OPEN ACCESS
Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) |ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Nonlinear Dynamic Analysis of Lumped Soil Mass Model against Seismic Loading

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DOI: 10.36348/sjce.2023.v07i08.001 | **Received:** 27.05.2023 | **Accepted:** 01.07.2023 | **Published:** 03.09.2023

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Abstract

Soil yielding mechanisms and seismic load responses are the key areas of study. The true behavior of soil is revealed by nonlinear analysis. A clump of dirt is used for the analysis. 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 conduct a nonlinear time-history analysis for this research. The hysteresis loops of nonlinear elastic, completely flexible soil undergo permanent deformation. 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 Dynamic Analysis, Lumped Soil Mass Model, Finite Element Model, DOF.

INTRODUCTION

Bangladesh is a populated country. There are several active tectonic plate boundaries in Bangladesh. Active faults such as those in the north and east of Bangladesh can be destructive. Also, it is very close to sea level and largest river delta in the world. Scientists predict it is a matter of time to occur a large earthquake [1]. Earthquake is frequently found to govern structural designs and many buildings are badly affected by tilting. Performance of foundations often degenerates during ground shaking. Differential settlements are the main reason causing tilting of the building. This refers to uneven load deformation behavior, which can be referred as asymmetric behavior also. It will happen when buildings display distinctive plastic yield scenarios. Then again, plastic deformation counteracts each other in the symmetric buildings when excited to seismic loading. But plastic deformations form in the direction of tilting for asymmetric yielding buildings when they are excited by seismic loading. It can be said more clearly that strong and weak ways will develop due to tilting for symmetric buildings. This kind of symmetrical building is not always possible in reality. That's why most of the buildings generate different yield strength in opposite directions. It damages the building significantly if the buildings are subjected to long duration seismic ground motions.

A 7.8 earthquake (Gorkha earthquake) struck Nepal on 25th April, 2015. Convergent collision plate boundaries between the Indian and Eurasian plates created this earthquake. The epicenter was just 60 kilometers north-west from the capital Kathmandu and the focus was only eight kilometers deep. About 9000 people were killed and over 20,000 were injured, while more than 600,000 structures in Kathmandu and other nearby towns were either damaged or destroyed (rendering more 3.5 million people homeless) [2]. It also damaged several structures in Bangladesh.

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 [3]. A dynamic load may be the result of an earthquake, the application of cyclic loads with varying cycle numbers, or any other

Citation: S. M. Tahmidur Rahman (2023). Nonlinear Dynamic Analysis of Lumped Soil Mass Model against Seismic Loading. *Saudi J Civ Eng, 7*(8): 158-177.

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 [4-6]. 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 [7].

In this study we will see the performance of nonlinear dynamic analysis of lumped soil mass model against seismic loading.

The mathematical expressions used in this paper are based on the Finite Element Model (FEM). One degree of freedom (1DOF), two degrees of freedom (2DOF) and multi degree of freedom (MDOF) of soil considered for analysis in case of lumped mass. A soil bore log is used to calculate soil parameters for MDOF. There are twelve layers of soil in case of MDOF. Time history nonlinear analysis is done by SAP 2000 for this study. Permanent deformation is observed for nonlinear elastic, perfectly plastic hysteresis loops in lumped soil mass. So lumped soil mass can be used to understand the behavior of soil mass during the earthquake.

OBJECTIVE OF THE STUDY

- To see the performance of nonlinear dynamic analysis of lumped soil mass model against seismic loading.

NUMERICAL MODELING OF SUB-STRUCTURE

Ground shaking is a non-periodic dynamic load which varies with time. It describes the vibration of the ground during an earthquake. It generates the rapid acceleration of the ground beneath the building which creates inertial forces in the structure. This can cause damage or may tilt the foundation if acceleration becomes too large.

This study evaluates the nonlinear analysis of lumped mass. Analysis of soil mass mainly focuses on displacement of the soil mass during ground shaking. It also includes earthquake wave propagation, soil amplification and soil-structure interaction.

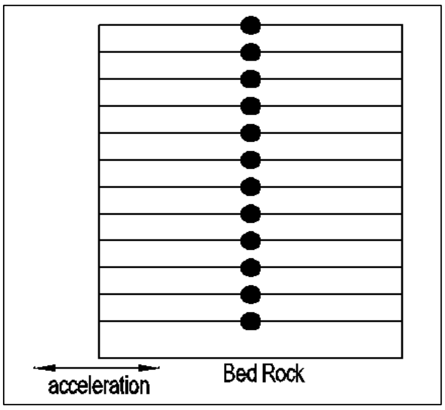
If mathematical models are too complex to provide analytical solutions especially in nonlinear system, then numerical modeling is required to study the behavior of the system. It implements mathematical model for a physical system. This study includes the numerical design approaches for characterization the soil behavior under a structure during earthquake.

Finite Elements Model

This analysis is used Finite Elements Model (FEM) method for numerical simulations. It is numerical procedure to determine the stresses and strain which includes complex engineering problems. It is a method by solving partial differential equations in two or three space variables which includes some boundary value problems. The FEM subdivides a large system into smaller, simpler parts to solve a problem that are named finite elements.

Lumped spring and Mass Model

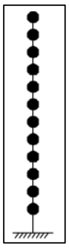
Degree of freedom (DOF) of a system is defined as the number of independent variables required to completely determine the positions of all parts of a system at any instant of time. Some systems, especially those involving continuous elastic members, have an infinite number of DOF. As an example of this is a soil layers.



Soil layers

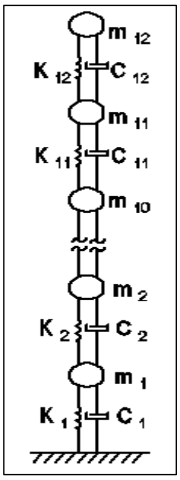
This soil layers has infinite mass points and need infinite number of displacements to draw its deflected shape and thus has an infinite DOF. Systems with infinite DOF are called continuous or distributed systems. Analysis with this distributed system may be named as mass model.

On the other hand, Systems with a finite number of degrees of freedom are called Discrete or Lumped mass parameter systems.



Lumped mass parameter systems

In a single degree of freedom system, the deformation of the entire structure can be described by a single number equal to the displacement of a point from an at-rest position. Single Degree of freedom systems do not normally exist in real life. We live in a three-dimensional world and all mass is distributed resulting in systems that have an infinite number of degrees of freedom. There are, however, instances where a structure may be approximated as a single degree of freedom system. In a Multi degree of freedom system, the deformation of the entire structure cannot be described by a single displacement. More than one displacement coordinates are required to completely specify the displaced shape.



Multi degree of freedom system

RESULTS

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.

Sub-Structure Models used for Analysis:

Nonlinear analysis is performed for multi degree of freedom (MDOF) only. 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. 1.

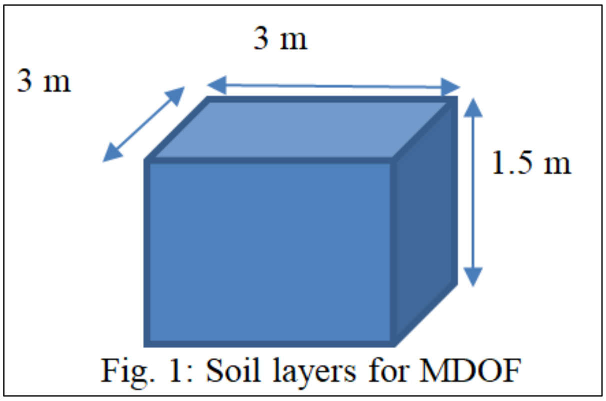


Fig. 1: Soil layers for MDOF

In this study ground motion data are used from UAP laboratory test (Fig. 2) which was performed for 20-seconds for time history analysis.

