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Response Of Framed Building Models Near Underground Excavation Due To Artificial Excitation using Shake Table Test

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Abstract**:** ***In urban areas where land is limited and buildings are closely spaced, deep excavations are necessary for the construction of surface and sub-surface facilities. Therefore, there is a concern that soil excavations resulting in a ditch or a trench adjacent to a building may adversely affect the response of nearby buildings when earthquakes occur. In this paper, the results of experimental study of building frame models in close proximity of excavations and subjected to artificial excitations are presented through a series of shake table tests. The study has been conducted to investigate the effects of the size and offset distances of excavations on the response of the building frame models founded on different types of foundation systems. It is observed that the width, depth and offset distance of the trench has a significant influence on the response of the building frame. It is seen that pile foundation with sufficient embedment depth produces less displacement at the top of the building as compared to other foundation systems.***

Keywords : Artificial Excitation, Building Frame Model, Nearby Excavation, Seismic Response, Shake Table.

I. INTRODUCTION

Rapid development of infrastructural facilities mostly in urban areas is the urgent need in developing countries. Such developments necessitate soil excavations to construct surface and sub-surface facilities such as transportation tunnels, sewers, buried pipelines, etc. These excavations may adversely affect mostly the building structures. Inappropriate planning and design of deep surface excavations may lead to collapse of buildings [1]. Therefore, it is important to investigate about the effect of deep excavations on the response of nearby buildings. Under seismic conditions, responses of structures are extremely affected due to underlying soil layers. Previous studies have been shown that underground structures are less vulnerable than above-surface structures [2]. For example, the Mexico-city underground tunnel [2–5] and the Los Angeles subway [2] during 1985 earthquake have suffered no damage.

In several cases, excavations are carried out in heavily populated areas therefore, estimation of ground movement and provisioning of necessary measures to ensure safety and serviceability of nearby structures are of extreme importance before undertaking the excavation works [6]. Some researchers have carried out studies through numerical modeling [2, 6–13] and experimental study [14,15] to estimate the performance of buildings due to nearby excavation. Zumrawi and El-Amin [16] investigated the role of deep excavation and its effects on nearby existing buildings situated on shallow foundations. They concluded that there are several sources of risk related with deep excavations in urban areas. Bhatkar et al. [6] investigated analytically the nature of wall deformation and settlement for deep excavations in soft soil during underground metro station construction. Zhang et al. [17] developed a theoretical method considering nonlinear characteristics of pile–soil load transfer, namely, Two-Stage Analysis Method (TSAM) for determining the free-field soil movements induced by deep excavations. The performance of a building in proximity to deep excavations is strongly influenced by many factors related to the underlying soil, the building and its foundation, the dimensions of the excavation and the magnitude and duration of the earthquake excitations [13]. Factors related to the excavations are depth, cross-sectional shape, plan dimensions and offset distance. Other factors are the source and pattern of the ground movements, type and embedment depth of the foundation, shape, size, structural type and conditions of the building and the mitigation measures employed to protect the building.

In this paper, results of an experimental study of seismic response behavior of models of frame buildings situated in proximity to soil excavation are presented. An effort has been made to predict the deformation pattern of the frame models supported on raft, isolated footing and pile foundations and close to deep surface excavations. The study also emphasizes on the estimation of horizontal deformations of building during each stage of excavation. The investigation of the structural response is conducted as per the following steps:

(a) fabrication of three-dimensional geometrically scaled framed building models of different storeys,
(b) preparation of a flexible soil container,
(c) determination of the properties of the soil and
(d) conducting a series of shaking table tests on the building frame models standing adjacent to excavations.

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II. TEST FRAME MODELS

In this study four, six and eight storeys moment resistant steel frame models of 1.2, 1.8 and 2.4m heights were fabricated [18]. These fabricated models represented 12, 18 and 24 m heights of actual residential buildings.

The dimensions of the actual building are given in Fig. 1. Angle sections [19] ISA 25 x 25 x 3 mm were used for beams and columns, whereas, 3mm thick mild steel plates for floors were used in the fabrication of models. The models were fabricated considering the following scaling factors as obtained from Buckingham π-theorem. Physical parameters are defined in terms of the geometrical scaling factor λ of the model and the full-scale structure. Scaling factors for mass density = 1, acceleration = 1, frequency = $\lambda^{-1/2}$, time = $\lambda^{1/2}$, stiffness = λ^2 and for force = λ^3. λ=1/10 was taken for the superstructure and isolated and mat foundations, whereas, λ=1/30 was adopted for the piles.

