



(RESEARCH ARTICLE)



## Comparative analysis of linear dynamic responses and undamped systems of soil-pile-footing interaction for various soil media

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### Abstract

It is seen from recent earthquakes that in case of fixed-base foundation system, damped systems have proved to be prolonging the lifespan of the structure by lengthening the lateral fundamental period that leads to higher damping in comparison to the assumptions of a fixed-base system.

In this study, to better understand the phenomenon involved in soil-pile interaction a finite element simulation model is developed in Abaqus FEA software. The numerical model made for transient analysis follows Rayleigh's Damping Coefficient model for material damping.

In this paper, a rational analysis of Dynamic Response of a Short-Bored Pile is made subject to axial load by the Finite Element Method. The analysis is performed using finite element Abaqus CAE software. The Soil media is developed for sand soil and clay soil with pile material as Mild Steel and RCC, and analysis is made for the combination of each material group with the incremental axial load. The same FE model is studied for damped material used in piles which results in a drastic change in displacement pattern.

**Keywords:** Friction Soils; Cohesive Soil; Mohr-Coulomb; Abaqus CAE; Damping Response; Soil-Pile System

### 1. Introduction

The ground vibrations phenomenon is many times experienced in various soil media. It is known that due to any kind of cyclic loading vibrations are developed in the surrounding soil media and is exposed to nearby structures in form of horizontal vibrations, which initiates interest in the field of geodynamics.

Studies in recent past have shown that the foundation interacts dynamically with the structure constructed upon it, resulting in a visible difference in the values of maximum deflection, stresses, and strains in comparison to that obtained by fixed base foundation underneath a structure.

It is in general practice of the various authorities or engineers for dynamic analysis that they ignore or belittle the effect of foundation flexibility on the dynamic response of a superstructure.

The disasters in pile foundation occur often, especially in liquefiable soil layer which can be established from all the earthquakes registered in the past.

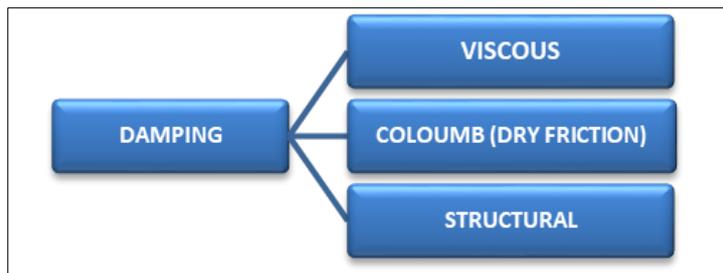
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It is in trends to study the liquefiable soil layer for the lateral capacity of pile foundation but the theory is found suitable for only with reference to the static condition of loading which also contributes in the shortage or misunderstanding to the mechanism of liquefied-related pile-soil interaction is another trouble.

The relationship among acceleration, pore-water pressure, deformation and modulus of soil layer, acceleration, the bending moment of pile and interaction force of soil and pile, response of pile-head can be analyzed through many tests. The results in this paper show the movement of soil layer surface and dynamic response of pile foundation in the pure friction and clay soil. The relative displacement between soil and pile in soil media is tested and found that the displacement observed by damped piles has substantially lower capacities than that observed by an undamped system and has observably higher axial loading capacities.

## 2. Concept of damping

Study of energy dissipation as a result of seismic response of structures by dampers and isolators has gained its popularity between researchers. In general terms damping is termed as the dissipation of mechanical energy into thermal energy. Knowledge of level of damping in dynamic systems is more important in analysis, testing and utilization of the structure. From this gained knowledge and past studies [1] damping is classified as follows.



**Figure 1** Types of Damping

### 2.1. Salient features of Viscous Damping

Viscous Damping is caused by energy losses in which mechanical energy is dissipated in the form of thermal or heat energy between surfaces.

There are 4 ways to gain or alter viscous damping [2]:

- Increasing the velocity of viscous material.
- Increasing the area containing the viscous material.
- Increasing the applied velocity.
- Amplifying the damping force of the viscous material.

### 2.2. Salient features of Coulomb (Dry) Damping

Models' incorporating Coulomb or dry friction has been a subject of active research since the finding contribution of Coulomb's hypothesis. The predictions of dynamic responses require robust dry friction models.

Generally, there are numerous types of dry friction models and it is crucial to appropriately choose one that best fits the model problem. The system with dry friction that follows the Coulomb hypothesis often exhibits complex dynamical behavior inclusive of chaotic and stochastic responses [4].

The developed model showing the dynamic and static frictional characteristics also describe hysterical dynamic behavior of dry friction developed by pre-displacement effect and frictional lag.

However, it is not practically possible to incorporate all the frictional effects in a single model for complete analysis for which small modular entities are developed for prototype analysis. For which my researches have been developed to solve the applied practical engineering problems involved.

### 2.3. Salient features of Structural/ Boundary Damping

Structural Damping is mainly due to the relative motion of mechanical components of the structure.

In the context of modelling and simulating the mathematical model it is treated as a difficult model than that dependent on Coulomb's frictional hypothesis for damping.

Mostly boundary damping can be seen as friction between steel joints and in element slippages [5]. In a complete built up system boundary damping can be seen as of higher magnitude than that of material damping.

### 2.4. Effect of Damping in Real Conditions

In real conditions a major natural source of energy dissipation of structure and foundation is its supporting soil media, which results in higher benefits to the structure in certain situations. The supporting soil media potentially benefits the structure by restricting responses developed in the structure from the base. Unfortunately, this major topic is many-a-times is neglected by engineers as soil-structure analysis is considered as a naive topic in theoretical concept which reduces its practical hugeness.

For a particular Soil Structure Interaction (SSI) from the theories already know about the impedance function related to the frequency dependent foundations, practical system identification methods for significant modes of vibrations can be accounted with the help of an experienced consultant.

It should also be noted that by studies happened to be in past regarding SSI experiments [3] and theoretical calculations of simple models like short-span bridges, fuel storage tanks, short and mid-rise buildings, etc, have yielded relatively large modal damping ratios.

## 3. Damping parameters used

Using the phenomenon of Structural Damping Rayleigh Damping concept is used.

### 3.1. Rayleigh Damping Coefficients

In the transient dynamic analysis, it is necessary to apply Rayleigh damping. Rayleigh damping is characterized by the two constants a and b, whereas the  $\zeta$  damping coefficient of material.