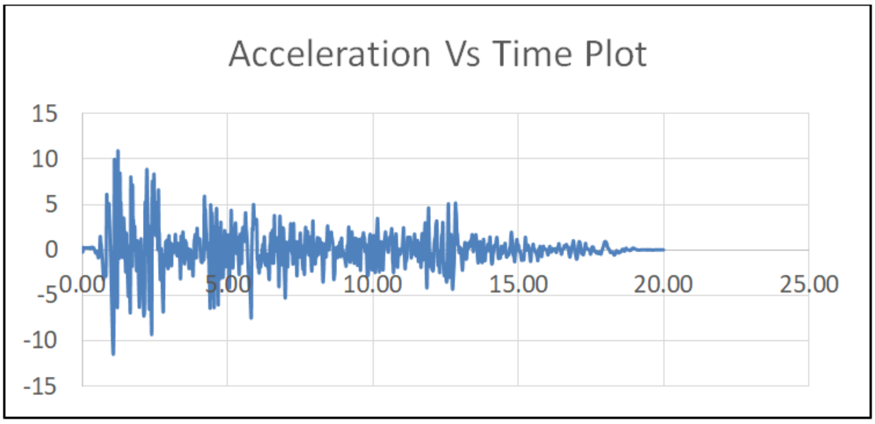


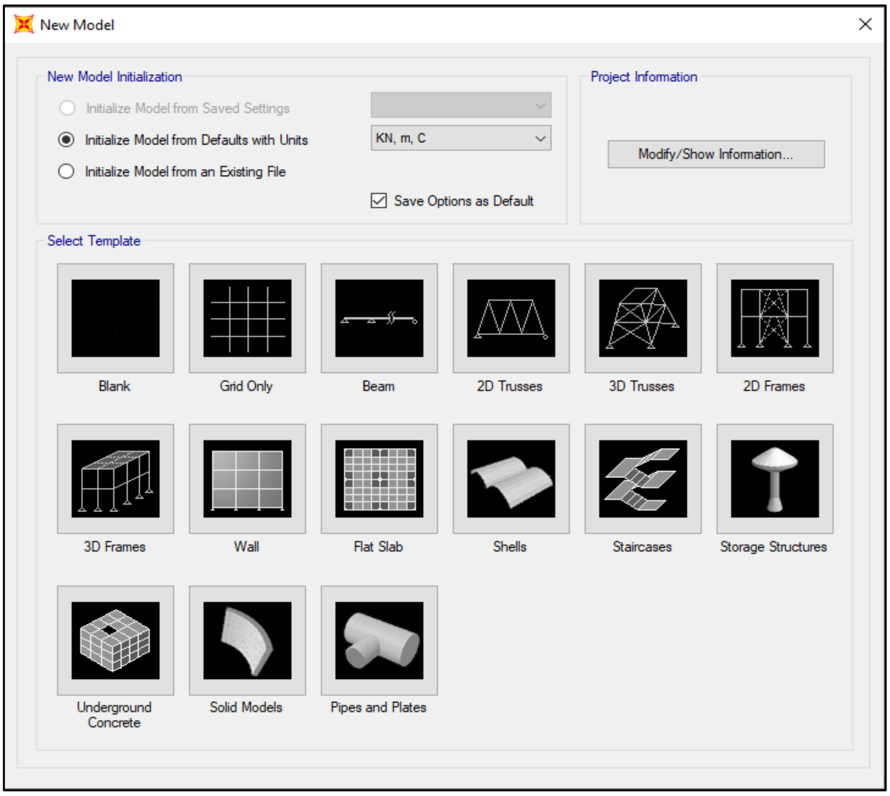
Fig. 2: Time history data

Table 1: 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

Lumped Spring Model for Nonlinear Analysis

1. Go to the File Menu > New Model > Select Unit > Click Grid only



New Model

New Model Initialization

○ Initialize Model from Saved Settings

● Initialize Model from Defaults with Units: KN, m, C

○ Initialize Model from an Existing File

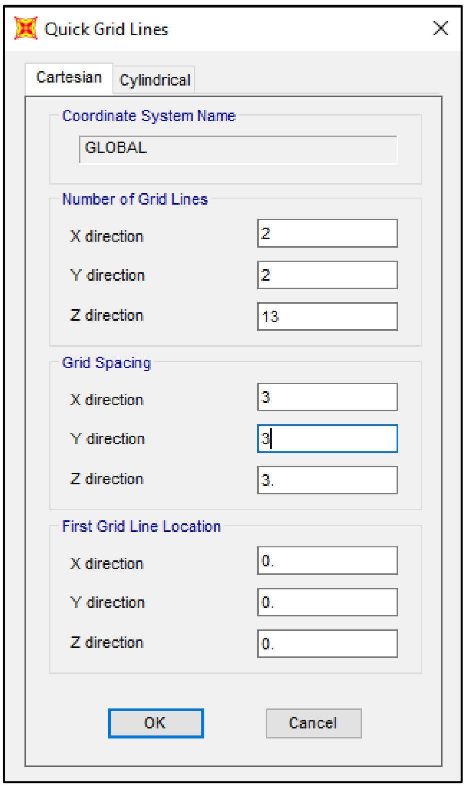
☑ Save Options as Default

Project Information

Select Template

Fig. 3: Defining model for lumped mass nonlinear analysis

2. Fill Quick Grid Lines



Coordinate System Name: GLOBAL

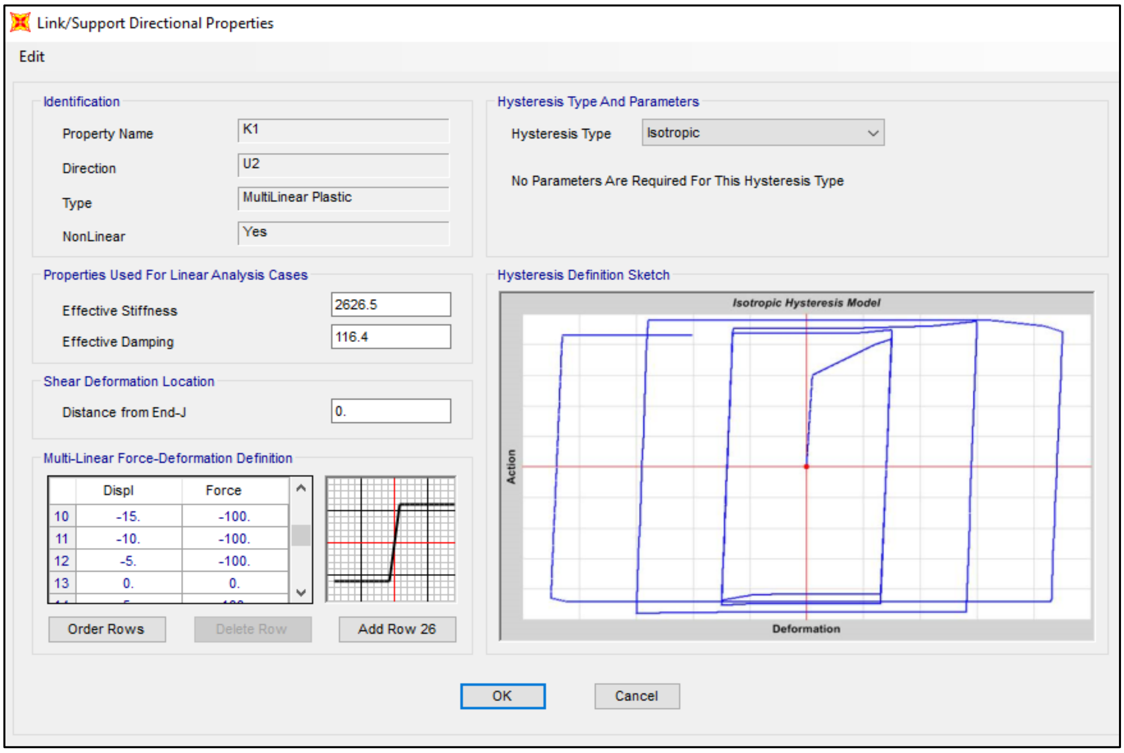
Number of Grid Lines
X direction: 2
Y direction: 2
Z direction: 13

Grid Spacing
X direction: 3
Y direction: 3
Z direction: 3.

First Grid Line Location
X direction: 0.
Y direction: 0.
Z direction: 0.

Fig. 4: Defining dimensional data

3. Define > Section Properties> Link Support Type Multi Linear Plastic> Link/Support Properties > Fill Directional Properties > Properties Modify/ Show For U2 > Hysteresis Type >Fill Stiffness & Damping> Multi Linear Force Deformation Definition



Identification
Property Name: K1
Direction: U2
Type: MultiLinear Plastic
NonLinear: Yes

Hysteresis Type And Parameters
Hysteresis Type: Isotropic
No Parameters Are Required For This Hysteresis Type

Properties Used For Linear Analysis Cases
Effective Stiffness: 2626.5
Effective Damping: 116.4

Shear Deformation Location
Distance from End-J: 0.

Multi-Linear Force-Deformation Definition

	Displ	Force
10	-15.	-100.
11	-10.	-100.
12	-5.	-100.
13	0.	0.

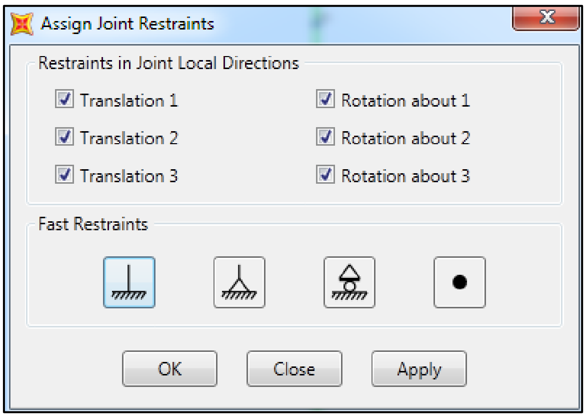
Hysteresis Definition Sketch

Fig. 5: Defining Link/Support Properties

4. Draw > Draw 2 Joint Link > Complete Lump Model

Fig. 6: Lumped-Mass Model for analysis

5. Select bottom most lower point > Assign > Joint > Restraints > Fixed Support



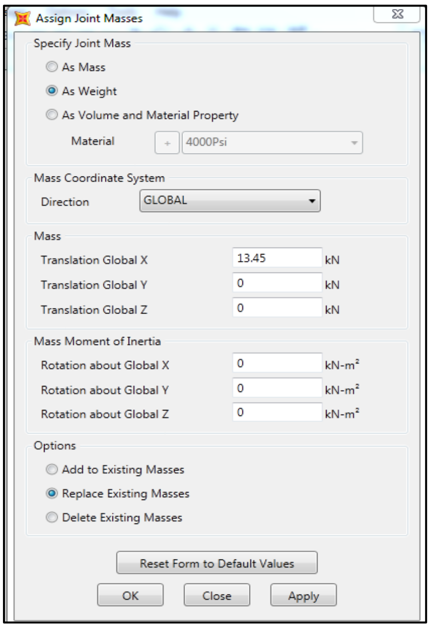
Assign Joint Restraints

Restraints in Joint Local Directions

☑ Translation 1
☑ Rotation about 1
☑ Translation 2
☑ Rotation about 2
☑ Translation 3
☑ Rotation about 3

Fig. 7: Assign support

6. Assign > Joint > Masses > Specify Joint Mass > As Weight > Mass Coordinate System > Global > Fill Mass as Translation Global X



Assign Joint Masses

Specify Joint Mass

○ As Mass
● As Weight
○ As Volume and Material Property

Material 4000Psi

Mass Coordinate System

Direction GLOBAL

Mass

Translation Global X 13.45 kN
Translation Global Y 0 kN
Translation Global Z 0 kN

Mass Moment of Inertia

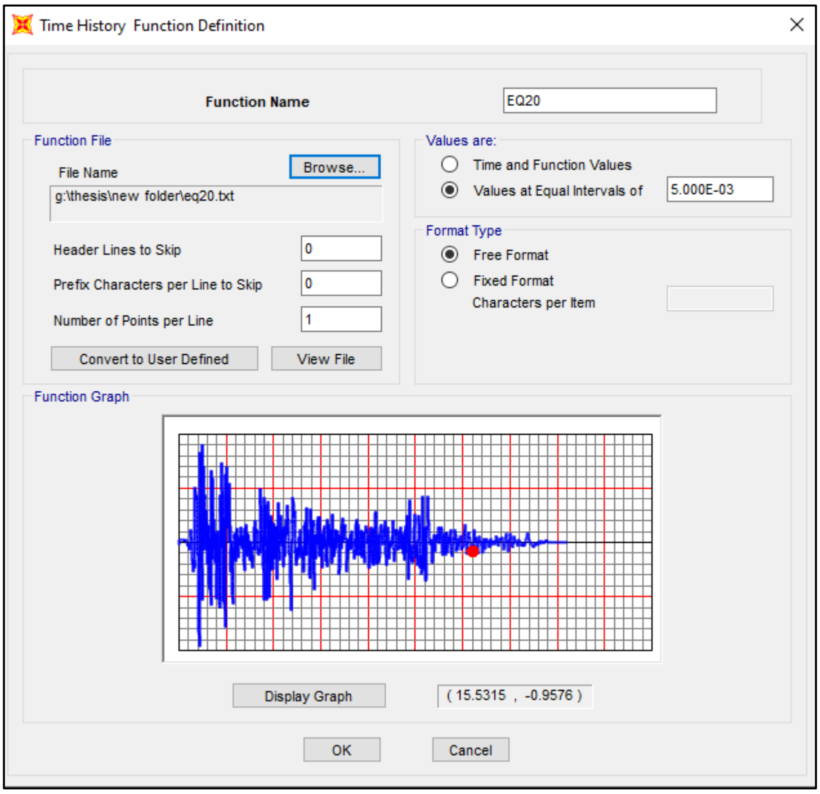
Rotation about Global X 0 kN-m²
Rotation about Global Y 0 kN-m²
Rotation about Global Z 0 kN-m²

Options

○ Add to Existing Masses
● Replace Existing Masses
○ Delete Existing Masses

Fig. 8: Assign mass of different layers

7. Define > function > Time history > Choose Function Type to Add from File > Add new function > Browse & Select given file


Time History Function Definition

Function Name: EQ20

Function File

File Name: g:\thesis\new folder\eq20.txt

Header Lines to Skip: 0

Prefix Characters per Line to Skip: 0

Number of Points per Line: 1

Values are:

