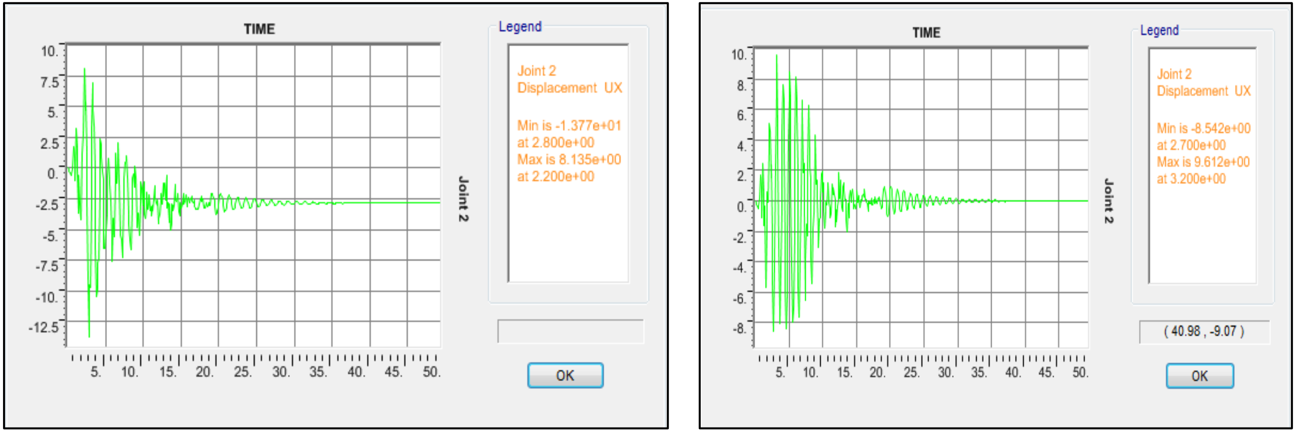


Fig. 21: Load vs. Deformation curve for Series 3 and 4

Series 3 (Joint 2)                Series 4 (Joint 2)



Joint 2
Displacement UX

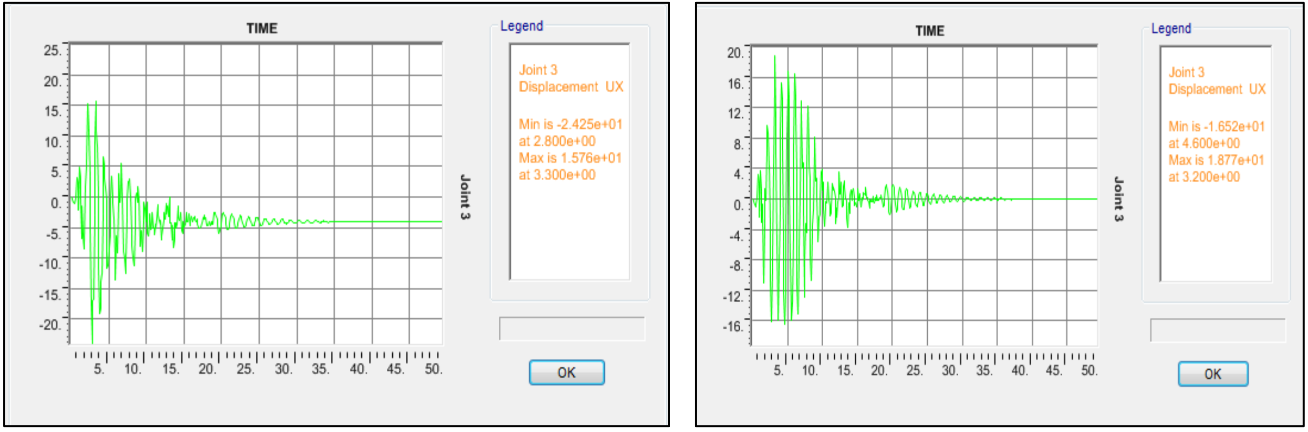
Min is -1.377e+01
at 2.800e+00
Max is 8.135e+00
at 2.200e+00

Joint 2
Displacement UX

Min is -8.542e+00
at 2.700e+00
Max is 9.612e+00
at 3.200e+00

( 40.98 , -9.07 )

Series 3 (Joint 3)                Series 4 (Joint 3)