The analysis is carried further as follows: For Modal analysis the lower and upper frequencies are taken as  $\zeta_1$  and  $\zeta_2$  for the two lowest frequencies  $\omega_1$  and  $\omega_2$  then,

$$a = 2\omega_1\omega_2\beta \text{ and } b = 2\beta$$

Where,

$$\alpha = \omega_1/\omega_2 \text{ and } \beta = (1-\alpha) \zeta / (\omega_2 - \alpha\omega_1)$$

For the model the Natural period of Structure was taken as

$$0.05 \text{ sec to } 2.00 \text{ sec}$$

In all the cases of soil-pile-footing system for the established loading system, the Natural Frequency of Structure was taken to be

$$\omega_1 = 0.2 \text{ and } \omega_2 = 20$$

## 4. Model parameters

The finite element software ABAQUS CAE is used in the analysis to find the consolidation of single pile using a 2-D SSI model. For the model under consideration the dimension parameters are described as in Table 1, Table 3 and Table 4.

The soil media surrounding foundation used for analysis are Pure friction soil (Table 2) and Clay soil (Table 2)

**Table 1** Soil Model Parameters Used

<b>Dimensions of the Soil Pit Model</b>		
<b>L (m)</b>	<b>B (m)</b>	<b>H (m)</b>
1.2	0.75	1.35

**Table 2** Soil Model Material Parameters Used

<b>Soil Type</b>	<b>Sand Soil</b>	<b>Clay Soil</b>
Unit Weight (KN/m <sup>3</sup> )	1500	2150
Modulus of Elasticity (Kg/m <sup>2</sup> )	540000	500000
Poisson's Ratio	0.4	0.4

The model is used for the simulation of soil-pile-footing analysis has structural parameters as in Table 3 and Table 4. The Damping coefficients used for Pile-Footing System of SSI model are described in table 5.

**Table 3** Material Parameters used for Pile-Footing system

<b>Diameter of Pile Bars Used in Analysis (mm)</b>	<b>18</b>	
<b>Material</b>	<b>Mild Steel</b>	<b>RCC</b>
Unit Weight (Kg/m <sup>3</sup> )	7850	2400
Modulus of Elasticity (Kg/m <sup>2</sup> )	200000	27387
Poisson's Ratio	0.33	0.15

**Table 4** Material Parameters used for Footing over Pile Model

<b>Diameter of Footing Used in Analysis (mm)</b>	<b>150</b>	
<b>Thickness of Footing Used in Analysis (mm)</b>	<b>10</b>	
<b>Material</b>	<b>Mild Steel</b>	<b>RCC</b>
Unit Weight (Kg/m <sup>3</sup> )	7850	2400
Modulus of Elasticity (Kg/m <sup>2</sup> )	200000	27387
Poisson's Ratio	0.33	0.15

**Table 5** Damping Parameters used for Pile-Footing System

<b>Applicable Constants</b>	<b>Mild Steel</b>	<b>RCC</b>
Alpha	0.025	0.025
Beta	0.00098	0.00025
Composite Damping	0.02	0.05
Structural Damping	0.02	0.02

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## 5. Development approach

Soil interaction with foundation is not same for all cases. It depends on physical conditions and mechanical properties of the soil media. A slight change in any of the above attribute displays drastic changes in the outcomes of a particular analysis.

Considering this change in analytical pattern multiple analysis models are supposed to be taken into research aspect for drawing better conclusions out of a simple analysis.

In context of the analysis taken into consideration of this paper the SSI models are developed for FEA analysis in Abaqus as in following hierarchy.

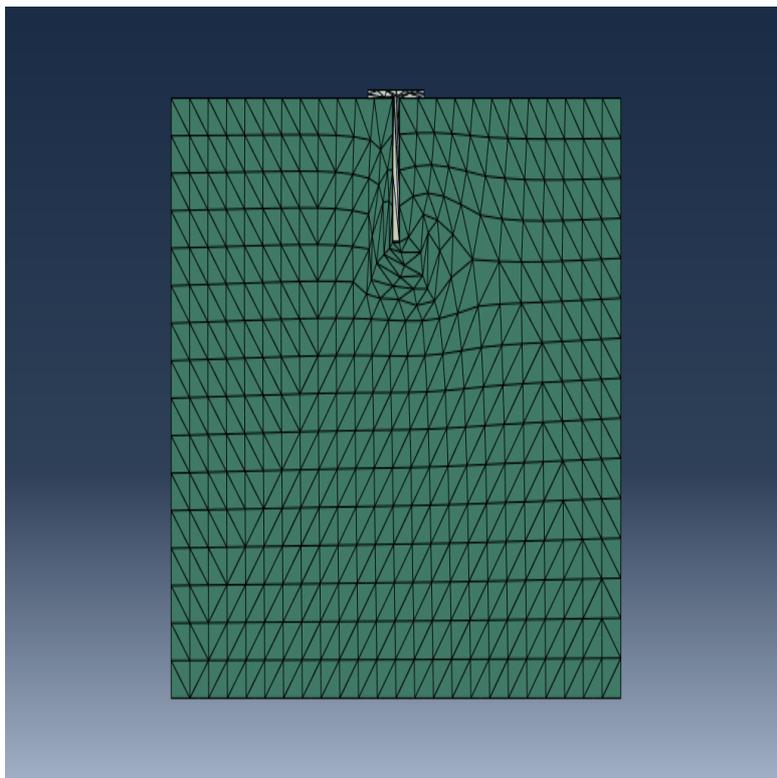
- Undamped Steel Pile-Footing System in Sand Soil Media.
- Damped Steel Pile-Footing System in Sand Soil Media.
- Damped Steel Pile-Footing System in Clay Soil Media.
- Damped RCC Pile-Footing System in Sand Soil Media.
- Damped RCC Pile-Footing System in Clay Soil Media.

Keeping all physical drawing entities same the mechanical properties are changed as per Table 2, Table 3, Table 4, and Table 5.