○ Time and Function Values

● Values at Equal Intervals of 5.000E-03

Format Type

● Free Format

○ Fixed Format

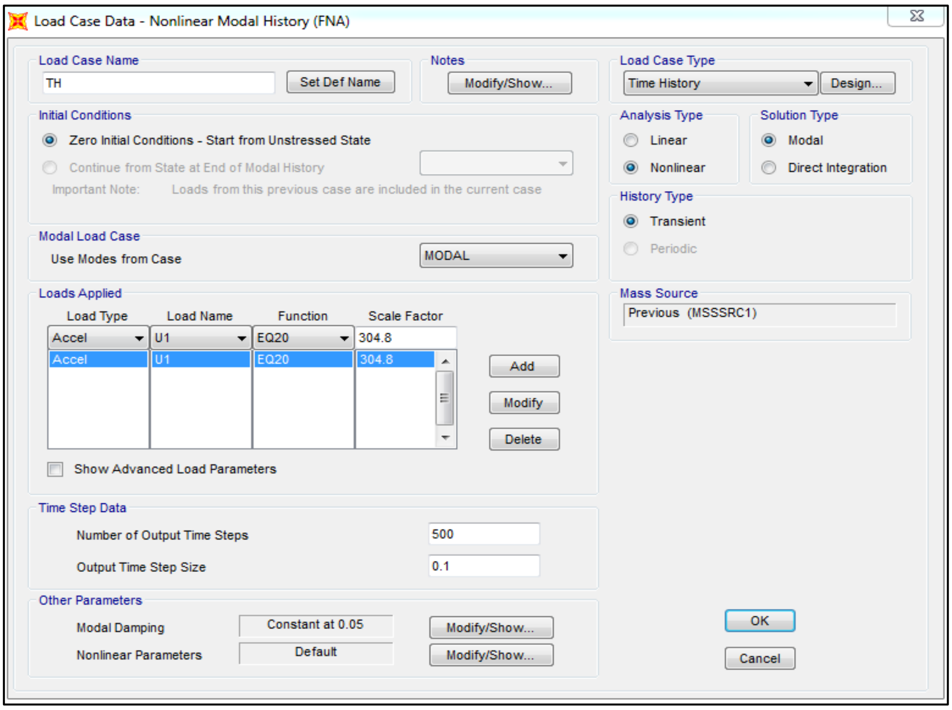
Characters per Item

Function Graph

(15.5315 , -0.9576)

Fig. 8: Defining time history data

8. Load Cases > Add New Load Cases > Load Case Type Time History > Analysis Type NonLinear> History Type Transient > Solution Type Modal > Select Load Type, Load Name, Function, Scale Factor > Fill Number of Output Time Steps, Output Time Step Size


Load Case Data - Nonlinear Modal History (FNA)

Load Case Name: TH

Load Case Type: Time History

Initial Conditions

● Zero Initial Conditions - Start from Unstressed State

○ Continue from State at End of Modal History

Important Note: Loads from this previous case are included in the current case

Analysis Type: ○ Linear ● Nonlinear

Solution Type: ● Modal ○ Direct Integration

History Type: ● Transient ○ Periodic

Modal Load Case

Use Modes from Case: MODAL

Mass Source: Previous (MSSSRC1)

Loads Applied

Load Type	Load Name	Function	Scale Factor
Accel	U1	EQ20	304.8
Accel	U1	EQ20	304.8

☐ Show Advanced Load Parameters

Time Step Data

Number of Output Time Steps: 500

Output Time Step Size: 0.1

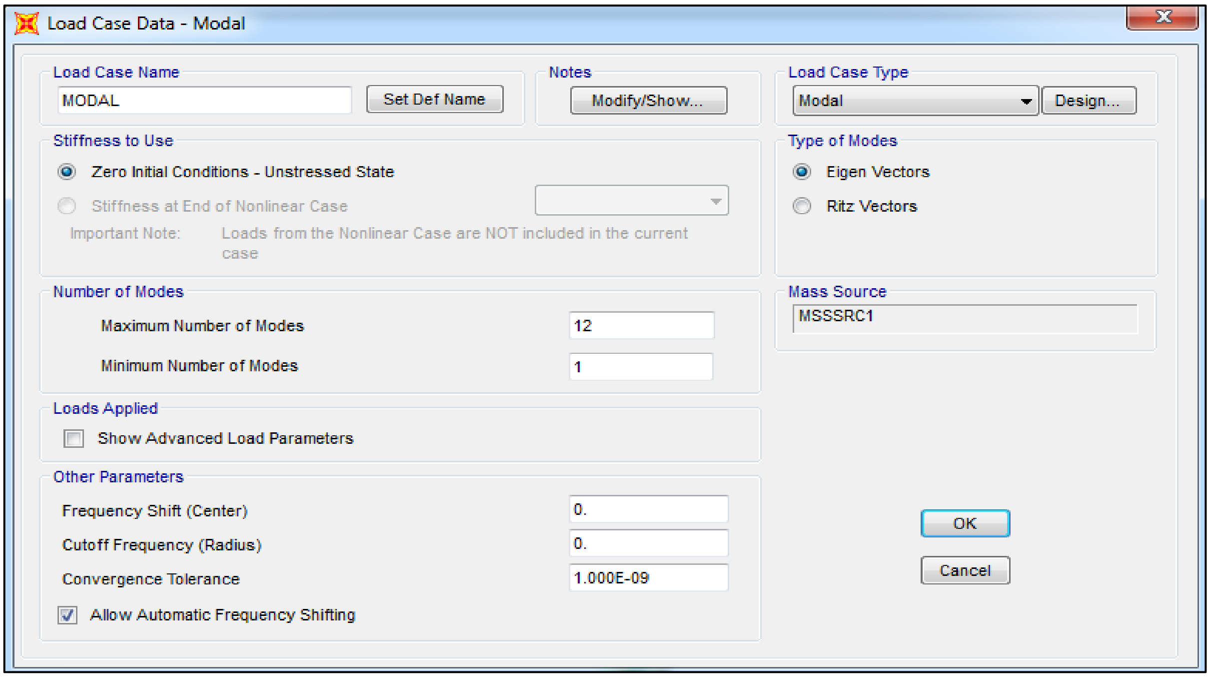
Other Parameters

Modal Damping: Constant at 0.05

Nonlinear Parameters: Default

Fig. 9: Defining Linear Modal History

9. Load Cases >Modal > Modify/Show Load Cases >Types of Modes Ritz Vectors > Fill Maximum no of Modes > Assign Load Applied



Load Case Name: MODAL

Load Case Type: Modal

Stiffness to Use:
● Zero Initial Conditions - Unstressed State
○ Stiffness at End of Nonlinear Case
Important Note: Loads from the Nonlinear Case are NOT included in the current case

Type of Modes:
● Eigen Vectors
○ Ritz Vectors

Maximum Number of Modes: 12
Minimum Number of Modes: 1

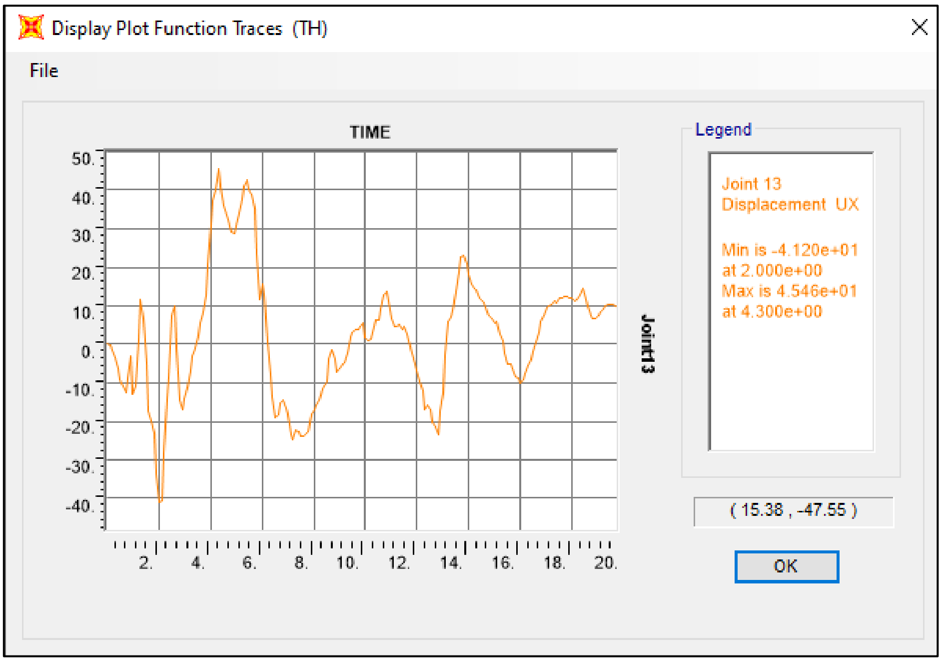
Mass Source: MSSSRC1

☐ Show Advanced Load Parameters

Frequency Shift (Center): 0.
Cutoff Frequency (Radius): 0.
Convergence Tolerance: 1.000E-09
☑ Allow Automatic Frequency Shifting

Fig. 10: Defining modes for modal analysis

10. Analyze > Run Analysis
11. Display > Show Plot Functions > Define Plot Function > Choose Function to Add to Joint Disps/Forces > Add Plot Function > Fill Joint ID, Vector Type, Component



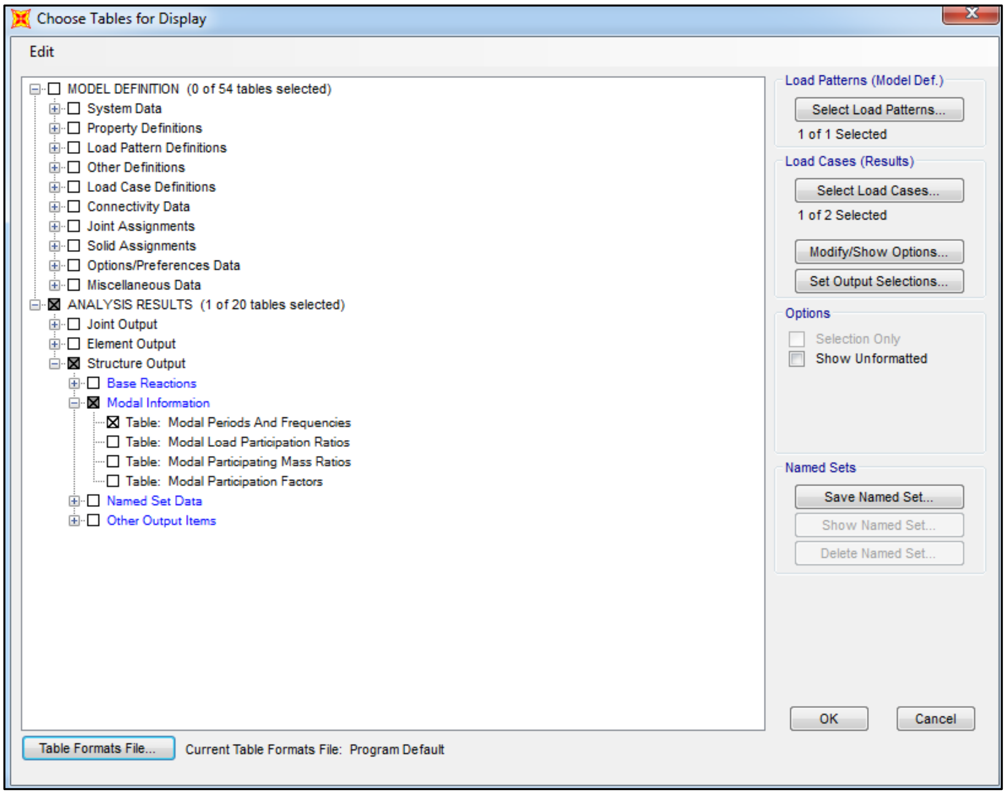
Joint 13
Displacement UX

Min is -4.120e+01
at 2.000e+00
Max is 4.546e+01
at 4.300e+00

(15.38 , -47.55)