Joint 3
Displacement UX

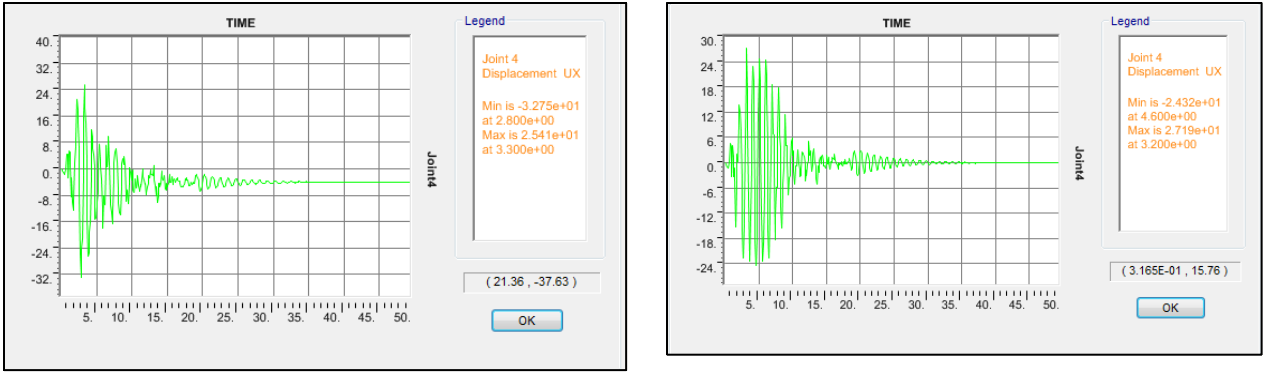
Min is -2.425e+01
at 2.800e+00
Max is 1.576e+01
at 3.300e+00

Joint 3
Displacement UX

Min is -1.652e+01
at 4.600e+00
Max is 1.877e+01
at 3.200e+00

Fig. 22: Displacement vs. Time for Joint 2 & 3 (Nonlinear Analysis - Series 3 and 4)

Series 3 (Joint 4) Series 4 (Joint 4)



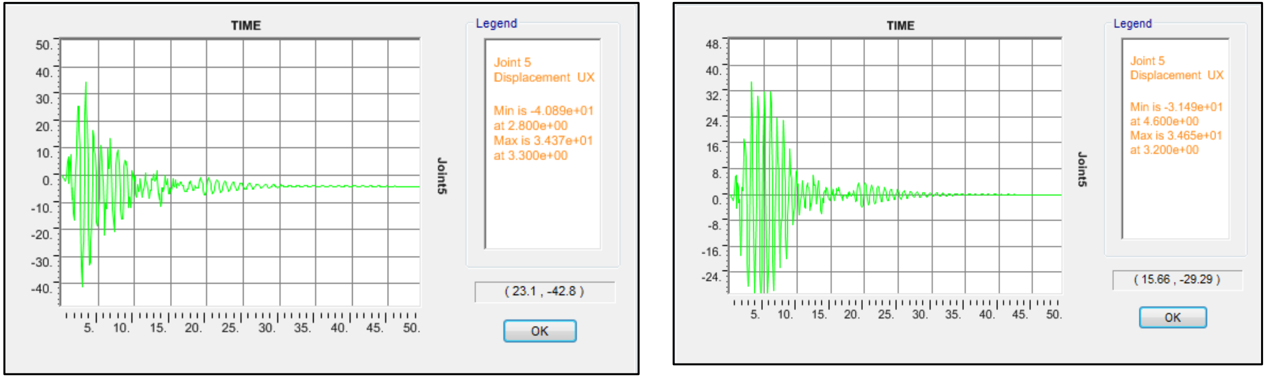
Joint 4
Displacement UX
Min is -3.275e+01
at 2.800e+00
Max is 2.541e+01
at 3.300e+00

( 21.36 , -37.63 )

Joint 4
Displacement UX
Min is -2.432e+01
at 4.600e+00
Max is 2.719e+01
at 3.200e+00

( 3.165E-01 , 15.76 )

Series 3 (Joint 5) Series 4 (Joint 5)



Joint 5
Displacement UX
Min is -4.089e+01
at 2.800e+00
Max is 3.437e+01
at 3.300e+00

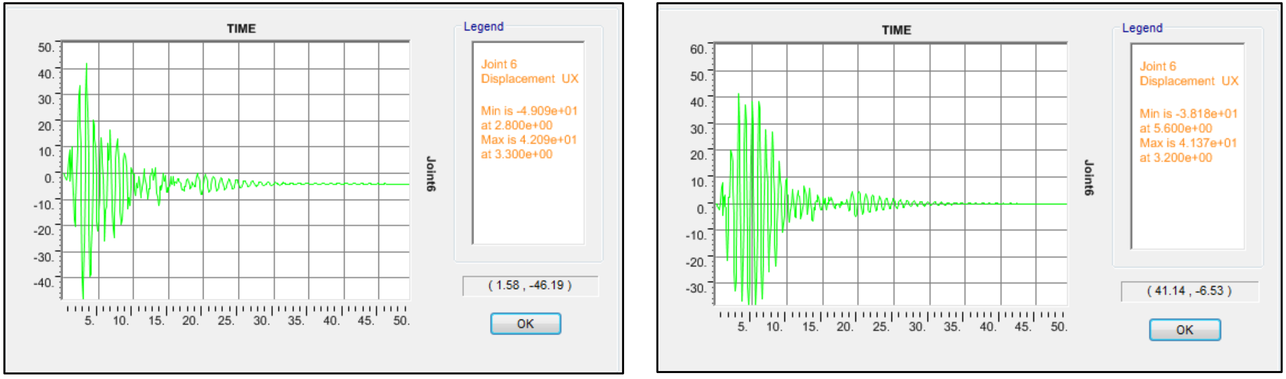
( 23.1 , -42.8 )