The isolated and mat foundations considered in this study are of 2m x 2m and 6m x 6m plan sizes, respectively. In addition to these foundations, two separate depths of piles have also been considered. The two pile depths adopted were 9m (namely Pile#1) and 11.25m (namely Pile#2).

The isolated footing of the model was made of steel plate of dimensions 200 mm × 200 mm × 8 mm and that of the mat footing 340 mm × 340 mm × 8 mm. Models of Pile#1 and Pile#2 had depths of 300 mm and 375 mm, respectively, whereas, each had a diameter of 25 mm. The reinforcements in the concrete piles were six nos. 2 mm diameter bicycle spokes.

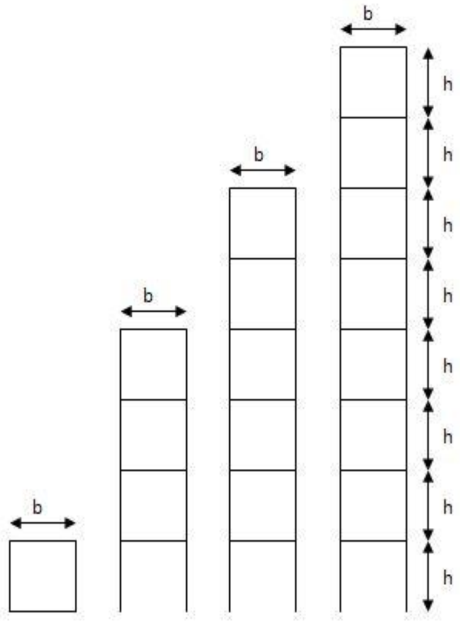


Fig. 1. Plan and elevations of the frame models. width, b=3m and storey height, h=3m.

III. SOIL PROPERTIES, TEST SETUP

Soil is an important component of modeling. The soil considered had an N value less than 10. The other geotechnical properties obtained were as follows: specific gravity = 2.69, dry density = 16.8 kN/m^3 and plasticity index = 15% .

Representation of soil boundary condition is of utmost important in carrying out any experimental investigation involving soil structure interaction. In the present investigation using shake table, the size of the soil container adopted was 650mm x 650mm x 650mm. The container was made of 3mm thick steel plate duly stiffened. The corners of the container were properly braced to avoid any distortion in its shape during vibration. Due to limitations in the dimensions of the soil container error is bound to take place since it did not represent the infinite extent of ground soil [20]. To minimize wave reflection from the boundary of the container [20–22] a foam layer of thickness 20mm was inserted between soil and container interface.

The shake table used in the experimental investigation had a table size of 1.5m x 1.5m and a payload capacity of 1000kN. It is capable of generating a maximum of 200mm displacement in all the axial directions. It can be run at a maximum frequency of 50Hz. The experimental setup of four, six and eight storey frame models is shown in Fig. 2.

Fig. 2. Experimental setup of frame models: (a) four, (b) six and (c) eight storey models

In the experiment, the fixed base condition of the building was represented by fastening the steel base plates of the model with the shake table. Accelerometers were fixed at all the floor levels of the model frames. The recorded accelerations were further processed to obtain the displacement of the model by using Seismosignal software [24].

IV. SOIL TRENCH

In this study, nine trenches were made of different widths and depths. All the trenches are of the same length, which is equal to the lateral dimension of the scaled model structure. The size of the trenches and their offsets from the edge of the footing of the frame are shown in Table 1. The view of the soil trenches near the frame model is shown in Fig. 3.

Table- I: Description of the trenchs and their respective dimensions

Size of the trenches and its offset from the edge of the building				
Trench No.	Offset from Building Edge (m)	Width (m)	Depth (m)	Length (m)
1	0.150	0.075	0.075	0.300
2			0.150	
3			0.225	
4			0.075	