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## 6. Analysis

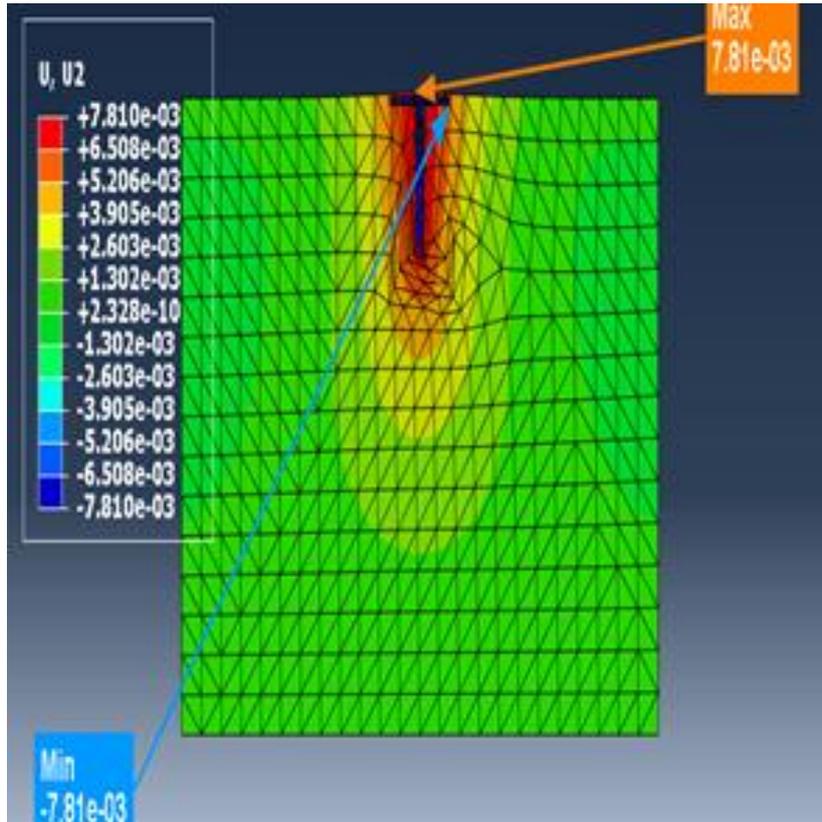
Multiple combinations of models are made as 2-D Axisymmetric finite element model for analysis for perfect contact in between the deformable parameters of the model. The models are made for the assumptions of Homogenous, Solid, Linear, Elastic material section with above-defined properties.



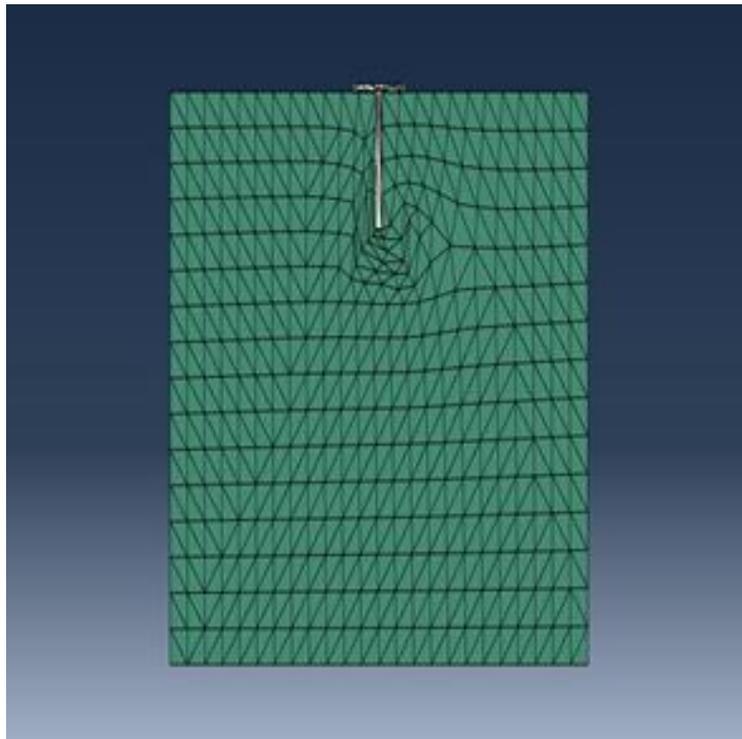
**Figure 2** Undamped Steel Pile-Footing system in Sand Soil

A Pile-Footing system with optimum physical parameters is modelled for Steady-State Dynamics, Direct Linear Perturbation Analysis Step with Surface-to-Surface Frictional Contact with Hard Normal Behavior.

Fix type of Boundaries are made at all the physical ends of the model, i.e.; no displacement and no rotation are allowed at the infinite edge of soil model at the time of loading the system. The Constraint applied is Equation type in between soil and pile-footing surfaces for axial load condition.

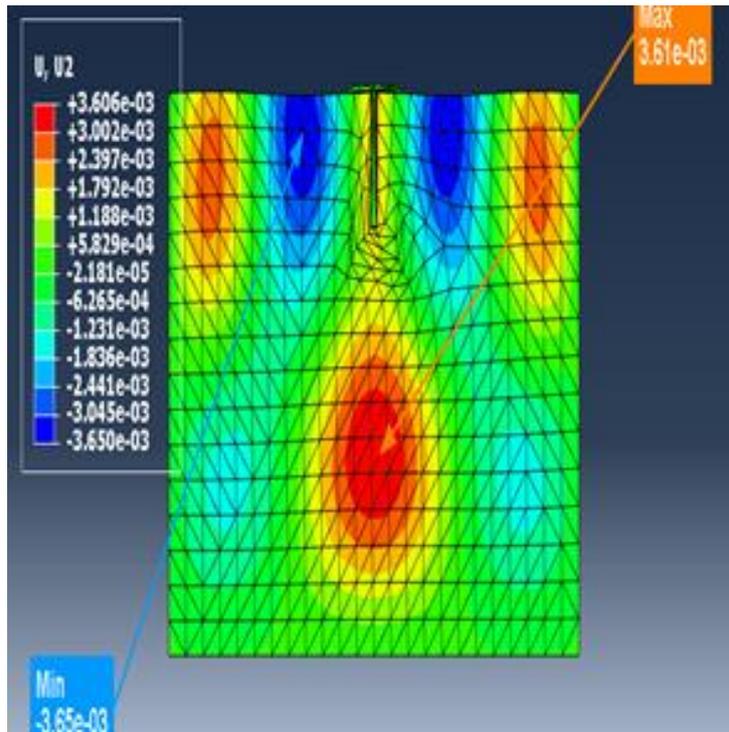


**Figure 3** Displacement Results of Front View of Undamped Steel Pile-footing in Sand Soil



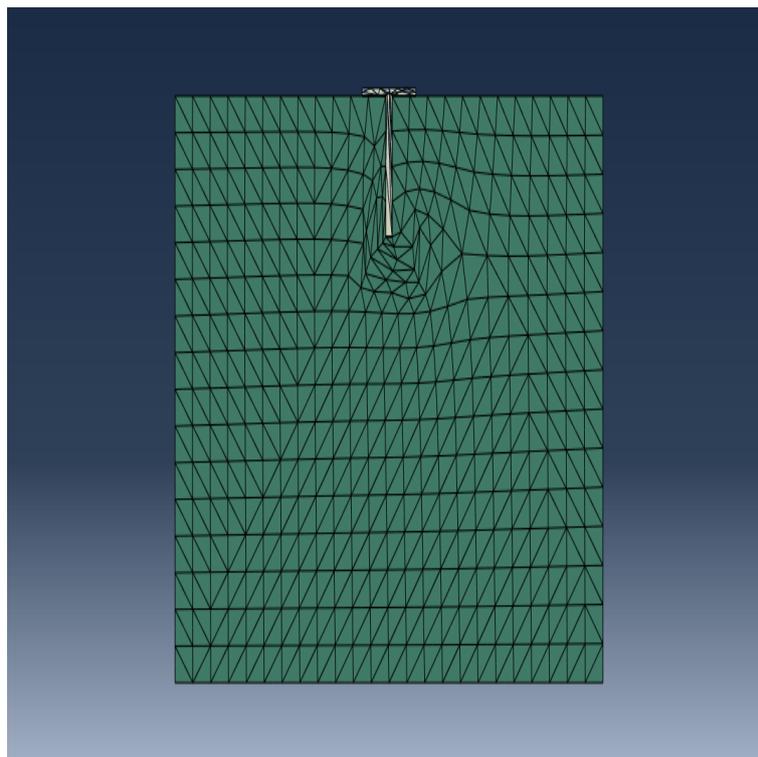
**Figure 4** Damped Steel Pile-Footing system in Sand Soil

