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Soil-Structure Interaction of Tall Buildings Comprising Shear Walls with Openings Under Seismic Loads

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ABSTRACT: As a result of population density in Egypt emerged the importance of the use of tall buildings. Tall buildings increase the displacement of top floors due to lateral loads effect and increase the settlement due to vertical loads. A numerical analysis is carried out to analyse buildings with shear walls that have regular and staggered openings and resting on piles raft with different pile configurations under seismic action. The behaviour of soil-structure interaction, with weak soil profile, on superstructure of 20, 25, and 30 storeys and rested on a pile raft was investigated and was found to have a significant effect on the buildings. It was found that the openings in the shear walls have a significant effect on the values of the settlement. Also, the staggered openings are preferable more than the regular openings and the effect of pile length in clay soil is greater than the pile diameter.

1 INTRODUCTION

Tall buildings require special consideration due to the heavy column loads and subjected to large lateral loads from seismic actions. Buildings with shear walls are receiving lateral forces from due to the diaphragm action and transmit them to the foundation. As a result of these loads, piled raft is used to promote the bearing capacity of the raft and also to reduce the its settlement. Likewise, shear walls are used to resist lateral loads, but architectural design requires openings for doors and windows in shear walls. Due to these openings, the value of displacement, drift, and moment on the piles raft will change. Different configurations of the openings affect the required efficiency in performance of shear walls under earthquake excitation. On the other hand**,** the openings have an indirect effect on piled raft foundation in clay subsoil. The Next paragraphs will review previous studies of these topics.

1.1 *Shear Wall Modelling*

Aarthi and Kumar (2015) investigated the effect of the staggered and vertical openings in shear walls for building consists of 7-storey and show that the staggered opening preferred to be highly advantageous and those openings were found to provide better lateral resistance than shear walls with vertical openings. The increase of stresses in staggered openings is small when compared to vertical openings. On the other hand, the displacement and drift in staggered openings is less when compared to vertical openings. The base shear in shear wall with vertical openings is much bigger when compared to shear wall with staggered openings. Swetha and Akhil (2017) studied the effect of opening in shear wall on 7- storey building and the research results were similar to Aarthi and Kumar (2015) results.

Sharma and Amin (2015) studied 30 storey buildings with different types of openings in shear wall with and without opening and concluded that the opening in shear wall decreases the stiffness of the building in the lateral direction and in turn the lateral displacement and inter-storey drift of the building increases. It was realized that the displacement and drift are not only dependent on the size of the opening, but the shape of opening also plays a major role when the aspect ratio is large.

1.2 *Soil Structure Interaction*

Kumar and Maruthi (2013) showed that the foundation differential settlements influence the load transmitted from one column to another, and hence the redistribution of forces in the superstructure members. The magnitude of the load redistribution is dependent on the stiffness of the elements of the superstructure as well as the magnitude of the differential settlement. Kotkar and Patankar (2017) studied the effect of soil structure interaction on buildings with stiffness irregularity under seismic loads. The study showed that buildings with stiffens irregularity have low base shear. Also, stiffness irregularity causes a large top storey displacement and storey drift.

Wood and Larnach (1974) concluded that the Foundation settlements may introduce new conditions of load distribution in the structure that cause distress and cracking of its elements, and may even lead to stress reversal. Inaba et al. (2000) studied effect of soil structure interaction on the Nippon Telegraph and Telephone building in Hanshin and Awaji area as a result of the 1995 earthquake. The study showed that the soil structure interaction had a large effect on the seismic response of the aforementioned building.

1.3 *Piled Raft Model*

Hain and Lee (1978) combined the finite and boundary element model for the analysis of piled raft. Finite elements were used for raft modelling and the boundary element method was used for the analysis of piles and the soil. Piled raft foundation has been analysed assuming that the raft is an elastic plate supported on compressible friction piles embedded in elastic homogenous and non-homogenous medium. The study was limited to the structural response only such as bending moment, shear forces, and the connecting force between the piles and the raft.

Russo (1998) employed a method where the piles and soil were modelled by linear or non-linear interacting springs. The soil displacements were calculated using Boussinesq's solution thus yielding a closed form solution. The non-linear behaviour of the piles was modelled by the assuming a hyperbolic load-settlement curve for a single pile. This method has the limitation of only allowing for pure vertical interaction between the raft, piles, and the soil.

El Gendy (2007) presented a more efficient analysis of a piled raft based on the elasticity theory by using composed coefficient technique to reduce the size of the entire soil stiffness matrix. A full interaction among piles raft elements is considered by generating the entire flexibility matrix of the piled raft. The method may be also applied to a single pile or a group of piles. Reda (2009) examined the behaviour of a single pile, pile groups, raft and piled raft on the classified six zones at Port Said under different foundation parameters and soil conditions. Both linear and nonlinear behaviours have been considered when analysing the foundation elements.