Joint 5
Displacement UX
Min is -3.149e+01
at 4.600e+00
Max is 3.465e+01
at 3.200e+00

( 15.66 , -29.29 )

Fig. 23: Displacement vs. Time for Joint 4 & 5 (Nonlinear Analysis - Series 3 & 4)

Series 3 (Joint 6) Series 4 (Joint 6)



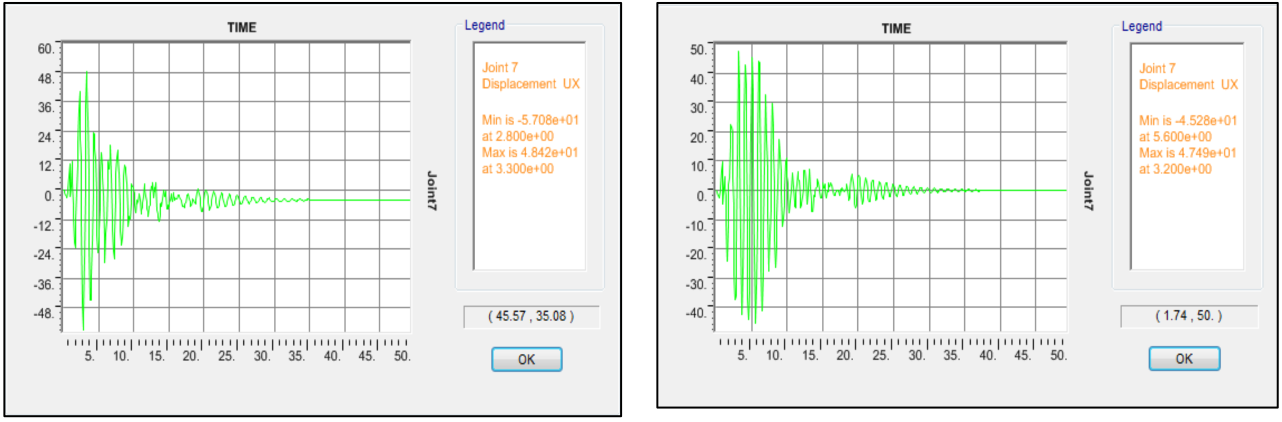
Joint 6
Displacement UX
Min is -4.909e+01
at 2.800e+00
Max is 4.209e+01
at 3.300e+00

( 1.58 , -46.19 )

Joint 6
Displacement UX
Min is -3.818e+01
at 5.600e+00
Max is 4.137e+01
at 3.200e+00

( 41.14 , -6.53 )

Series 3 (Joint 7) Series 4 (Joint 7)



Joint 7
Displacement UX
Min is -5.708e+01
at 2.800e+00
Max is 4.842e+01
at 3.300e+00

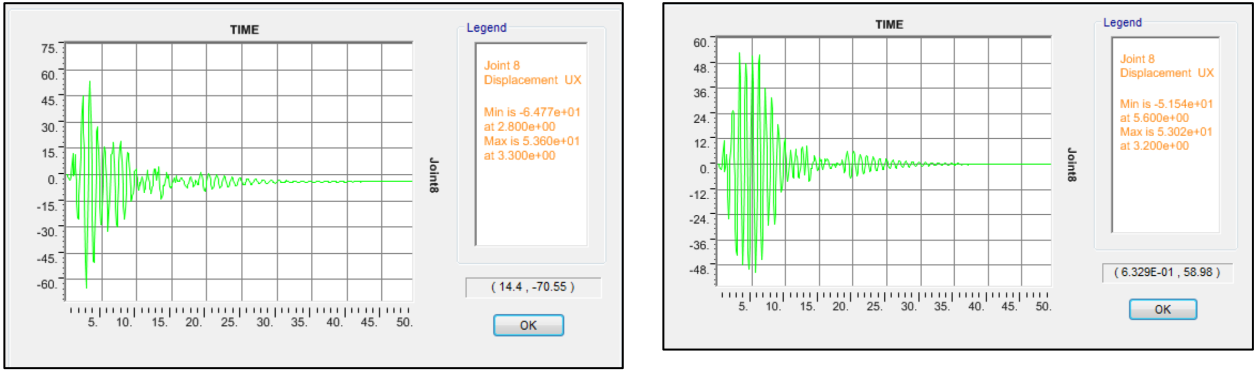
( 45.57 , 35.08 )

Joint 7
Displacement UX
Min is -4.528e+01
at 5.600e+00
Max is 4.749e+01
at 3.200e+00

( 1.74 , 50. )

Fig. 24: Displacement vs. Time for Joint 6 & 7 (Nonlinear Analysis - Series 3 & 4)

Series 3 (Joint 8) Series 4 (Joint 8)