Fig. 11: Defining displacement versus time plot

12. Display > Show Table > Analysis results > Structure Output > Modal Information > Modal Periods & Frequencies > Select Load Cases



- ☐ MODEL DEFINITION (0 of 54 tables selected)
  - ☐ System Data
  - ☐ Property Definitions
  - ☐ Load Pattern Definitions
  - ☐ Other Definitions
  - ☐ Load Case Definitions
  - ☐ Connectivity Data
  - ☐ Joint Assignments
  - ☐ Solid Assignments
  - ☐ Options/Preferences Data
  - ☐ Miscellaneous Data
- ☒ ANALYSIS RESULTS (1 of 20 tables selected)
  - ☐ Joint Output
  - ☐ Element Output
  - ☒ Structure Output
    - ☐ Base Reactions
    - ☒ Modal Information
      - ☒ Table: Modal Periods And Frequencies
      - ☐ Table: Modal Load Participation Ratios
      - ☐ Table: Modal Participating Mass Ratios
      - ☐ Table: Modal Participation Factors
    - ☐ Named Set Data
    - ☐ Other Output Items

1 of 1 Selected

1 of 2 Selected

☐ Selection Only

☐ Show Unformatted

Current Table Formats File: Program Default

Fig. 12: Display modal periods & frequencies

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

Table 2: 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

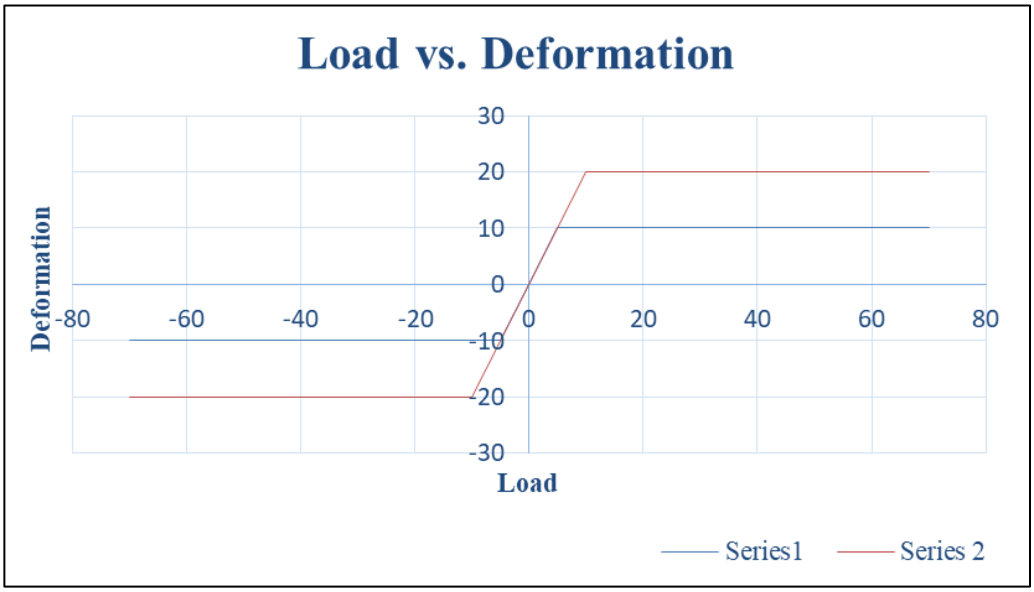


Fig. 13: Load vs. Deformation curve for Series 1 & 2

Lumped Mass Nodes No for Both Series 1 & 2

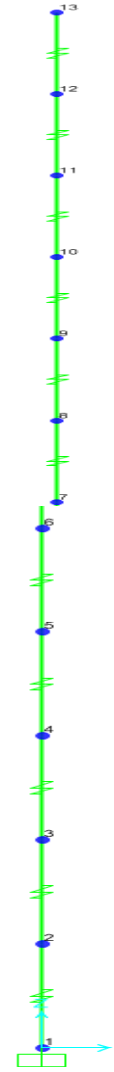
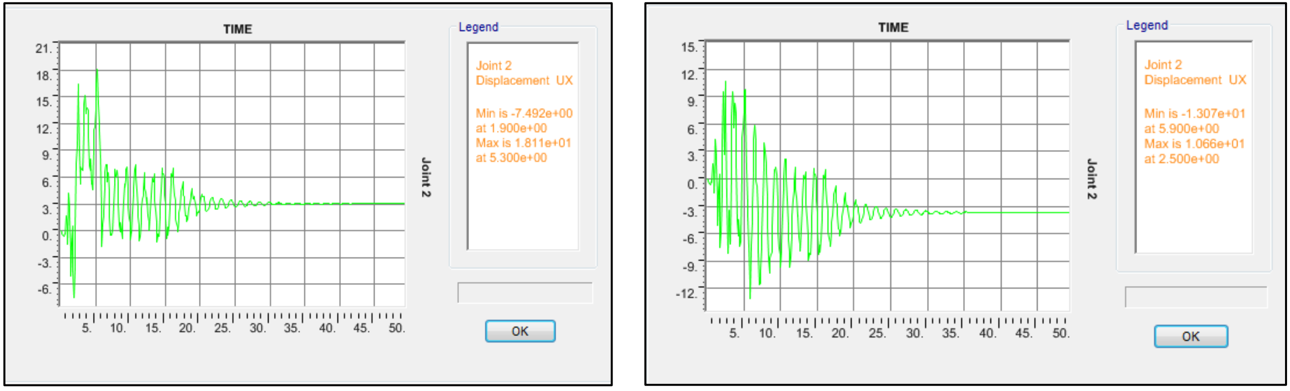


Fig. 14: 3D model for MDOF

Series 1 (Joint 2)

Series 2 (Joint 2)

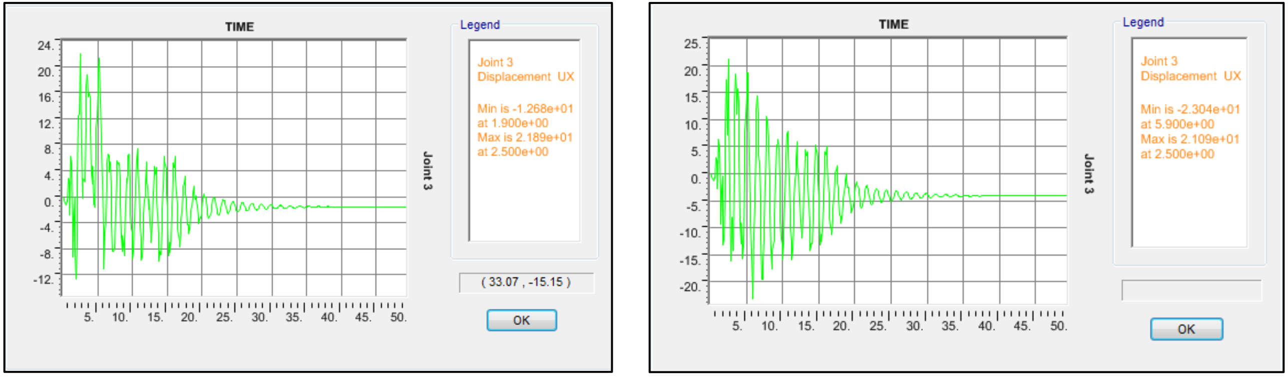


Joint 2
Displacement UX
Min is -7.492e+00
at 1.900e+00
Max is 1.811e+01
at 5.300e+00

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

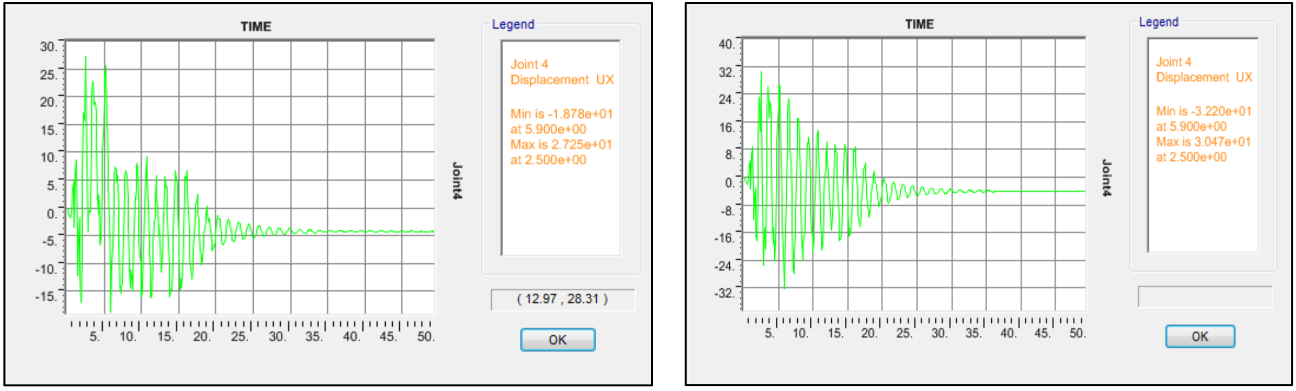
(33.07 , -15.15)

Joint 3
Displacement UX
Min is -2.304e+01
at 5.900e+00
Max is 2.109e+01
at 2.500e+00

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

Series 1 (Joint 4)

Series 2 (Joint 4)



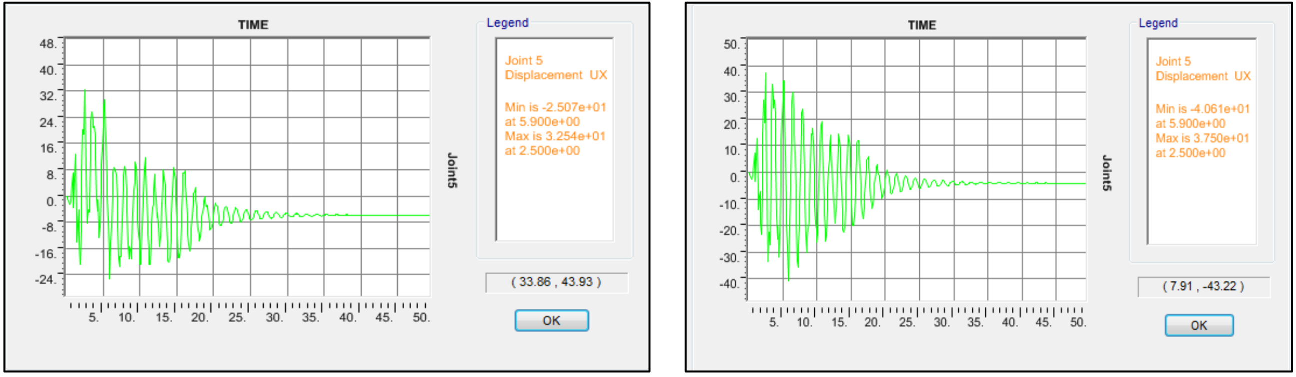
Joint 4
Displacement UX
Min is -1.878e+01
at 5.900e+00
Max is 2.725e+01
at 2.500e+00

(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

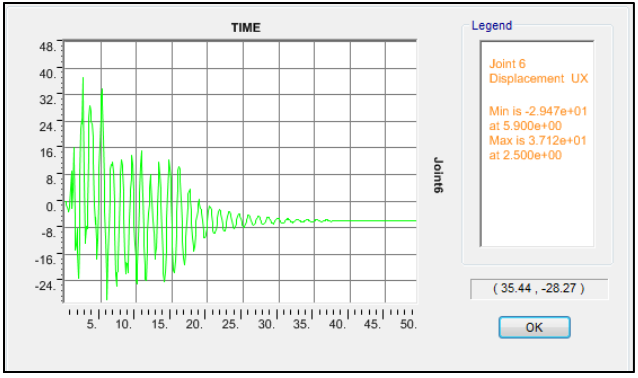
(33.86 , 43.93)