2 SOIL PROPERTIES AND NUMERICAL MODEL

The study in this research was performed at Port-Said zone which characterized by a soft clay soil. The subsoil profile has been based upon the extensive geotechnical study performed by Golder Associates, 1979. Numerical study of this research is carried out by commercial program ETABS for the superstructure, which can analyse 3-D models and using finite element method, and the ELPLA program for the substructure model, which can analyse piled raft and raft using subsoil models. In the analysis, the piled raft is treated as a rigid member having a uniform settlement on its nodes. Pile foundation was considered the nonlinear effect and using a hyperbolic function. Theoretical bases of soil models and methods in ELPLA are well documented by EL Gendy, 2006 and 2007.

2.1 *Investigated Area*

The location of Port-Said zones according to a study performed by Golder Associates (1979) shown in Figure 1, is divided into six regions as follows:

1) Zone 1 contains Al Qabuti and Al Salam Regions.
2) Zone 2 contains Port–Said water treatment station, few apartment buildings, agricultural and industrial development.
3) Zones 3 and 4 contain El Zohor Region.
4) Zone 5 contains industrial zone.
5) Zone 6 still unused.

Figure 1. Location of soil zone.

2.2 *Soil log*

The subsoil profile of the studied area zones can be classified into four main layers as shown in Figure 2. The four layers are as follows:

- Fill or Surface clay
- Sand stratum
- Transition zone
- Lower clay

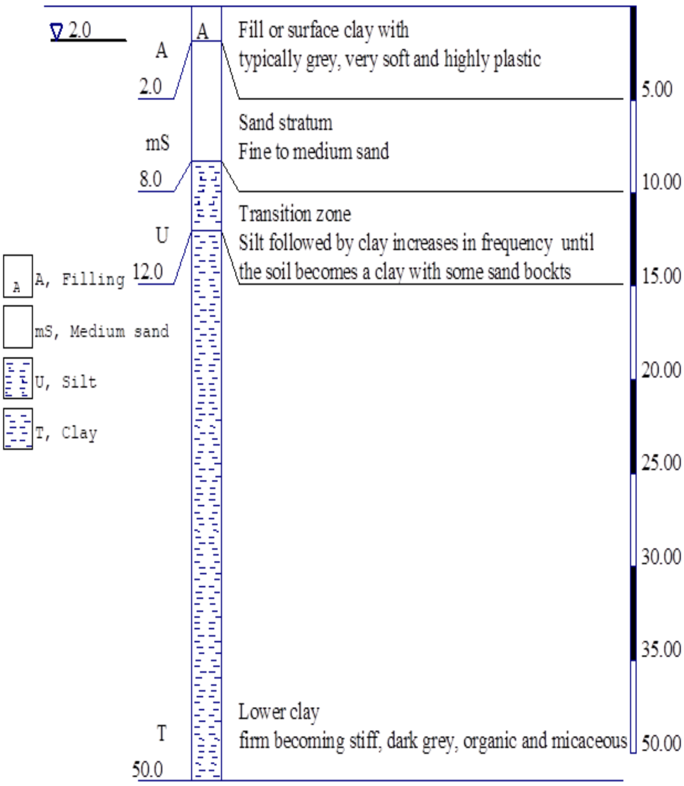


Figure 2. Main soil profile of Port-Said zone.

2.3 *Soil parameter*

2.3.1 *Modulus of compressibility*

The modulus of compressibility of the clay, E_s, is a major soil parameter for using a continuum model in the analysis. Reda (2009) specified the modulus of compressibility which showed that E_s increases with depth and can be approximated by the following linear equation:

$$Es = Eso(1 + 0.06z) \quad (1)$$

where:

E_s Modulus of compressibility, [MN/m^2].

E_{so} Initial modulus of compressibility with the value of $E_{so} = 2$ [MN/m^2].

z Depth measured from the clay surface, [m].

2.3.2 *Limited Shaft Friction*

The nonlinear analysis of piles is required to assess the limit shaft friction of the pile ql=180 [kN/m^2] as Russo [7] submits, the value of undrained cohesion Cu = 200 [kN/m^2]. This value of ql may be used in the nonlinear analysis as the undrained cohesion Cu of Port-Said lower clay does not exceed 200.

2.3.3 *Groundwater*

Groundwater lies under the ground surface of the studied zone by almost 2 m, which is used at the current study level = -2 m from the ground surface.

2.4 *Numerical Modelling*

2.4.1 *Superstructure Model*

The Finite Element Analysis is used to model the superstructure that has been modelled and analysed by program ETABS as a three-dimensional frame structure as shown in Figure 3. Frame element was used for column and beam and shell element for slabs and shear walls, and the response spectrum method was used to model seismic loads. The loading calculations were based on the Egyptian code of loads calculations 2012. The analysis considered different configurations for the stiffness of the different structural elements. The results cover the global behaviour of the structures; namely building displacement, the inter-storey drift, the base shear, drift behaviour, and lateral displacement distribution.