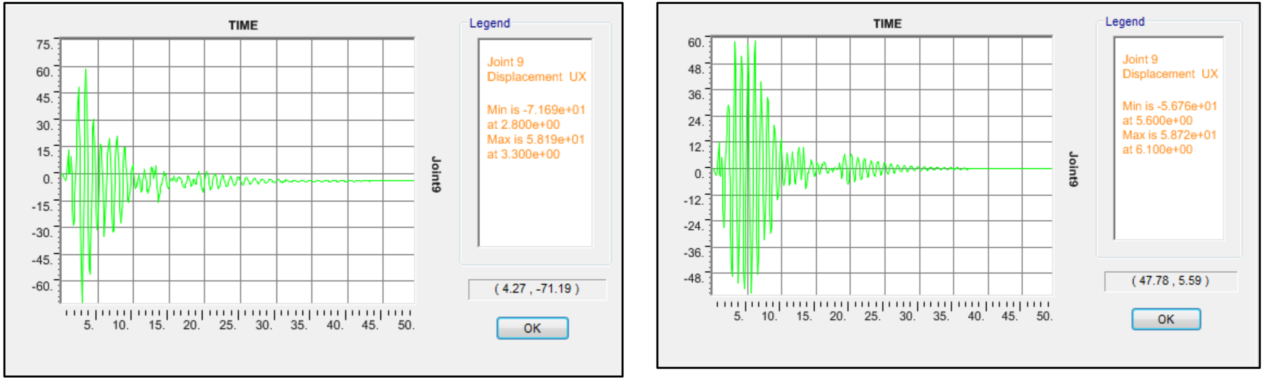
Joint 8
Displacement UX
Min is -6.477e+01
at 2.800e+00
Max is 5.360e+01
at 3.300e+00

( 14.4 , -70.55 )

Joint 8
Displacement UX
Min is -5.154e+01
at 5.600e+00
Max is 5.302e+01
at 3.200e+00

( 6.329E-01 , 58.98 )

Series 3 (Joint 9) Series 4 (Joint 9)



Joint 9
Displacement UX
Min is -7.169e+01
at 2.800e+00
Max is 5.819e+01
at 3.300e+00

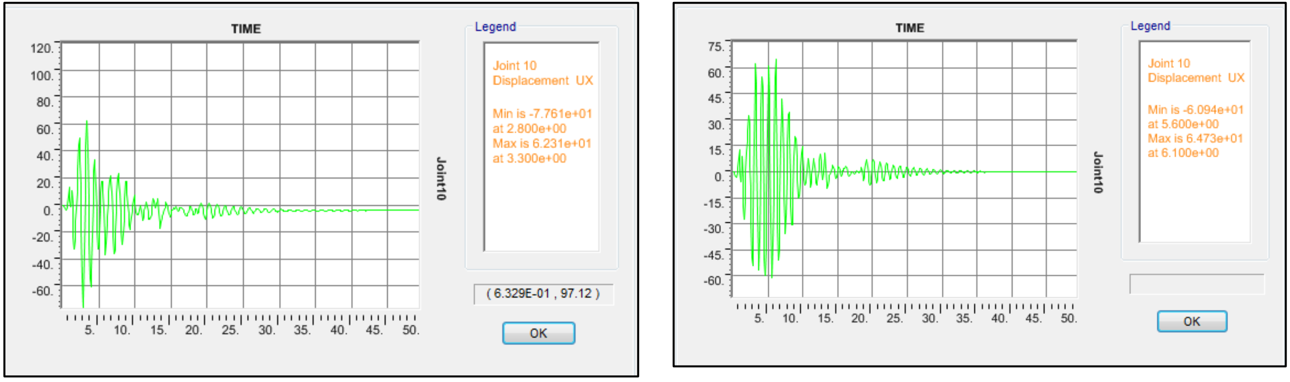
( 4.27 , -71.19 )

Joint 9
Displacement UX
Min is -5.676e+01
at 5.600e+00
Max is 5.872e+01
at 6.100e+00

( 47.78 , 5.59 )

**Fig. 25: Displacement vs. Time for Joint 8 & 9 (Nonlinear Analysis - Series 3 & 4)**

Series 3 (Joint 10) Series 4 (Joint 10)