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

Series 1 (Joint 6)

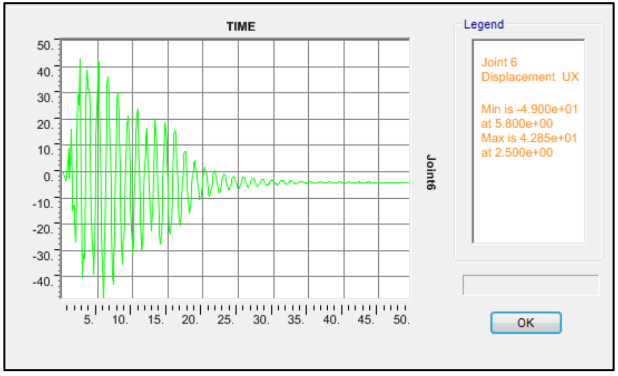


Joint 6
Displacement UX

Min is -2.947e+01
at 5.900e+00
Max is 3.712e+01
at 2.500e+00

(35.44 , -28.27)

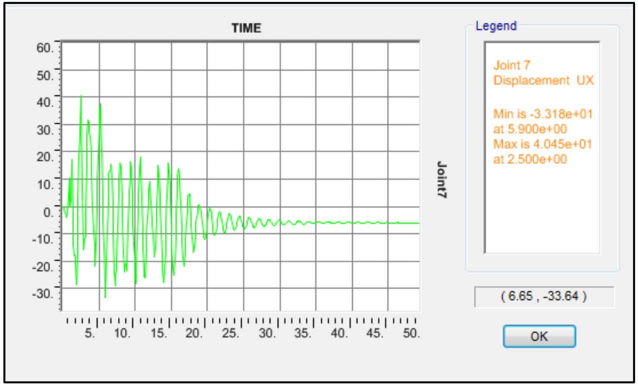
Series 2 (Joint 6)



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)

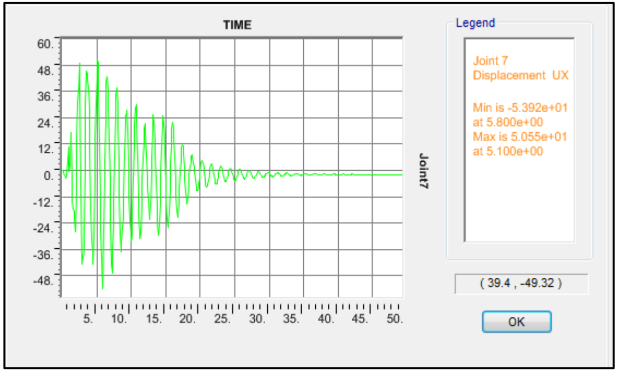


Joint 7
Displacement UX

Min is -3.318e+01
at 5.900e+00
Max is 4.045e+01
at 2.500e+00

(6.65 , -33.64)

Series 2 (Joint 7)



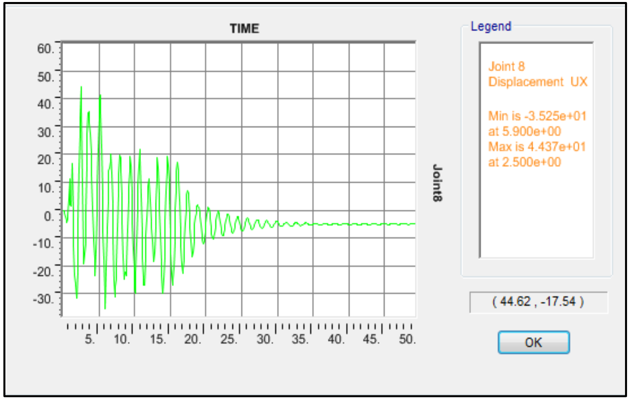
Joint 7
Displacement UX

Min is -5.392e+01
at 5.800e+00
Max is 5.055e+01
at 5.100e+00

(39.4 , -49.32)

Fig. 17: Displacement vs. time for joint 6 & 7 (Nonlinear Analysis - Series 1 & 2)

Series 1 (Joint 8)

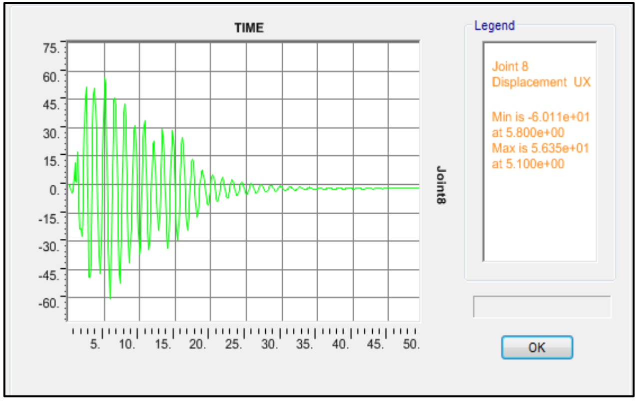


Joint 8
Displacement UX

Min is -3.525e+01
at 5.900e+00
Max is 4.437e+01
at 2.500e+00

(44.62 , -17.54)

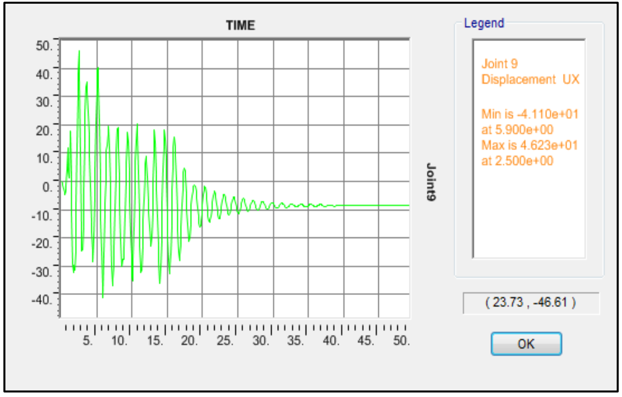
Series 2 (Joint 8)



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)

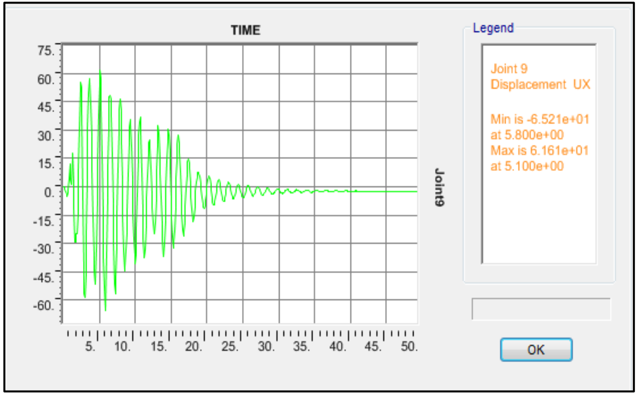


Joint 9
Displacement UX

Min is -4.110e+01
at 5.900e+00
Max is 4.623e+01
at 2.500e+00

(23.73 , -46.61)

Series 2 (Joint 9)

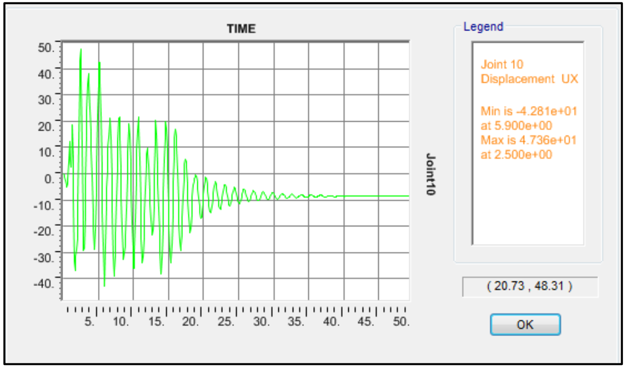


Joint 9
Displacement UX

Min is -6.521e+01
at 5.800e+00
Max is 6.161e+01
at 5.100e+00

Fig. 18: Displacement vs. Time for Joint 8 & 9 (Nonlinear Analysis - Series 1 & 2)

Series 1 (Joint 10)

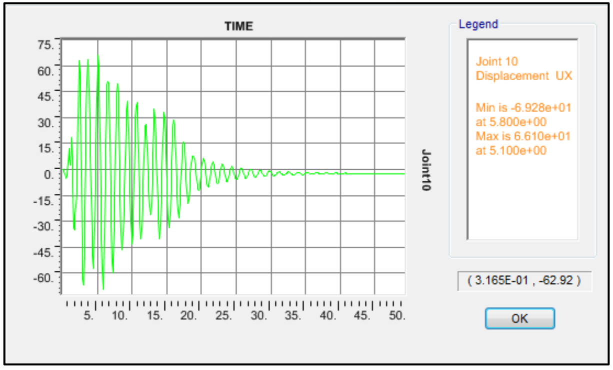


Joint 10
Displacement UX

Min is -4.281e+01
at 5.900e+00
Max is 4.736e+01
at 2.500e+00

(20.73 , 48.31)

Series 2 (Joint 10)

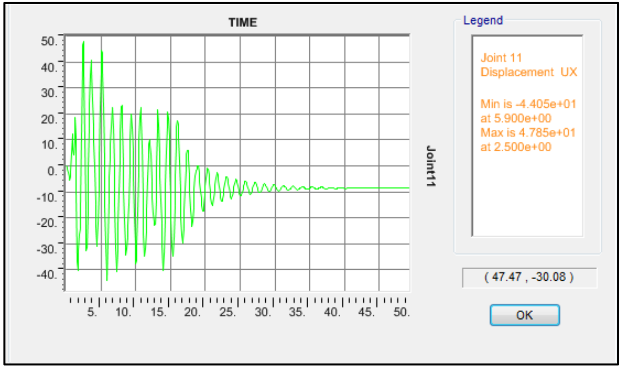


Joint 10
Displacement UX

Min is -6.928e+01
at 5.800e+00
Max is 6.610e+01
at 5.100e+00

(3.165E-01 , -62.92)

Series 1 (Joint 11)

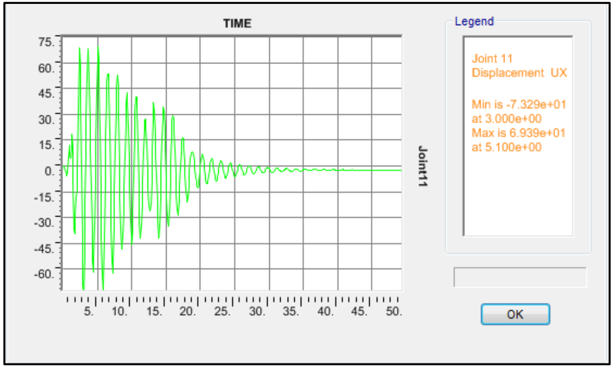


Joint 11
Displacement UX

Min is -4.405e+01
at 5.900e+00
Max is 4.785e+01
at 2.500e+00

(47.47 , -30.08)

Series 2 (Joint 11)