The job is declared for complete stress stain analysis and various analysis and calculations for the model are procured. Various results obtained from all the cases are enlisted as follows and are discussed further.



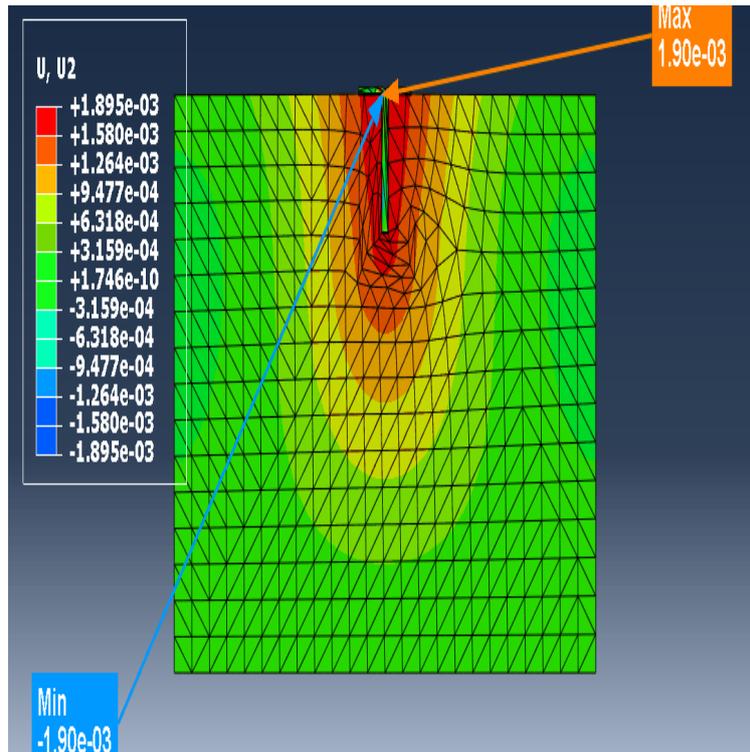
**Figure 5** Displacement Results of Front View of Damped Steel Pile-footing in Sand Soil

In the results obtained it is found that the pressure bulbs formed in sand soil media and clay soil media to conform to the theory of overlapping of stress areas due to piles in close vicinity as follows.



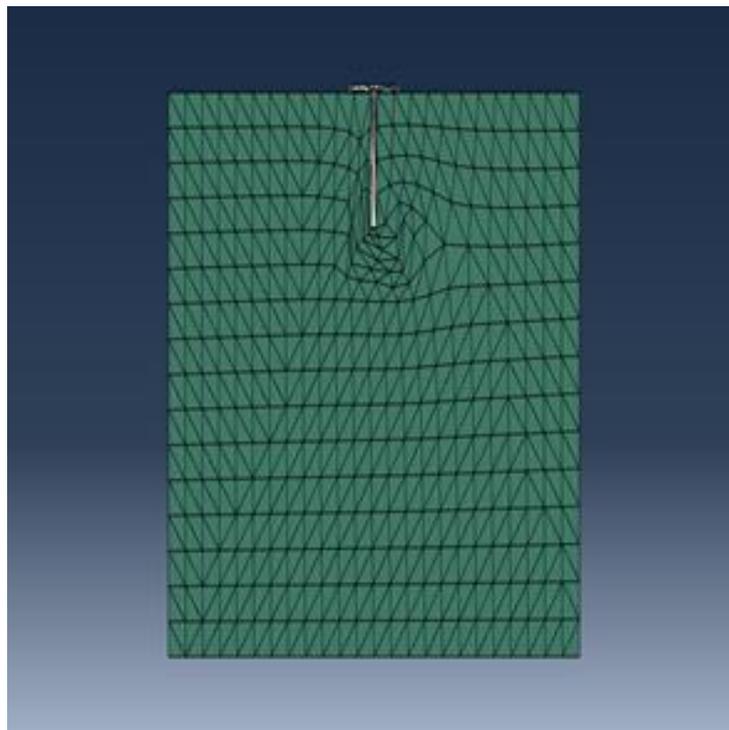
**Figure 6** Damped Steel Pile-Footing system in Clay Soil

Majorly the displacement analysis and load bearing capacity of SSI model is tested and compared for each type of soil media and undamped and damped pile-footing system for simulation.



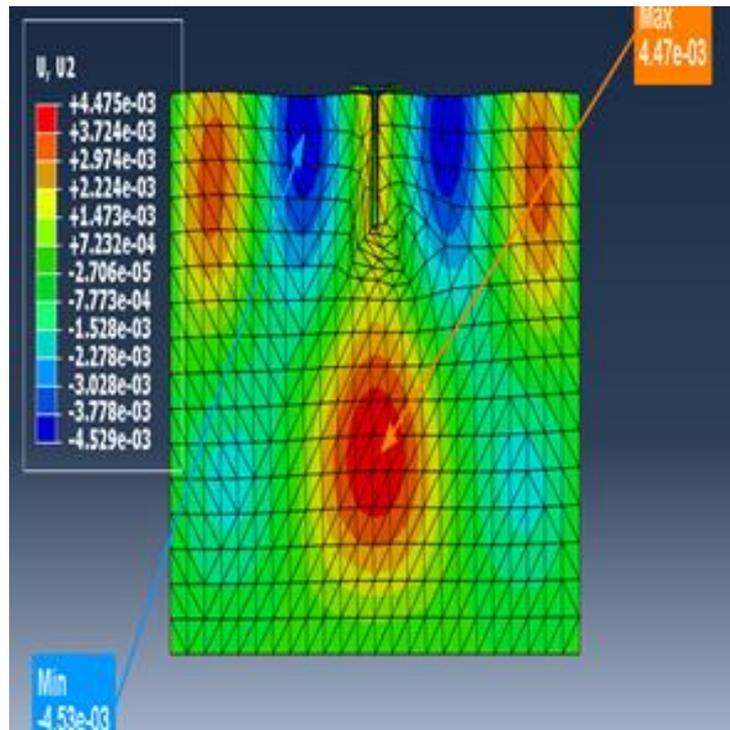
**Figure 7** Displacement Results of Front View of Damped Steel Pile-footing in Clay Soil

After analyzing the data obtained by the Damped Steel Pile-Footing system in Sand and Clay Soil media in comparison to the Undamped Steel Pile-Footing system in sand soil media it is observed that there exist a greater load carrying capacity in the damped system than that observed in the undamped system as described in Graph 1 and Graph 2.