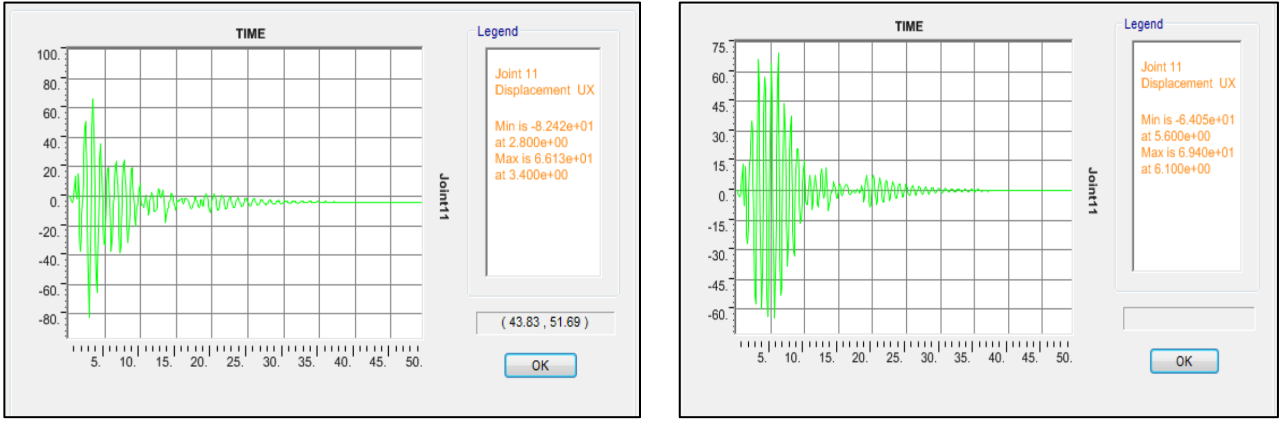


Joint 10
Displacement UX
Min is -7.761e+01
at 2.800e+00
Max is 6.231e+01
at 3.300e+00

( 6.329E-01 , 97.12 )

Joint 10
Displacement UX
Min is -6.094e+01
at 5.600e+00
Max is 6.473e+01
at 6.100e+00

Series 3 (Joint 11) Series 4 (Joint 11)

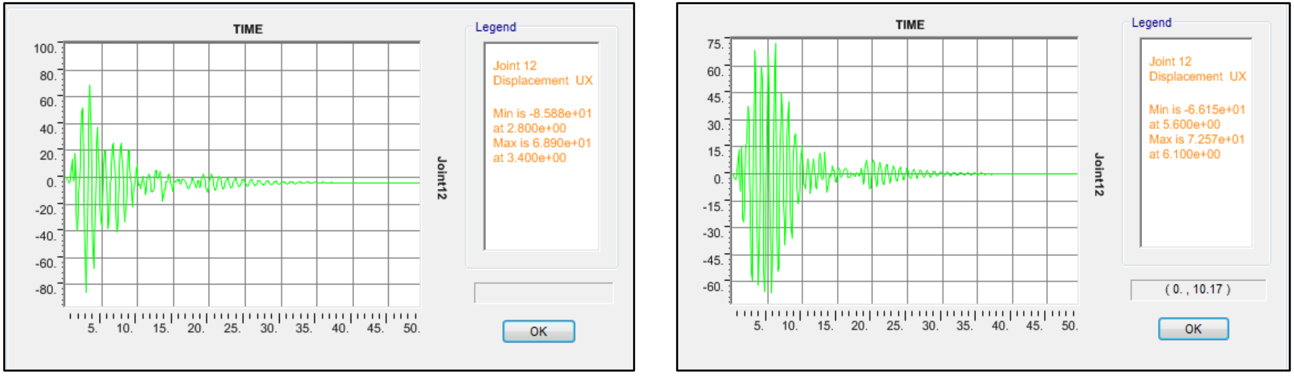


Joint 11
Displacement UX
Min is -8.242e+01
at 2.800e+00
Max is 6.613e+01
at 3.400e+00

( 43.83 , 51.69 )

Joint 11
Displacement UX
Min is -6.405e+01
at 5.600e+00
Max is 6.940e+01
at 6.100e+00

**Fig. 26: Displacement vs. Time for Joint 10 & 11 (Nonlinear Analysis - Series 3 & 4)**



Series 3 (Joint 12)

Joint 12
Displacement UX

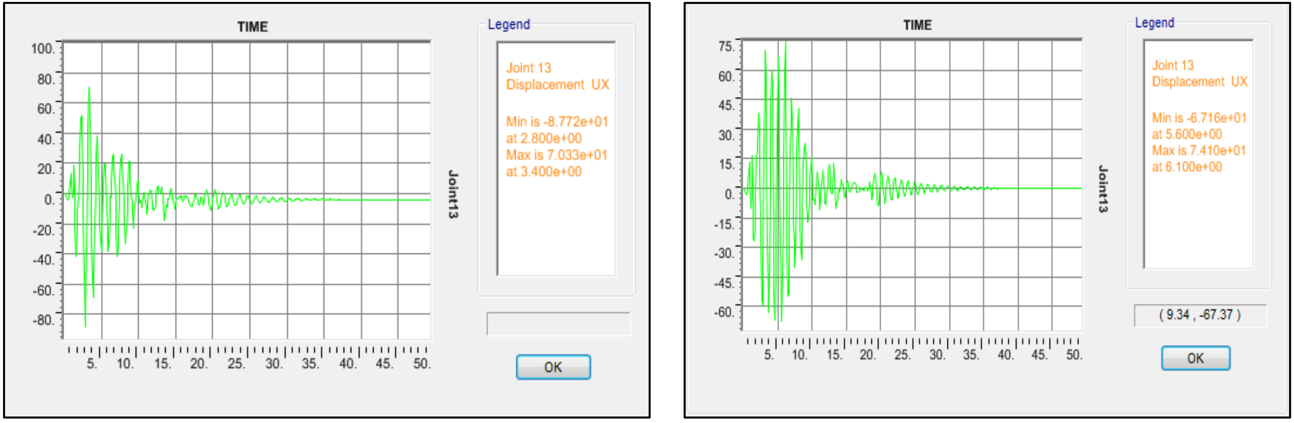
Min is -8.588e+01
at 2.800e+00
Max is 6.890e+01
at 3.400e+00