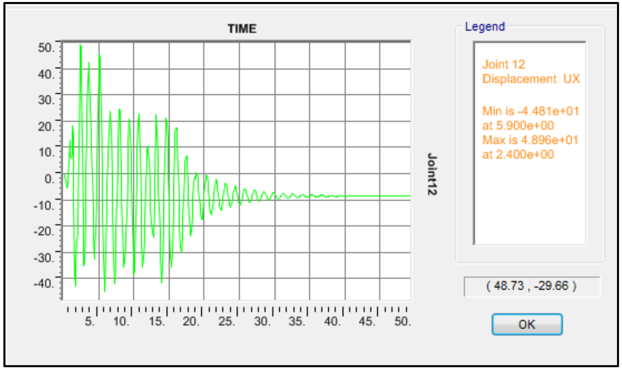


Joint 11
Displacement UX

Min is -7.329e+01
at 3.000e+00
Max is 6.939e+01
at 5.100e+00

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

Series 1 (Joint 12)

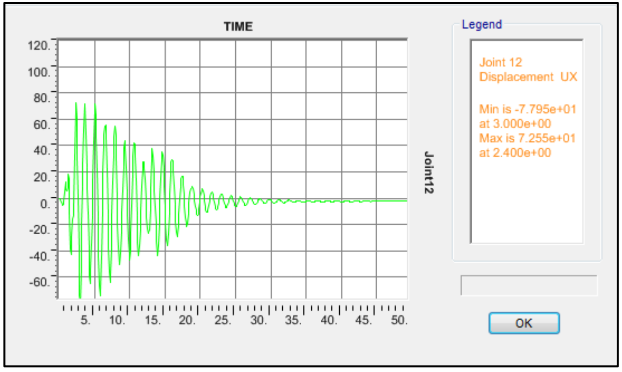


Joint 12
Displacement UX

Min is -4.481e+01
at 5.900e+00
Max is 4.896e+01
at 2.400e+00

(48.73 , -29.66)

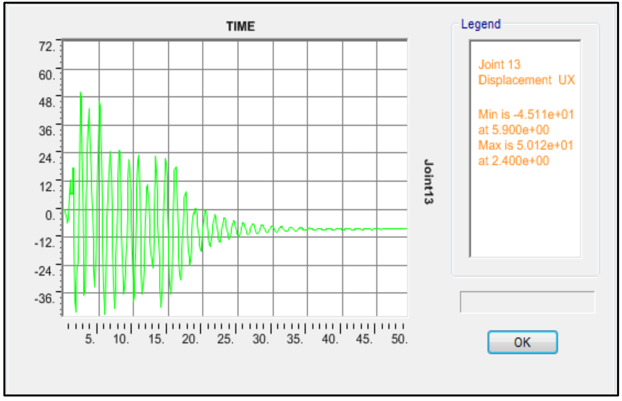
Series 2 (Joint 12)



Joint 12
Displacement UX

Min is -7.795e+01
at 3.000e+00
Max is 7.255e+01
at 2.400e+00

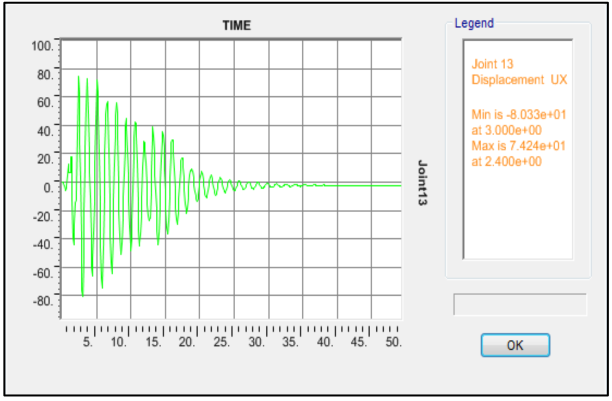
Series 1 (Joint 13)



Joint 13
Displacement UX

Min is -4.511e+01
at 5.900e+00
Max is 5.012e+01
at 2.400e+00

Series 2 (Joint 13)

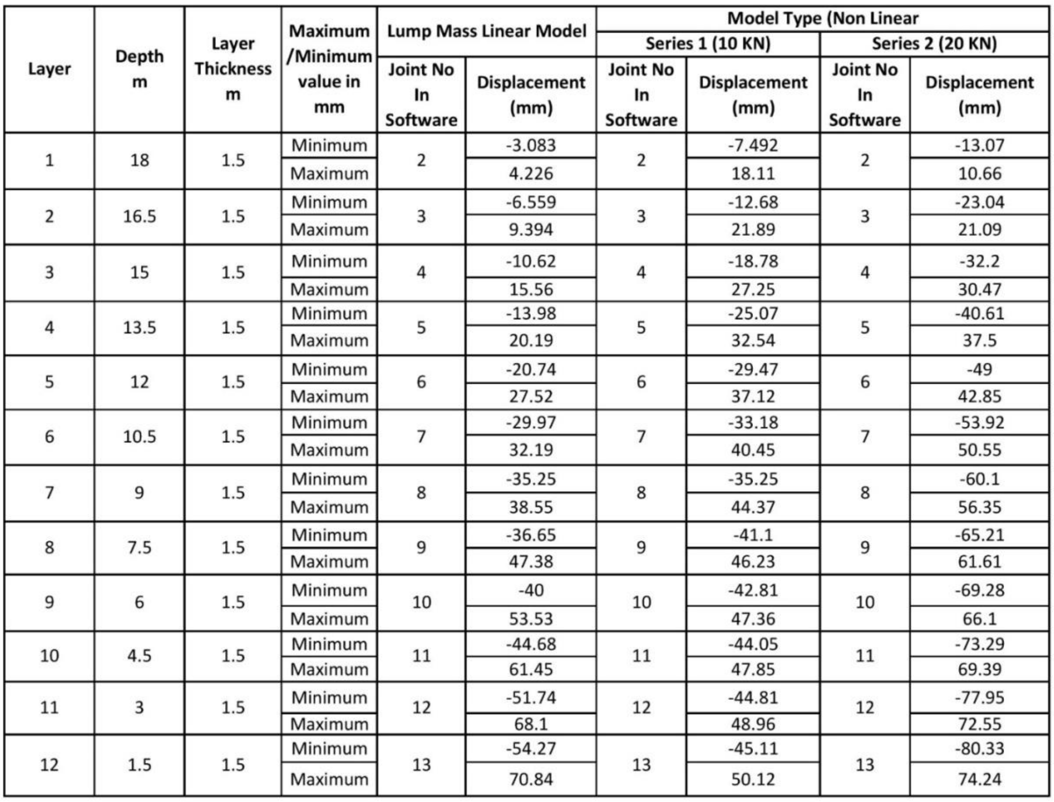


Joint 13
Displacement UX

Min is -8.033e+01
at 3.000e+00
Max is 7.424e+01
at 2.400e+00

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

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

Series 3			**Series 4**		
Displacement, mm	**Force, kN**	**Stiffness, kN/m**	**Displacement, mm**	**Force, kN**	**Stiffness, kN/m**
-70	-30	428.57	-70	-40	571.43
-68	-30	441.18	-68	-40	588.24
-61	-30	491.80	-61	-40	655.74
-53	-30	566.04	-53	-40	754.72
-47	-30	638.30	-47	-40	851.06
-38	-30	789.47	-38	-40	1052.63
-32	-30	937.50	-32	-40	1250.00
-27	-30	1111.11	-27	-40	1481.48
-20	-30	1500.00	-20	-40	2000.00
-15	-30	2000.00	-15	-40	2666.67
-12	-30	2500.00	-12	-40	3333.33
-10	-30	3000.00	-10	-40	4000.00
0	0	0.00	0	0	0.00
10	30	3000.00	10	40	4000.00
12	30	2500.00	12	40	3333.33
15	30	2000.00	15	40	2666.67
20	30	1500.00	20	40	2000.00
27	30	1111.11	27	40	1481.48
32	30	937.50	32	40	1250.00
38	30	789.47	38	40	1052.63
47	30	638.30	47	40	851.06
53	30	566.04	53	40	754.72
61	30	491.80	61	40	655.74
68	30	441.18	68	40	588.24
70	30	428.57	70	40	571.43

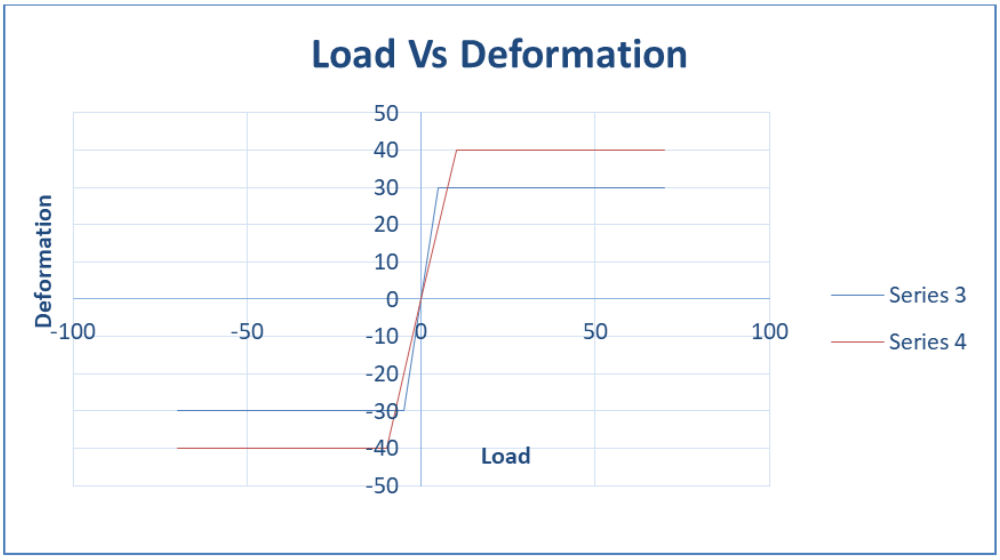
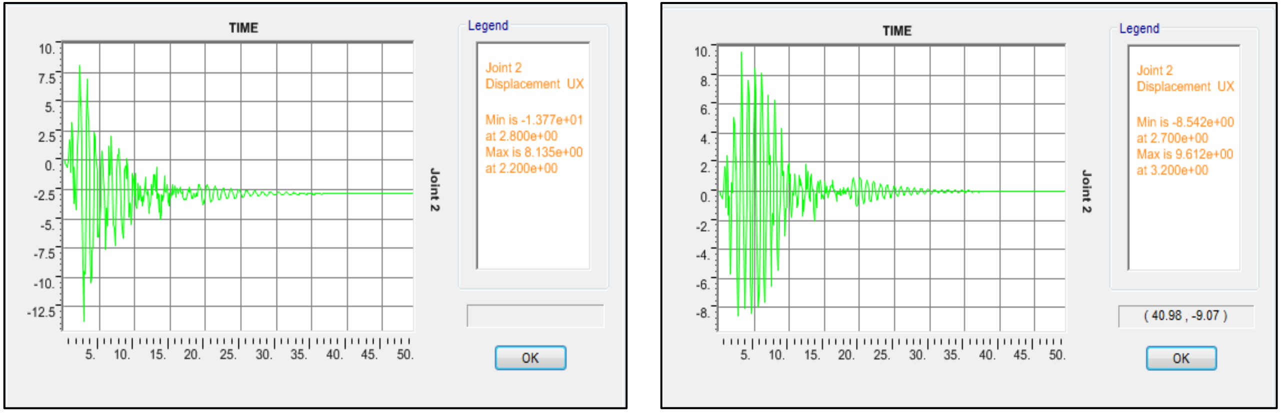