5	0.075	0.150	0.150	
6			0.225	
7	0.000	0.225	0.075	
8			0.150	
9			0.225	

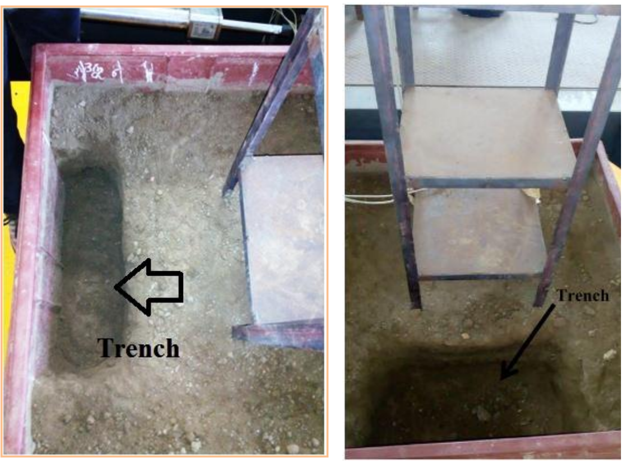


Fig. 3. View of the Soil excavations near building frame
models

V. INPUT MOTION

For this study the acceleration time history of the N-S component of El-Centro (California, 1940) earthquake has been used and is presented in Fig. 4. In order to consider the influence of seismic wave to the structural system, seismic wave excitations are considered acting horizontally.

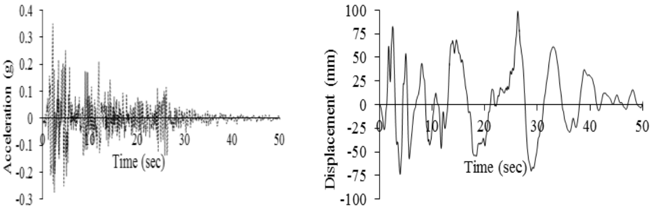


Fig. 4. El-Centro N-S earthquake motion

VI. SHAKE TABLE TESTS ON THE FRAME-TRENCH MODEL

Two free vibration tests were performed first by fixing frame model directly on the shake table, and second by embedding the frame models with different types of foundations in container soil. The natural frequency by cycle-counting and damping ratio by using Eq.1 for each frame models were estimated from the free vibration records [23].

$$\zeta = \frac{1}{2\pi j} \ln \frac{\ddot{x}_i}{\ddot{x}_{i+j}} \tag{1}$$

where, $j =$ number of cycles, $\ddot{x}_i =$ acceleration at i^{th} peak, $\ddot{x}_{i+j}$ = acceleration at $(i+j)^{th}$ peak.

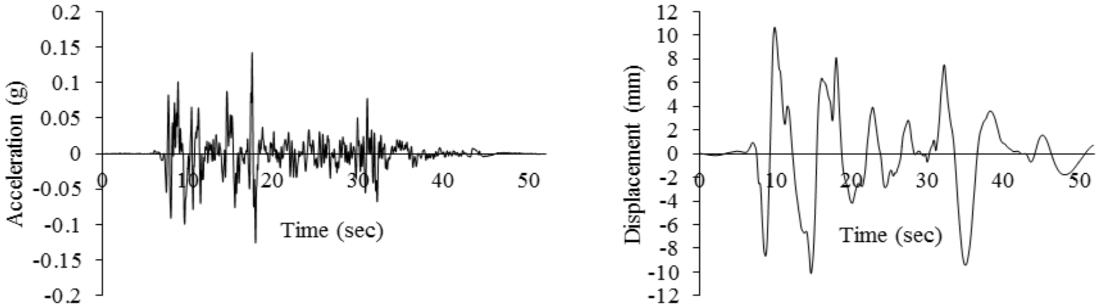


Fig. 5. Responses of eight storey frame model at top due to El-Centro earthquake for fixed base condition

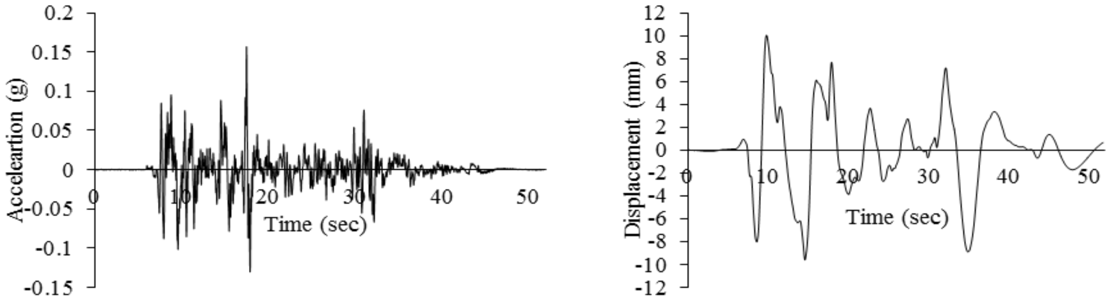


Fig. 6. Responses of six storey frame model at top due to El-Centro earthquake for fixed base condition