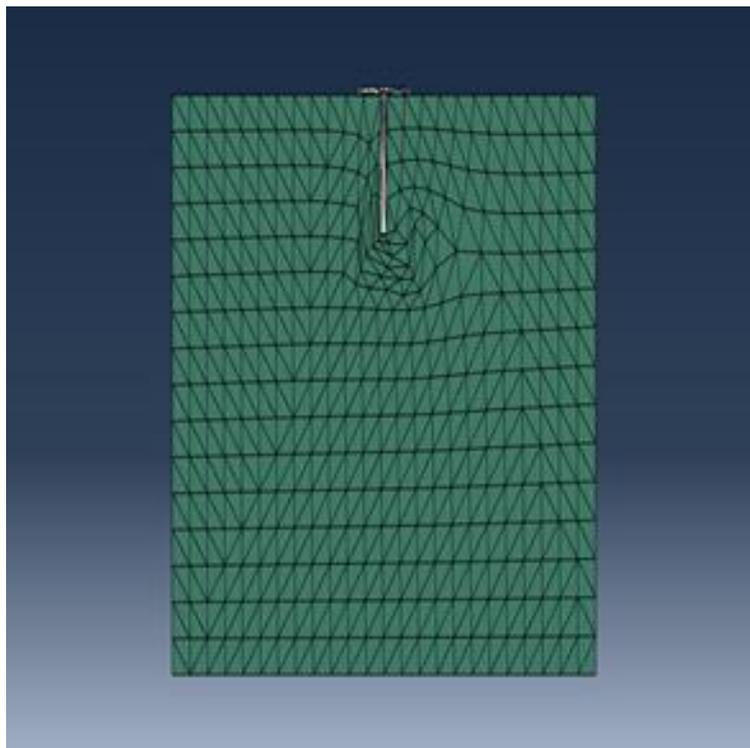


**Figure 8** Damped RCC Pile-Footing system in Sand Soil

Pictorial analysis of Undamped Steel Pile-Footing System in Sand Soil media is compared with Damped Steel Pile-Footing System. In this analysis it is found that the displacement caused in system is drastically lowered by over 73%.



**Figure 9** Displacement Results of Front View of Damped RCC Pile-footing in Sand Soil

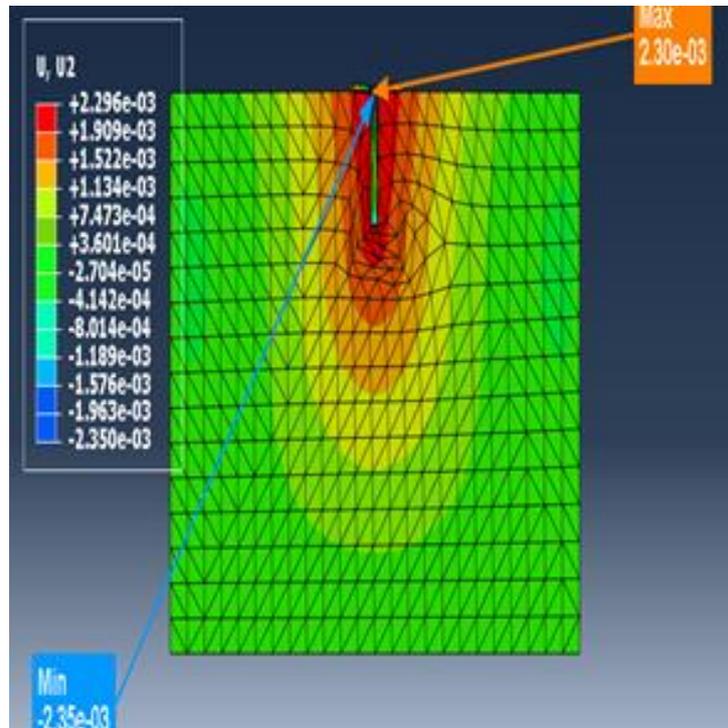


**Figure 10** Damped RCC Pile-Footing system in Clay Soil

Further extending this analysis, it is found that soil media surrounding the Pile-Footing system has drastic effects on the displacement pattern and the displacement caused at each load point. For analyzing this effect of soil media on the Pile-Footing system the mechanical properties of soil media are changed to Clay Soil and are analyzed further.

After this simulation it is found that the displacement caused in at Damped Steel Pile-Footing System in Clay Soil as in Graph 3 has nearly 9% more resistance than that of displacement caused by Damped Steel Pile-Footing System in Sand Soil Media. The study is further advanced for changes in Pile-Footing material to Damped RCC material with Sand Soil Media in surrounding.

Simulating this response it is concluded that there exists a difference of nearly 20% when compared between Damped Steel Pile-Footing System to that of Damped RCC Pile-Footing System in Sand Soil media. Upon this result, the discussion is further developed to analyze for the RCC Pile-Footing system as described in Graph 4.



**Figure 11** Displacement Results of Front View of Damped RCC Pile-footing in Clay Soil

After this set of simulation it is observed that there exists a difference of nearly 12% when the displacement values between Damped RCC Pile-Footing System in Sand Soil Media with that of Damped RCC Pile-Footing System in Clay Soil Media Graph 5

## 7. Results

The pressure bulbs observed in all cases were graphically similar to that of the elastic foundations for axial loading applied upon each system. The percentage difference helps to conclude that the Frictional Resistances offered by the damped pile-footing to the soil media is found to be greater than that of the undamped pile-footing system.

The loading resistances of pile-footing system are found to be greater in clay soil than that of the sand soil. The practical scaled real life models would yield the same results as developed from the model.

Hierarchical order of load carrying capacities of damped and undamped models of Steel and RCC Pile-Footing System in sand and clay soil media is as follows (table 6).