Fig. 21: Load vs. Deformation curve for Series 3 and 4


Series 3 (Joint 2)

Series 4 (Joint 2)

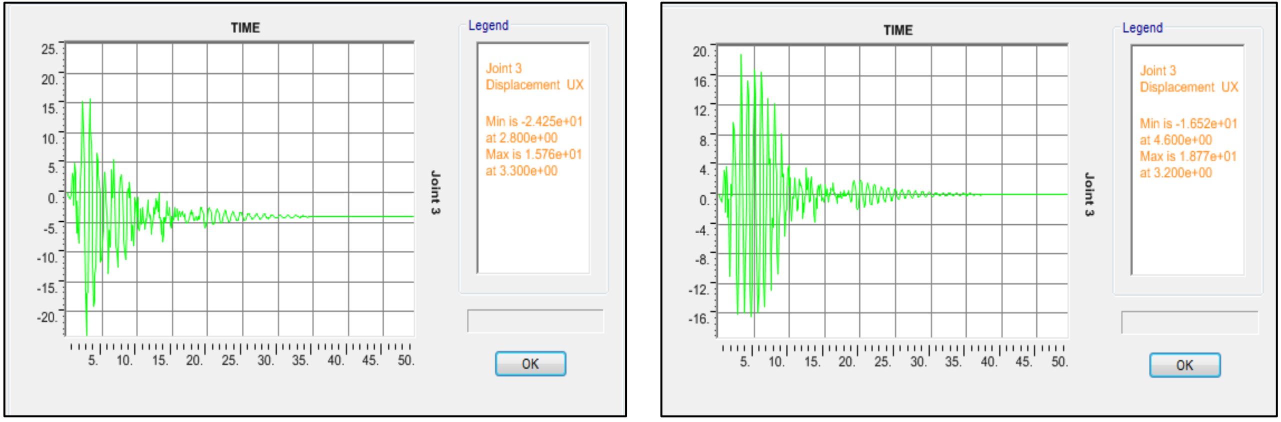
```
Joint 2
Displacement  UX

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)

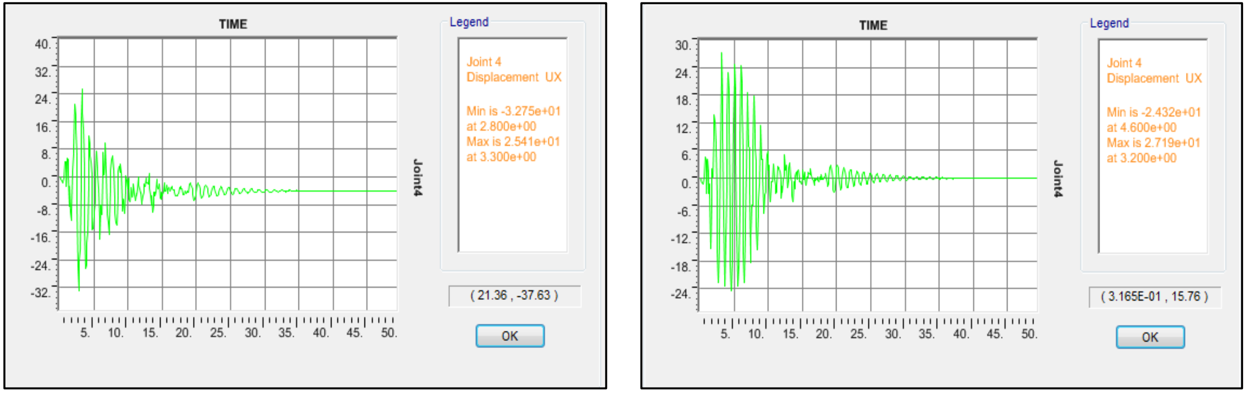
```
Joint 3
Displacement  UX

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)

Joint 4
Displacement UX

Min is -3.275e+01
at 2.800e+00
Max is 2.541e+01
at 3.300e+00

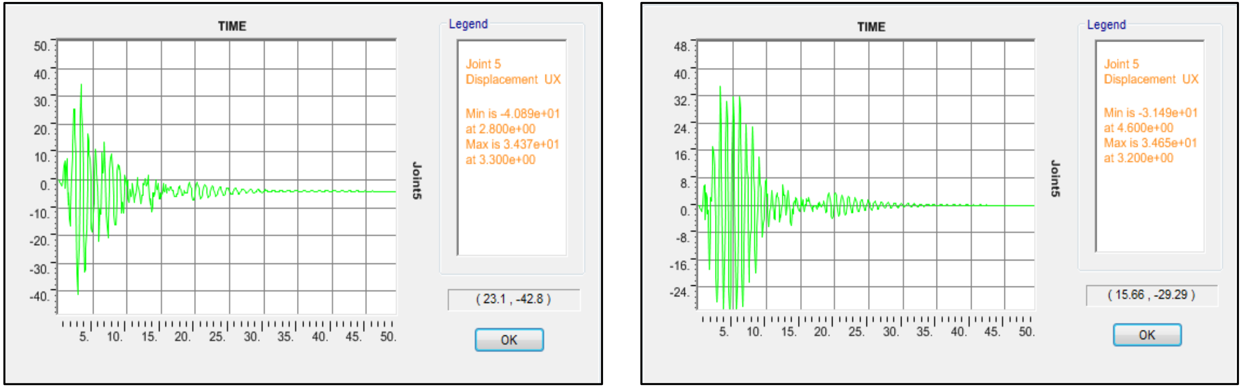
(21.36 , -37.63)

Series 4 (Joint 4)

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)

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)

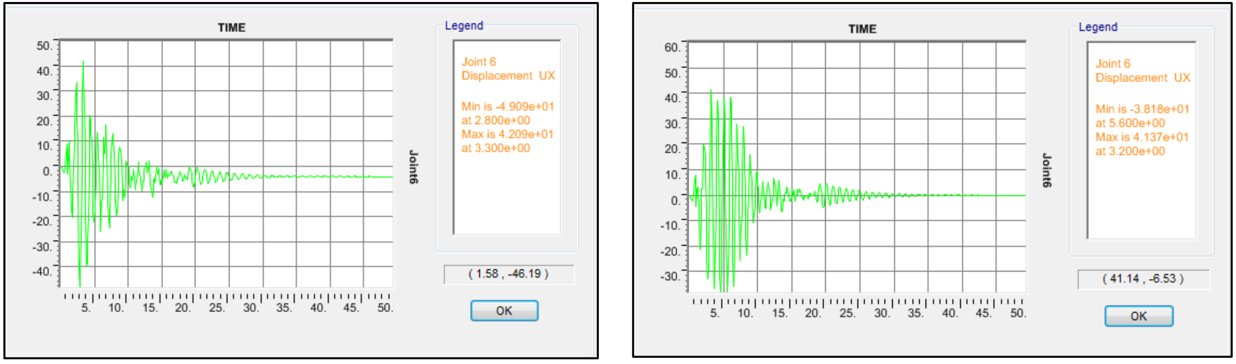
Series 4 (Joint 5)

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)

Joint 6
Displacement UX

Min is -4.909e+01
at 2.800e+00
Max is 4.209e+01
at 3.300e+00

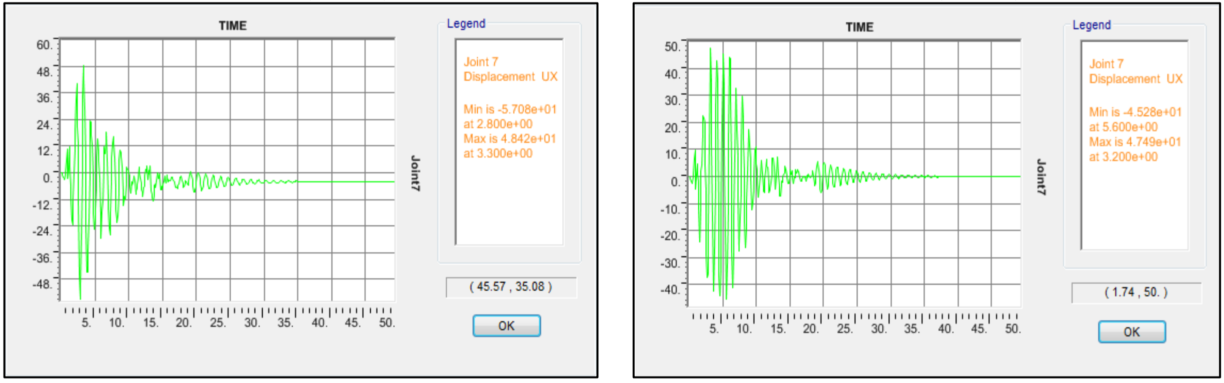
(1.58 , -46.19)

Series 4 (Joint 6)

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)

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)

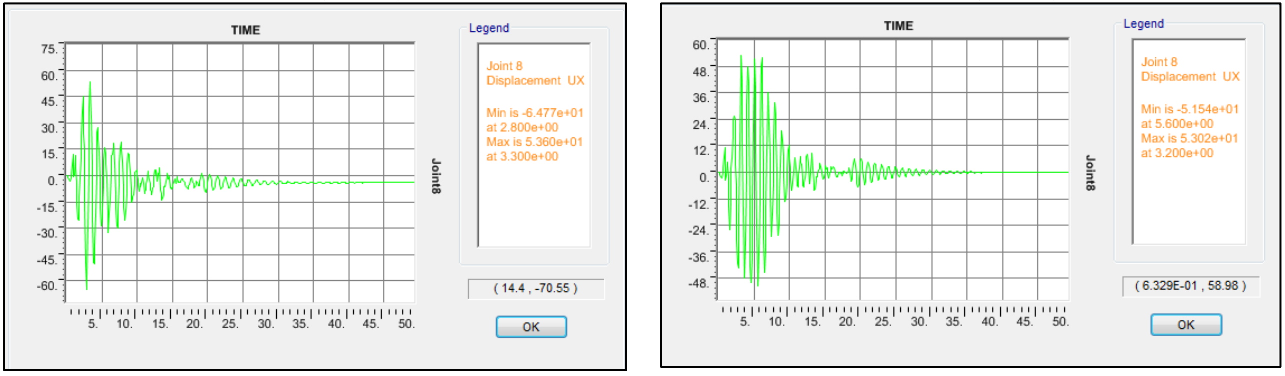
Series 4 (Joint 7)

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)

Legend

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)

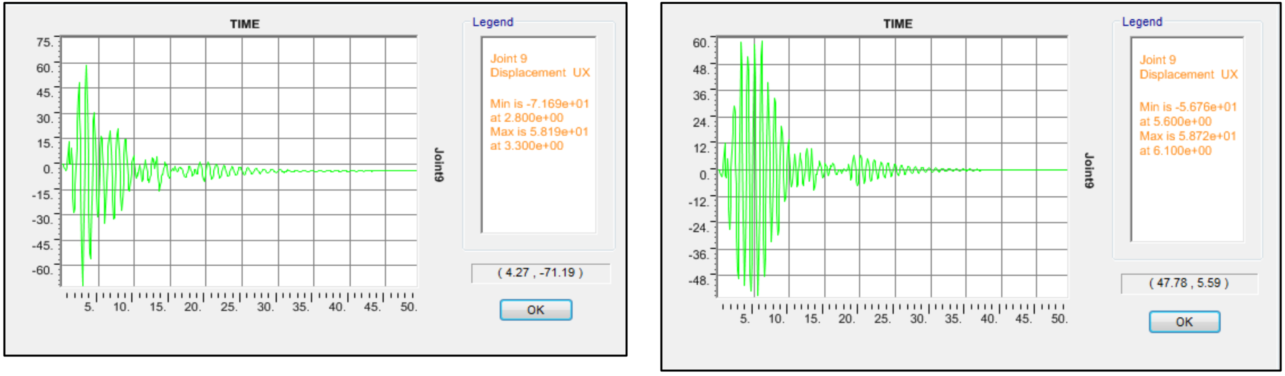
Series 4 (Joint 8)