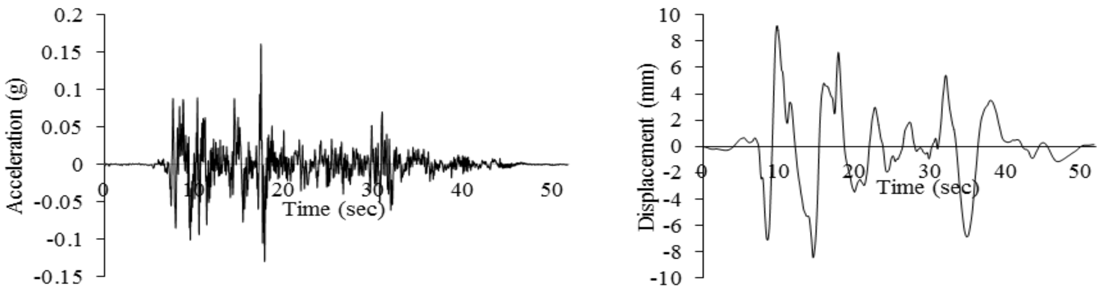
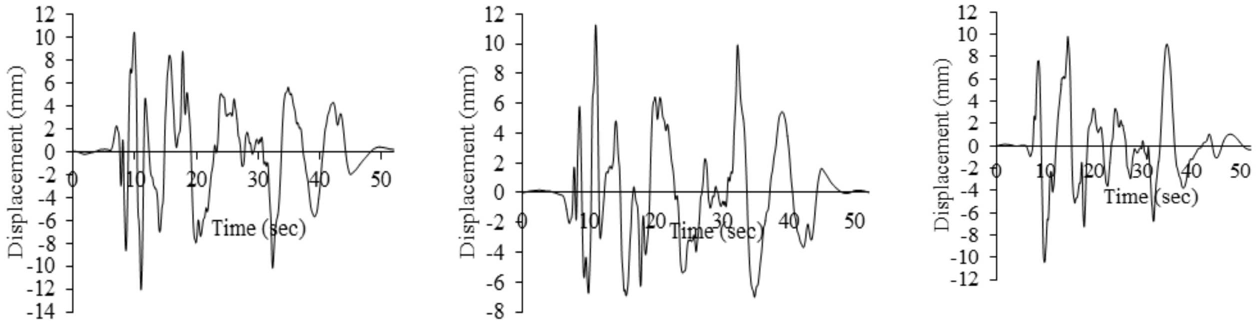
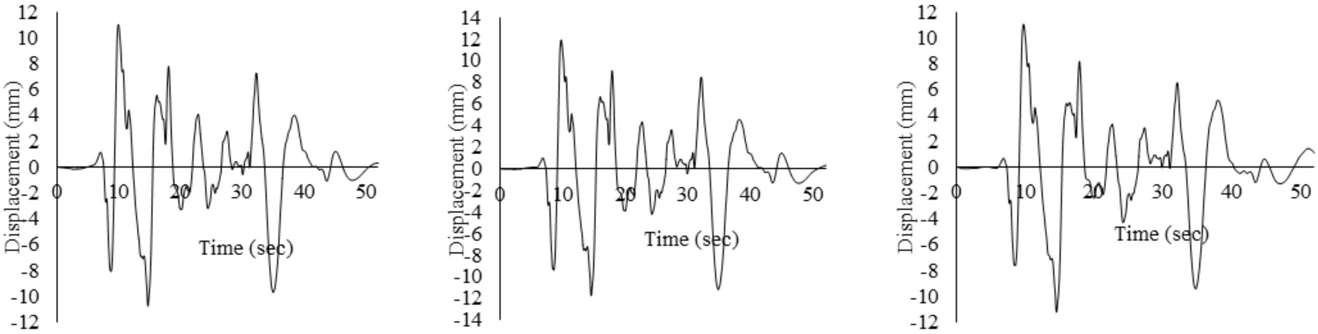