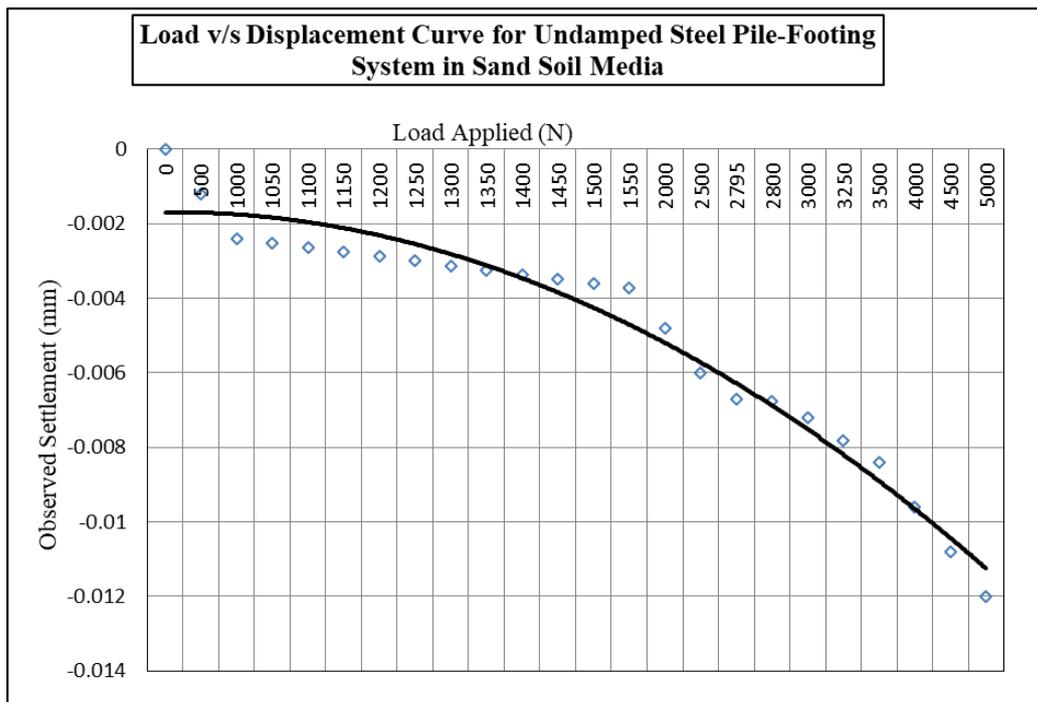
While comparatively analyzing the damped and undamped system the following conclusions were made (Table 7, Graph 6 and Graph 7).

**Table 6** The hierarchal order for load carrying capacity

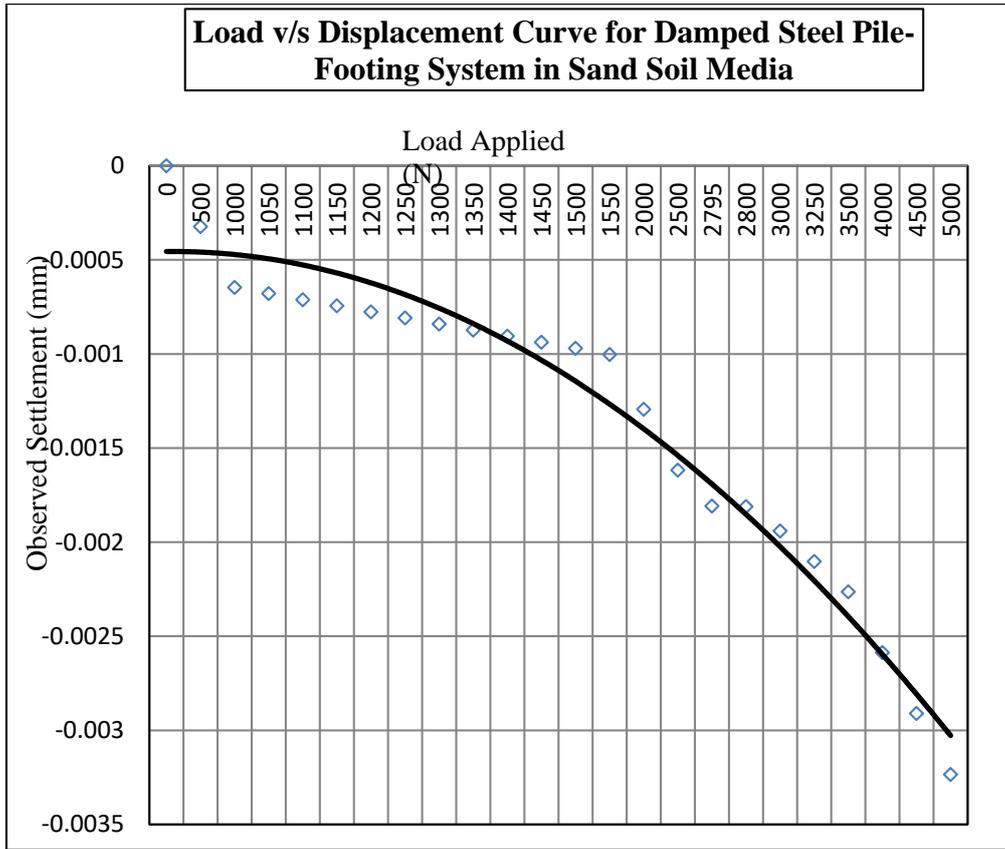
S. No.	Hierarchal Order for Load Carrying Capacity
1	Damped Steel Pile-Footing System in Clay Soil Media
2	Damped Steel Pile-Footing System in Sand Soil Media
3	Damped RCC Pile-Footing System in Clay Soil Media
4	Damped RCC Pile-Footing System in Sand Soil Media
5	Undamped Steel Pile-Footing System in Sand Soil Media