Series 4 (Joint 12)

Joint 12
Displacement UX

Min is -6.615e+01
at 5.600e+00
Max is 7.257e+01
at 6.100e+00

( 0. , 10.17 )



Series 3 (Joint 13)

Joint 13
Displacement UX

Min is -8.772e+01
at 2.800e+00
Max is 7.033e+01
at 3.400e+00

Series 4 (Joint 13)

Joint 13
Displacement UX

Min is -6.716e+01
at 5.600e+00
Max is 7.410e+01
at 6.100e+00

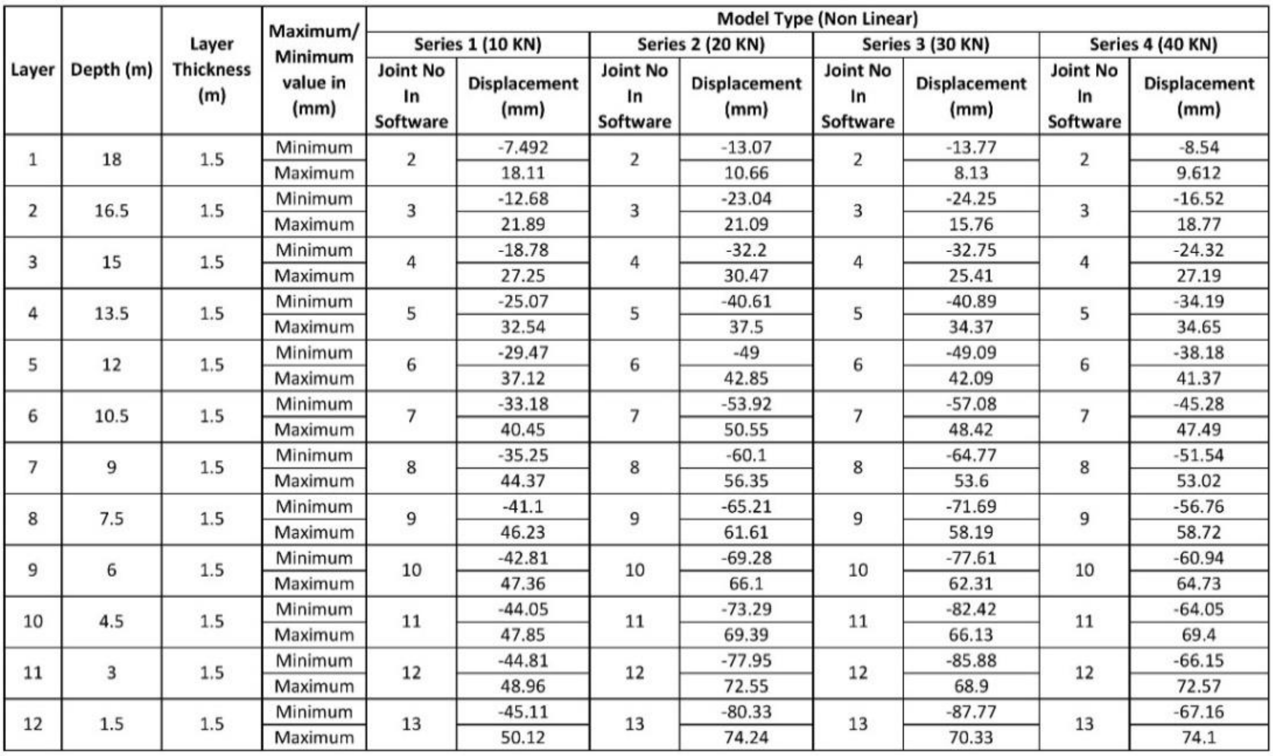
( 9.34 , -67.37 )