Fig. 7. Responses of four storey frame model at top due to El-Centro earthquake for fixed base condition



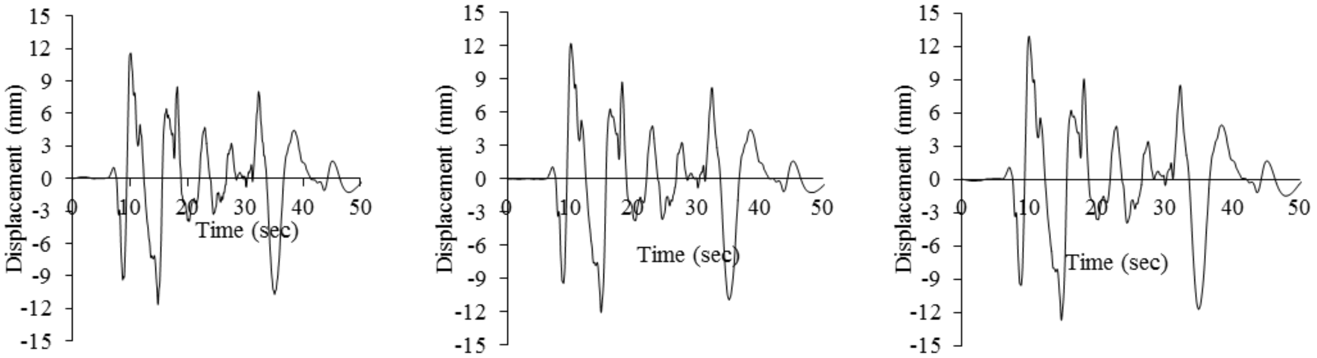
(a) (b) (c)

Fig. 8. Top floor displacement responses of (a) eight, (b) six and (c) four storey frame due to El-Centro N-S component of earthquake for isolated footing with excavation



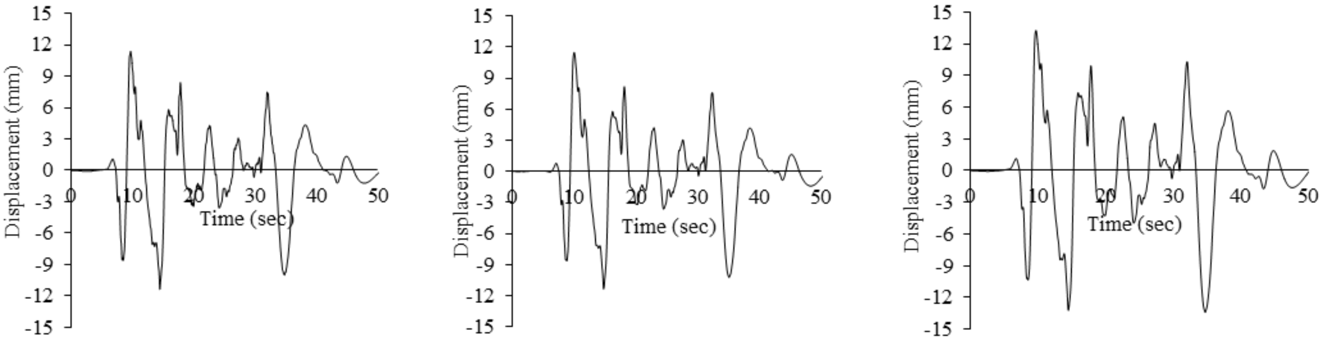
(a) **(b)** **(c)**

Fig. 9. Top floor displacement responses of (a) eight, (b) six and (c) four storey due to El-Centro N-S component of earthquake for mat footing with excavation



(a) **(b)** **(c)**

Fig. 10. Top floor displacement responses of (a) eight, (b) six and (c) four storey due to El-Centro N-S component of earthquake for pile #1 foundation with excavation



(a) (b) (c)

Fig. 11. Top floor displacement responses of (a) eight, (b) six and (c) four storey due to El-Centro N-S component of earthquake for pile#2 foundation with excavation