**Table 7** Comparative analysis of all the case models

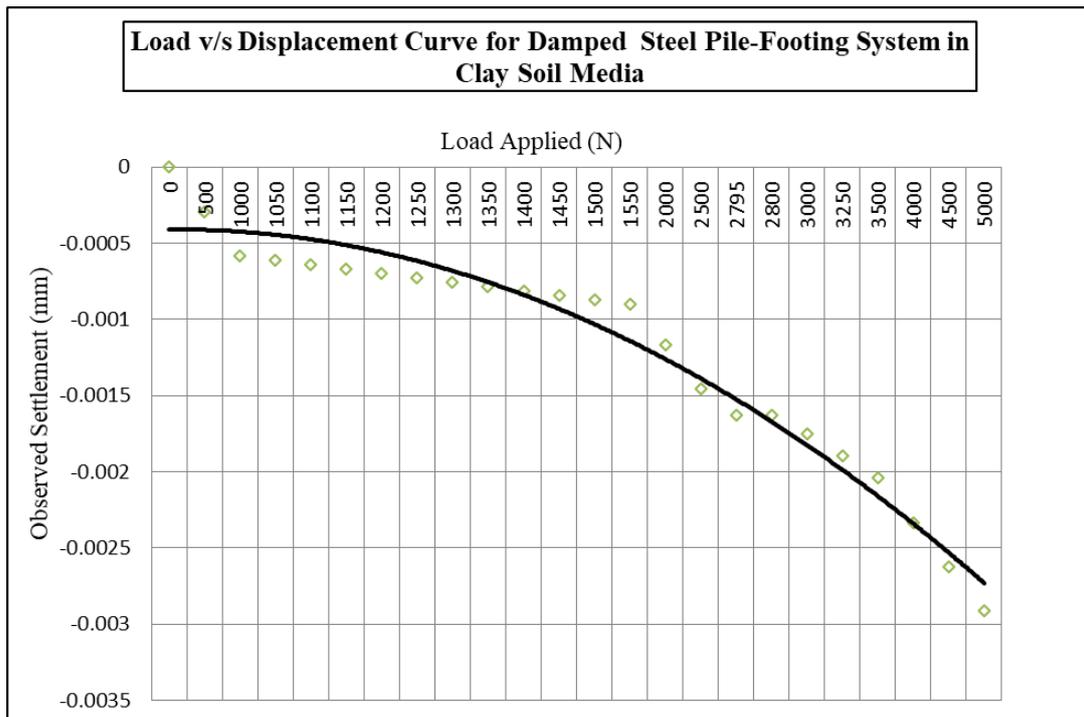
Comparative Analysis Model		Percentage Difference
Undamped Steel Pile-Footing System in Sand Soil Media	Damped Steel Pile-Footing System in Sand Soil Media	73%
Damped Steel Pile-Footing System in Sand Soil Media	Damped RCC Pile-Footing System in Sand Soil Media	19-20%
Damped Steel Pile-Footing System in Sand Soil Media	Damped Steel Pile-Footing System in Clay Soil Media	9-10%
Damped RCC Pile-Footing System in Sand Soil Media	Damped RCC Pile-Footing System in Clay Soil Media	11-12%



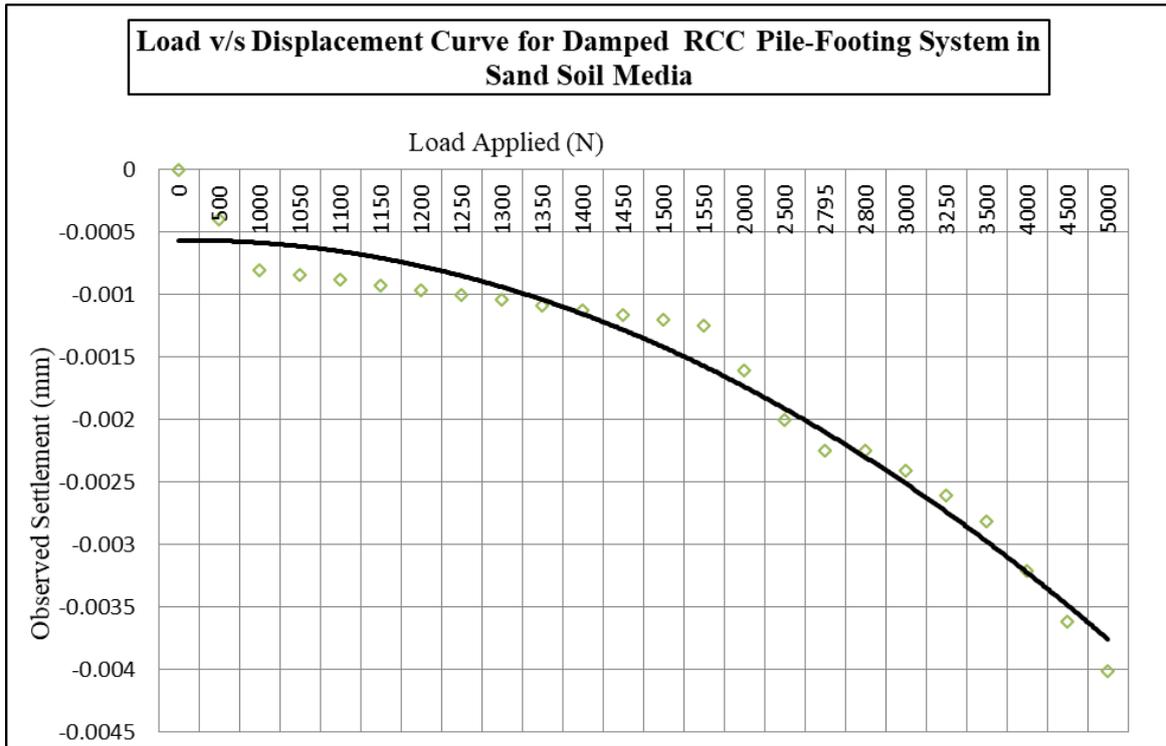
**Figure 12** Load v/s Displacement Curve for Undamped Steel Pile-Footing System in Sand Soil Media



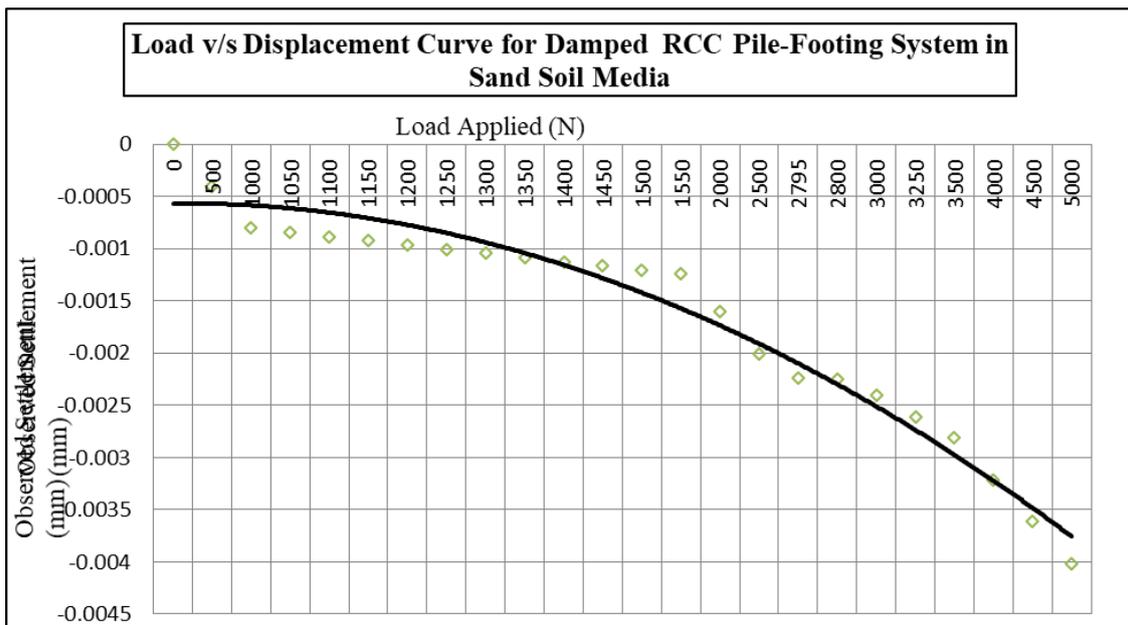
**Figure 13** Load v/s Displacement Curve for Damped Steel Pile-Footing System in Sand Soil Media