Legend

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)

Legend

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)

Series 4 (Joint 9)

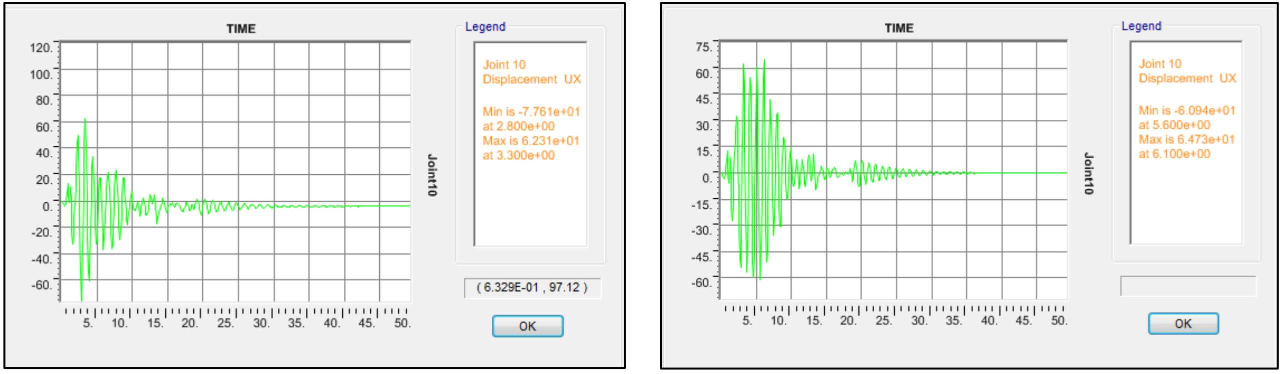
Legend

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)

Legend

Joint 10
Displacement UX

Min is -7.761e+01
at 2.800e+00
Max is 6.231e+01
at 3.300e+00

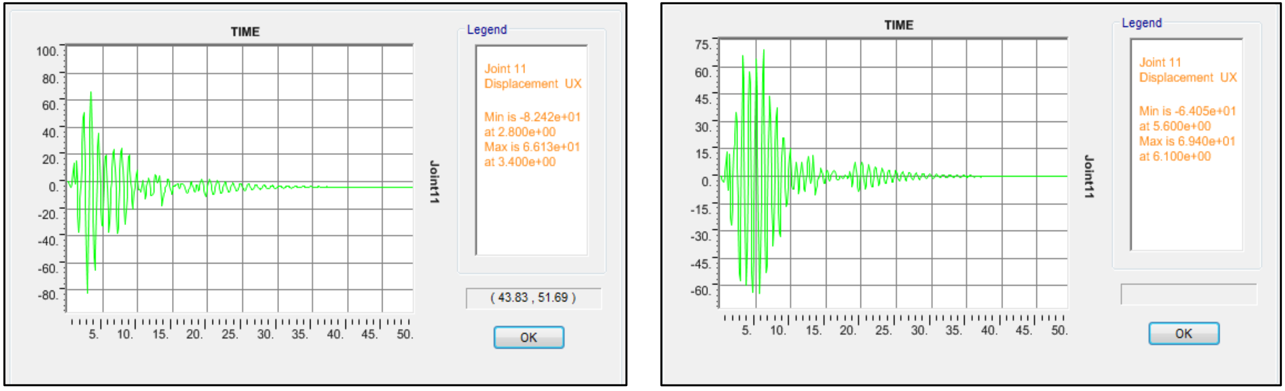
(6.329E-01 , 97.12)

Series 4 (Joint 10)

Legend

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)

Legend

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)

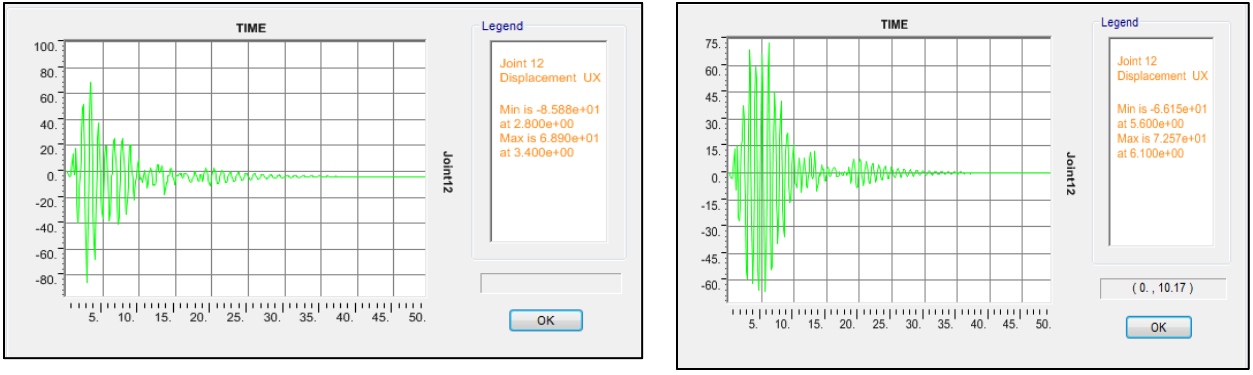
Series 4 (Joint 11)

Legend

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

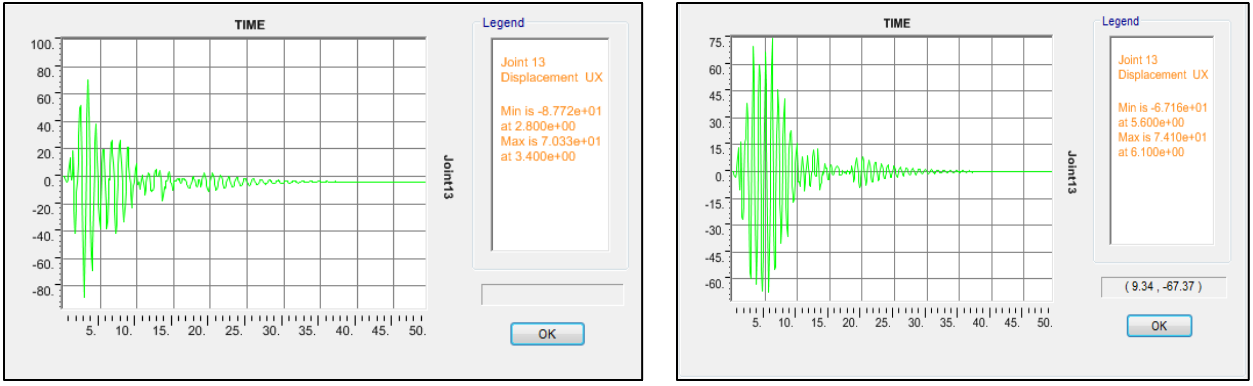
Min is -8.588e+01
at 2.800e+00
Max is 6.890e+01
at 3.400e+00

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

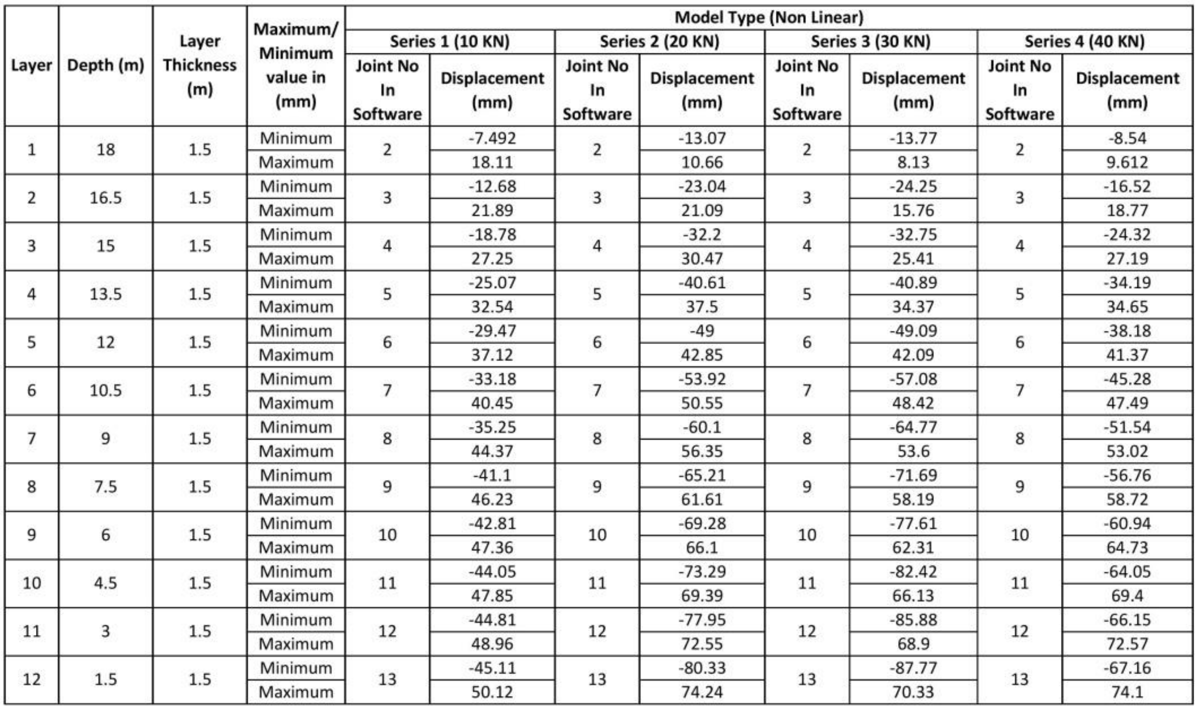
(9.34 , -67.37)

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

Table 5: 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 6: 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 7: 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 7 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

Lumped-mass model is found reasonably accurate and suitable for nonlinear analysis due to ground motion. This is used for subsequent nonlinear analysis models.

First, two series (Series 1 and 2) of load vs. displacement hysteresis loops are assumed for nonlinear analysis. Permanent deformations take place in both cases which cause tilting of buildings. Then two more series (Series 3 and 4) of load vs. displacement hysteresis loops are assumed for nonlinear analysis. Here permanent deformation has been found for Series 3 (although smaller than Series 1) but no deformation has been observed 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. Lumped soil mass can be used to understand the behavior of soil mass during earthquake. Amplification of soil is higher near surface. It indicates the effect of earthquake. If the stiffness of the soil is high then deformation starts with relatively small values. Deformation indicates elastic strain is small compared to plastic strain. Sometimes, it can take more time than ground motion time to settle down the vibration of the soil mass due to slender effect. Soil parameters play a very important role in case of the behavior of soil mass during earthquake. Failure of soil mass during earthquake is of the main cause of tilting of the buildings. Permanent deformation is observed for nonlinear elastic, perfectly plastic hysteresis loops. If the stiffness of the soil is higher than permanent deformation may not take place.

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