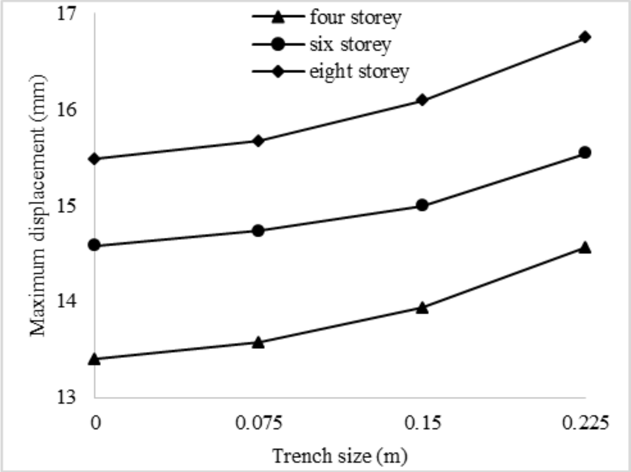


Fig. 12. Maximum deflection vs. trench depth for Isolated footing

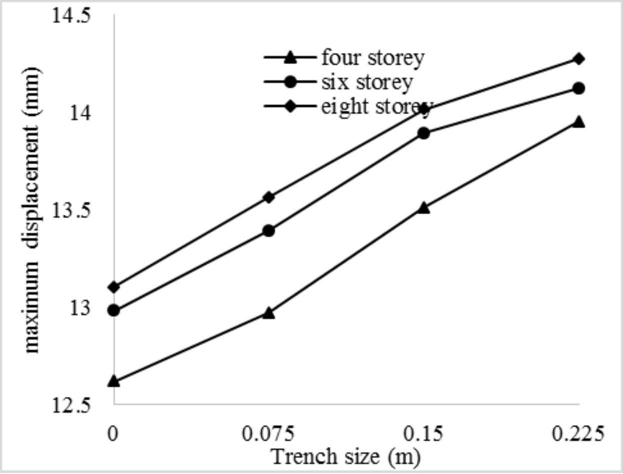


Fig. 13. Maximum deflection vs. trench depth for mat footing

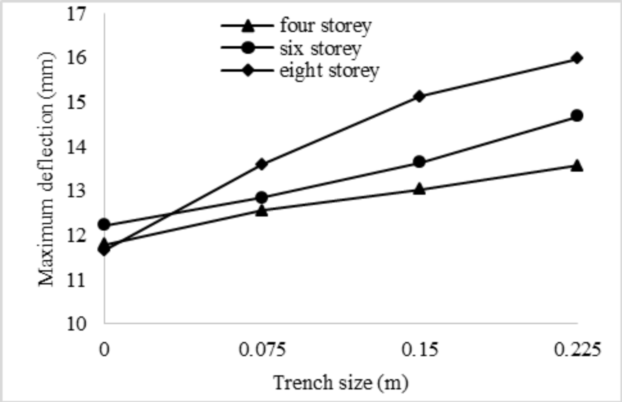


Fig. 14. Maximum deflection vs. trench depth for pile#1

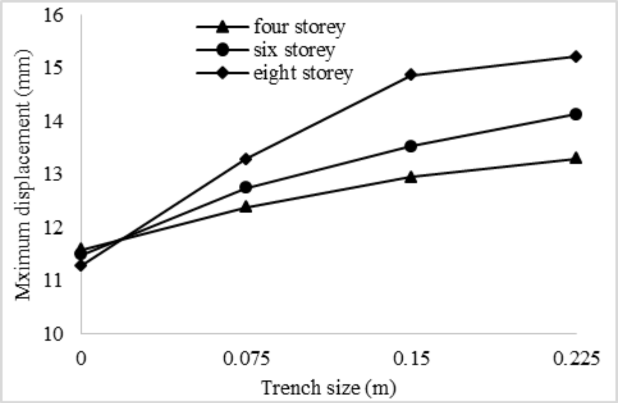


Fig. 15. Maximum deflection vs. trench depth for pile#2

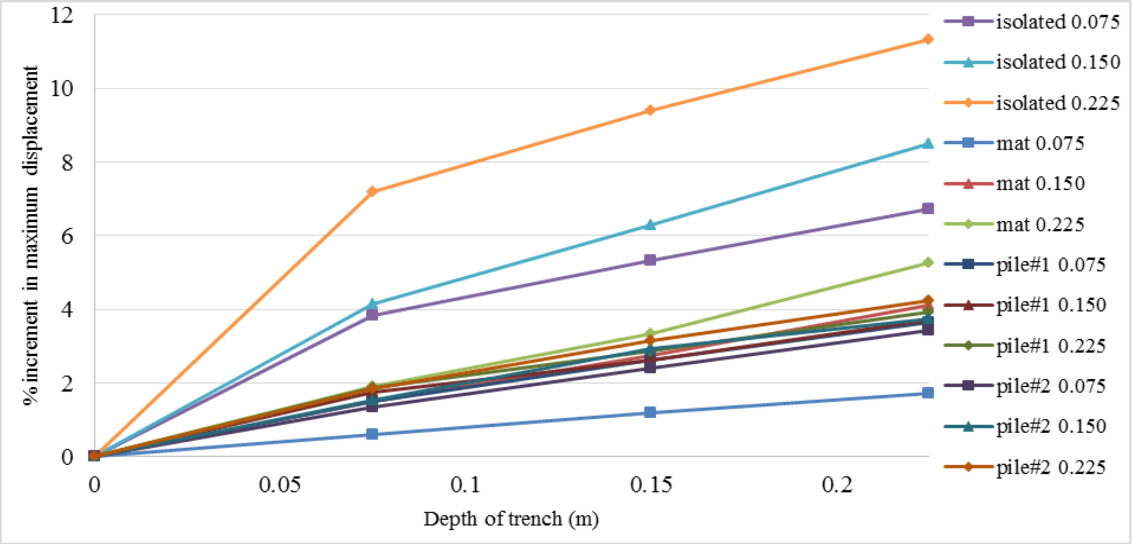


Fig. 16. Percentage increment in maximum deflection at top floor vs trench depth for different foundation systems. Numerals shows the trench width in m.

VII. TEST RESULTS AND DISCUSSION

The input excitation applied was El-Centro N-S component of the earthquake due to which output acceleration response of the frame model in the horizontal directions was recorded. The frame models were tested with and without isolated footing, raft footing and pile foundation. Output deflections were determined from the recorded acceleration responses. It is seen from Fig. 12 to 15 that the increasing trench depth increases the deflections of the buildings in all types of foundations. After a certain depth of excavation equal to approximately a quarter of the lateral dimension of the building, it is observed that the model is getting excessively deflected. Fig. 12 and 13 indicate that isolated and mat footings produce almost equal deflections at the top floor.

However, when the trench depth is more than quarter of the lateral dimension of the building, it is seen that the rate of the top story deflections of the buildings with the isolated footing is more than that for the mat footing. All the buildings supported on the mat foundations show approximately the same (with a little difference) top floor deflections. In other words, a smaller height building supported on mat foundation shows a greater storey drift with increasing trench depth. From Figure 14 and 15, it is seen that with increasing trench depth, pile#2 as compared to pile#1 yields lesser deflection to the eight-storey building. However, for four and six storey buildings, founded on pile#1 and pile#2, the deflections do not show appreciable