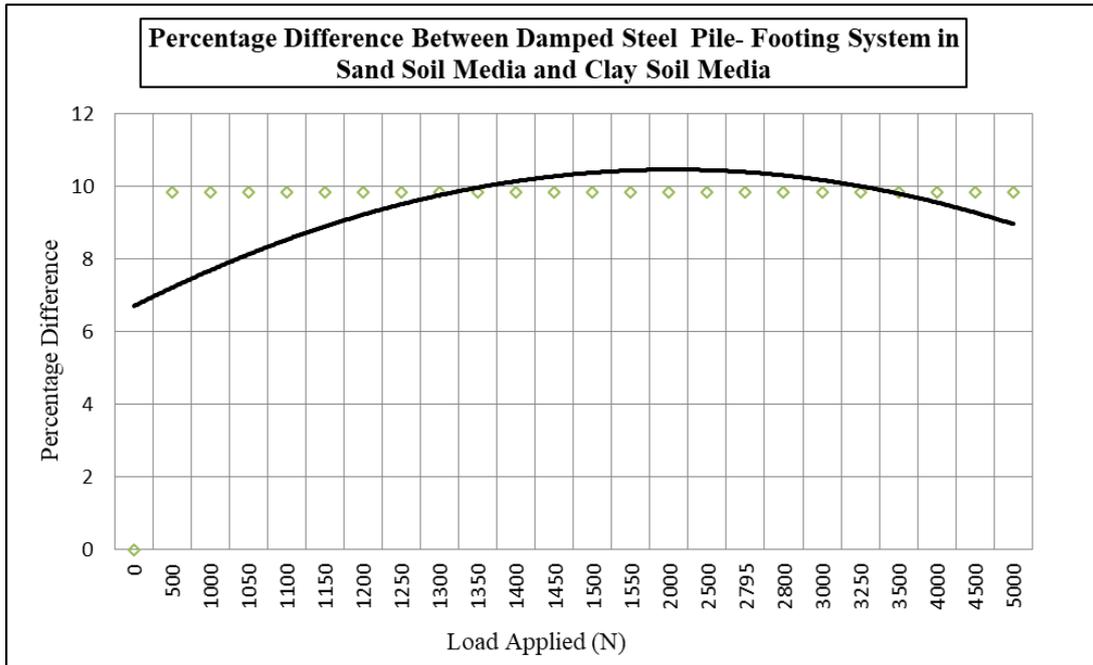
**Figure 14** Load v/s Displacement Curve for Damped Steel Pile-Footing System in Clay Soil Media



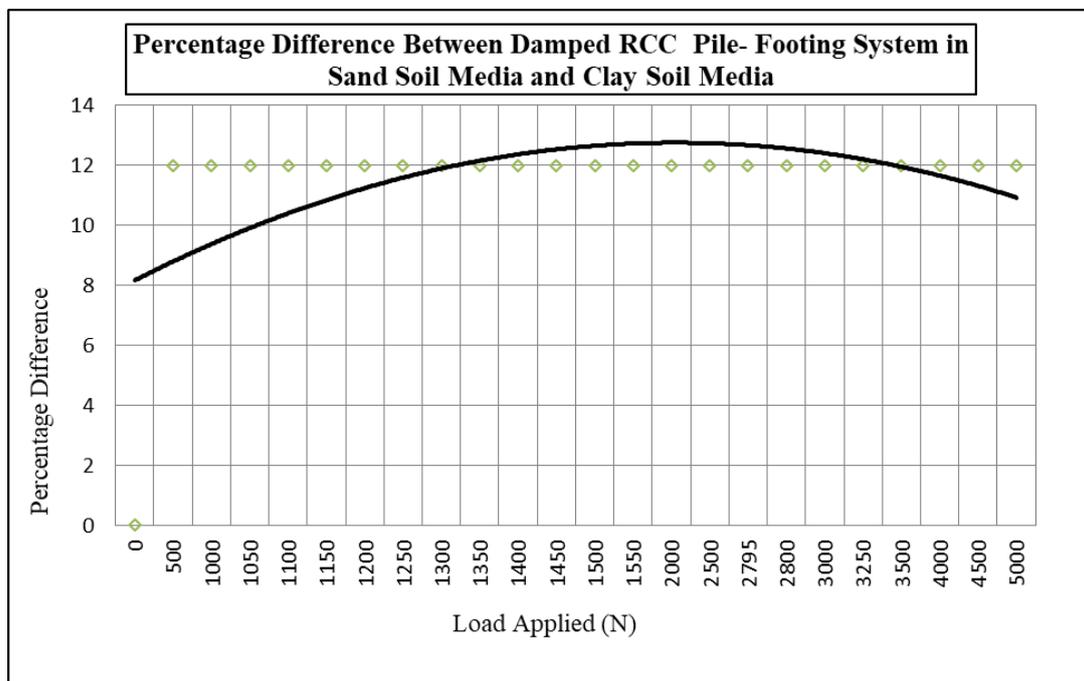
**Figure 15** Load v/s Displacement Curve for Damped RCC Pile-Footing System in Sand Soil Media



**Figure 16** Load v/s Displacement Curve for Damped RCC Pile-Footing System in Clay Soil Media



**Figure 17** Percentage Difference between Damped Steel Pile- Footing System in Sand Soil Media and Clay Soil Media



**Figure 18** Percentage Difference between Damped RCC Pile- Footing System in Sand Soil Media and Clay Soil Media

## 8. Conclusion

It is found that the Frictional Resistances offered by the damped pile-footing to the soil media is found to be greater than that of the undamped pile-footing system and the loading resistances of pile-footing system are found to be greater in clay soil than that of the sand soil. Same results can be found and applied for the real life SSI model. It is recommended that Damped Pile Foundation System should be used for greater load carrying capacity per foundation unit and least settlement or displacement from the load applied upon it.

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## Compliance with ethical standards

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### *Disclosure of conflict of interest*

Meghna Pathak, Ravindra Pathak and Dr. Jagdish Narayan Vyas declare that they have no conflict of interest.

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