**Fig. 27: Displacement vs. Time for Joint 12 & 13 (Nonlinear Analysis - Series 3 & 4)**

**Table 15: Displacement Results vs. Time for Series 3 & 4 (Nonlinear Analysis)**

| Layer | Depth m | Layer Thickness m | Maximum/ Minimum value in mm | Lump Mass Linear Model | | Model Type (Non Linear) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Series 3 (30 KN) | | Series 4 (40 KN) | |
| | | | | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) |
| 1 | 18 | 1.5 | Minimum | 2 | -3.083 | 2 | -13.77 | 2 | -8.54 |
| | | | Maximum | | 4.226 | | 8.13 | | 9.612 |
| 2 | 16.5 | 1.5 | Minimum | 3 | -6.559 | 3 | -24.25 | 3 | -16.52 |
| | | | Maximum | | 9.394 | | 15.76 | | 18.77 |
| 3 | 15 | 1.5 | Minimum | 4 | -10.62 | 4 | -32.75 | 4 | -24.32 |
| | | | Maximum | | 15.56 | | 25.41 | | 27.19 |
| 4 | 13.5 | 1.5 | Minimum | 5 | -13.98 | 5 | -40.89 | 5 | -34.19 |
| | | | Maximum | | 20.19 | | 34.37 | | 34.65 |
| 5 | 12 | 1.5 | Minimum | 6 | -20.74 | 6 | -49.09 | 6 | -38.18 |
| | | | Maximum | | 27.52 | | 42.09 | | 41.37 |
| 6 | 10.5 | 1.5 | Minimum | 7 | -29.97 | 7 | -57.08 | 7 | -45.28 |
| | | | Maximum | | 32.19 | | 48.42 | | 47.49 |
| 7 | 9 | 1.5 | Minimum | 8 | -35.25 | 8 | -64.77 | 8 | -51.54 |
| | | | Maximum | | 38.55 | | 53.6 | | 53.02 |
| 8 | 7.5 | 1.5 | Minimum | 9 | -36.65 | 9 | -71.69 | 9 | -56.76 |
| | | | Maximum | | 47.38 | | 58.19 | | 58.72 |
| 9 | 6 | 1.5 | Minimum | 10 | -40 | 10 | -77.61 | 10 | -60.94 |
| | | | Maximum | | 53.53 | | 62.31 | | 64.73 |
| 10 | 4.5 | 1.5 | Minimum | 11 | -44.68 | 11 | -82.42 | 11 | -64.05 |
| | | | Maximum | | 61.45 | | 66.13 | | 69.4 |
| 11 | 3 | 1.5 | Minimum | 12 | -51.74 | 12 | -85.88 | 12 | -66.15 |
| | | | Maximum | | 68.1 | | 68.9 | | 72.57 |
| 12 | 1.5 | 1.5 | Minimum | 13 | -54.27 | 13 | -87.77 | 13 | -67.16 |
| | | | Maximum | | 70.84 | | 70.33 | | 74.1 |

**Table 16: Maximum and Minimum Displacement Results (Nonlinear Analysis)**



| Layer | Depth (m) | Layer Thickness (m) | Maximum/ Minimum value in (mm) | Model Type (Non Linear) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Series 1 (10 KN) | | Series 2 (20 KN) | | Series 3 (30 KN) | | Series 4 (40 KN) | |
| | | | | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) | Joint No In Software | Displacement (mm) |
| 1 | 18 | 1.5 | Minimum | 2 | -7.492 | 2 | -13.07 | 2 | -13.77 | 2 | -8.54 |
| | | | Maximum | | 18.11 | | 10.66 | | 8.13 | | 9.612 |
| 2 | 16.5 | 1.5 | Minimum | 3 | -12.68 | 3 | -23.04 | 3 | -24.25 | 3 | -16.52 |
| | | | Maximum | | 21.89 | | 21.09 | | 15.76 | | 18.77 |
| 3 | 15 | 1.5 | Minimum | 4 | -18.78 | 4 | -32.2 | 4 | -32.75 | 4 | -24.32 |
| | | | Maximum | | 27.25 | | 30.47 | | 25.41 | | 27.19 |
| 4 | 13.5 | 1.5 | Minimum | 5 | -25.07 | 5 | -40.61 | 5 | -40.89 | 5 | -34.19 |
| | | | Maximum | | 32.54 | | 37.5 | | 34.37 | | 34.65 |
| 5 | 12 | 1.5 | Minimum | 6 | -29.47 | 6 | -49 | 6 | -49.09 | 6 | -38.18 |
| | | | Maximum | | 37.12 | | 42.85 | | 42.09 | | 41.37 |
| 6 | 10.5 | 1.5 | Minimum | 7 | -33.18 | 7 | -53.92 | 7 | -57.08 | 7 | -45.28 |
| | | | Maximum | | 40.45 | | 50.55 | | 48.42 | | 47.49 |
| 7 | 9 | 1.5 | Minimum | 8 | -35.25 | 8 | -60.1 | 8 | -64.77 | 8 | -51.54 |
| | | | Maximum | | 44.37 | | 56.35 | | 53.6 | | 53.02 |
| 8 | 7.5 | 1.5 | Minimum | 9 | -41.1 | 9 | -65.21 | 9 | -71.69 | 9 | -56.76 |
| | | | Maximum | | 46.23 | | 61.61 | | 58.19 | | 58.72 |
| 9 | 6 | 1.5 | Minimum | 10 | -42.81 | 10 | -69.28 | 10 | -77.61 | 10 | -60.94 |
| | | | Maximum | | 47.36 | | 66.1 | | 62.31 | | 64.73 |
| 10 | 4.5 | 1.5 | Minimum | 11 | -44.05 | 11 | -73.29 | 11 | -82.42 | 11 | -64.05 |
| | | | Maximum | | 47.85 | | 69.39 | | 66.13 | | 69.4 |
| 11 | 3 | 1.5 | Minimum | 12 | -44.81 | 12 | -77.95 | 12 | -85.88 | 12 | -66.15 |
| | | | Maximum | | 48.96 | | 72.55 | | 68.9 | | 72.57 |
| 12 | 1.5 | 1.5 | Minimum | 13 | -45.11 | 13 | -80.33 | 13 | -87.77 | 13 | -67.16 |
| | | | Maximum | | 50.12 | | 74.24 | | 70.33 | | 74.1 |