difference. The pile foundations show a linear increment of deflections with increasing trench depth. Variations of maximum lateral deflection with respect to the depth of the trench for different footing systems are shown in Fig. 16. Here, it is observed that isolated footings show greater increments of deflections at the top floor. With the increase in the width of the trench, the top floor displacements of all the buildings irrespective of their foundations increase. In case of isolated footing as shown in Fig. 12, the top floor maximum displacement in case of 0.225m trench width is 4.04% higher than 0.150m trench width. Similarly, it is 6.83% higher than 0.075m trench width. The top floor displacement is more than 8.15% as compared to the displacement in no-excavation case in isolated footing system. Fig. 13 clearly shows that with the increase of trench width the maximum displacement increases, but after 0.150m width it increases with steep slopes. While comparing with no-excavation condition, the top floor of the model with mat footing adjacent to 0.225m trench width observed 8.93% more displacement.

VIII. CONCLUSIONS

Following conclusions can be derived from the foregoing results.

The top floor displacement of the frame model is influenced by the nearby excavation. The deflections at the top level of the buildings increase with increasing depth and width of the trench. The maximum deflections are more in the case of an isolated footing than for the other type of footings. A smaller height building supported on mat foundation shows greater storey drift. Deep pile as compared to isolated footing is found to have less effect on the deflection of the building adjacent to a trench (excavation). For the depth of excavation equal to approximately a quarter of the lateral dimension of the building, it is observed that the model is getting excessively deflected. Therefore, the depth of the excavation should be limited upto the quarter width of the building. An adequately designed temporary structures for safeguarding the effected existing building and its foundation should be provided.

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