**Table 17: Permanent Deformations (mm)**

| Model | Series 1 | Series 2 | Series 3 | Series 4 |
|---|---|---|---|---|
| Joint 2 | 3.0 | -3.3 | -2.6 | 0.0 |
| Joint 3 | -1.5 | -4.5 | -4.3 | 0.0 |
| Joint 4 | -4.8 | -4.0 | -4.0 | 0.0 |
| Joint 5 | -7.0 | -3.0 | -4.0 | 0.0 |
| Joint 6 | -6.5 | -3.0 | -4.0 | 0.0 |
| Joint 7 | -5.5 | -1.2 | -4.0 | 0.0 |
| Joint 8 | -5.0 | -0.5 | -4.0 | 0.0 |
| Joint 9 | -9.5 | -0.5 | -4.0 | 0.0 |
| Joint 10 | -9.5 | -0.5 | -3.0 | 0.0 |
| Joint 11 | -9.5 | -0.5 | -3.0 | 0.0 |
| Joint 12 | -9.5 | -0.5 | -3.0 | 0.0 |
| Joint 13 | -9.5 | -0.5 | -3.0 | 0.0 |

Table 17 shows permanent deformations at different joints of the four nonlinear models (Series 1, 2, 3 and 4). The large permanent deformations of Series 1 (most flexible) and no permanent deformation of Series 4 (most rigid) are to be noted.

## DISCUSSION

Soil mass is first analyzed linearly, and then nonlinearly, in this study. For 1DOF, 2DOF, and MDOF, we compare the displacements and times between solid mass and lumped mass.

Solid mass maximum displacements (9.821 mm) and lumped mass maximum displacements (9.755 mm) are quite close when using the same soil characteristics for 1 degree of freedom. For a given lumped mass, there is only one mode shape discovered, with a period value of 0.240 seconds. However, solid mass is revealed to have twelve modes. Duration might be anywhere from 0.106 to 0.417 seconds. Mode 7 has a value of 0.292 seconds, whereas mode 8 has a value of 0.227 seconds. They are very close to the values for a lumped mass.

Then, the same steps are taken for 2 degrees of freedom. Solid mass can be displaced a maximum of 7.094 mm in the first layer and 23.15 mm in the second. Maximum layer 1 and 2 lumped mass displacements are 9.742 and 21.26 mm, respectively. Two different mode shapes are found for lumped mass, and twenty-four different shapes are found for solid mass. For solid matter, the time duration can range from 0.082sec to 0.884 sec. For a lumped mass, the time duration is 0.378 seconds for Mode 1 and 0.194 seconds for Mode

2. These numbers are in close proximity to those for solid mass modes 4, 11, and 12.

Again, linear analysis compares MDOF displacements and times. Both solid mass and lumped mass displacements are sufficiently near. For solid mass, the time range is 0.055-11.822 seconds, and for lumped mass, the range is 0.085-1.767% of a second. The mode forms 6, 11, 25, 60, 90, 102, 122, 123, 124, 127, 131, and 137 of solid mass are quite similar to the results for the first through twelfth modes of lumped mass. As a result, the lumped-mass model is acceptable for nonlinear analysis of ground motion and is found to be reasonably accurate. This data feeds into subsequent models employing nonlinear analysis.

To begin, let's assume that the nonlinear analysis is a hysteresis loop, where the load varies as a function of the displacement (Series 1 and Series 2). Both scenarios result in permanent deformations, which tips buildings over. Nonlinear analysis then assumes a further two series (Series 3 and 4) of load vs. displacement hysteresis loops. Here, we find permanent deformation for Series 3 (albeit to a lesser extent than Series 1), but no deformation for Series 4.

## CONCLUSION

This thesis shows the nonlinear behavior deformation results of numerical analysis of soil mass during earthquake. Principal concentration of this study is to find out the permanent deformation takes place during earthquake which may cause tilting of the building. Numerical analysis was done using SAP2000 (V 2020) by nonlinear time history analysis.

In the case of linear analysis, it is discovered that the displacements derived from software are very similar for both solid mass and the Lumped-Mass Model. The behavior of soil mass during earthquakes can be analyzed using the concept of lumped soil mass. The soil's amplification is greatest close to the surface. It's a clear sign of seismic damage. If the soil is firm, deformation will begin at smaller levels. In the presence of deformation, plastic strain dominates elastic strain. Due to the slender effect, it may take longer for the soil mass to stop vibrating than the ground motion time. In the case of soil mass behavior during an earthquake, soil characteristics play a crucial influence. The collapse of soil mass during an earthquake is a major contributor to structure lean. In the case of nonlinear elastic, completely plastic hysteresis loops, the deformation is irreversible. If the soil is sufficiently firm, permanent deformation may not occur.

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