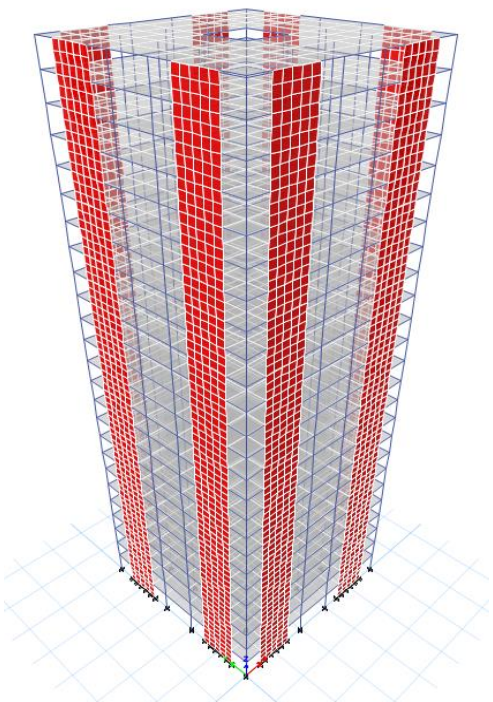


Figure 3. 3D Model by ETABS.

2.4.2 *Substructure Model*

The numerical model in this research for the sub-structure was carried out by ELPLA for analysing deep foundations considering different subsoil models. The analysis was carried out by (Modulus of compressibility for rigid raft) which are available in ELPLA. The model used in the subsoil is Continuum model, the continuum model is relatively the most complicated, but it considers the interaction between all foundation elements and soil. It represents the soil as a layered continuum medium. The load-settlement relationship of the pile in piled raft was determined according to the nonlinear analysis of piled raft using Egyptian code 2005. For the rigid pile models, the settlement is assumed to be uniform for all nodes along the entire pile length. The soil log used in this study is shown in Figure 4.

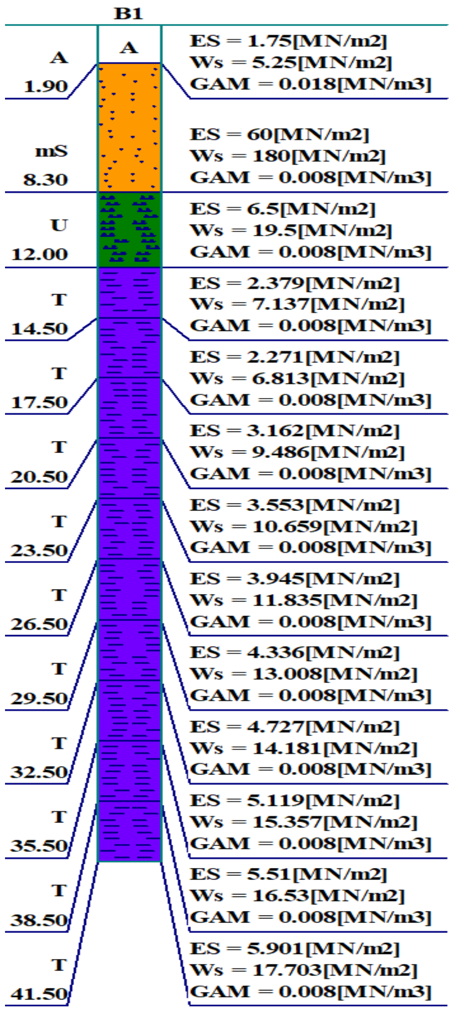


Figure 4. Soil properties used in the current study.

2.5 *Model Description & Parametric study*

A 3D model for 20, 25, and 30 storey building is studied. The building plan area is 25 × 25m, 5 × 5 m bay frame and shear walls with 5m span in X and Y-directions and floor height of 3m, as shown in Figure 5. Five models were analysed by finite element program ETABS as follows:
(a) Shear wall without openings,
(b) Shear wall with regular openings (1m×1m),
(c) Shear wall with staggered openings (1m×1m),
(d) Shear wall with regular openings (2m×1m),
(e) Shear wall with staggered openings (2m×1m),
as shown in Figure 6.
The structural system of all floors is a of flat slab type of 20 cm thickness and it was also represented as a shell element. The building is assumed to be used as a residential building with maximum live load of 2 [kN/m^2] and total uniform load 7.5 [kN/m^2]. Because of the symmetry in both directions, the torsional effect has not been taken into consideration in modelling. Shear walls were represented as a thin shell element. The size of beams is 25 cm in width and 60 cm in depth while columns dimensions are 90 cm × 90 cm. The plane of the model is shown in Figure 5. The earthquake load and load combinations were applied according to Egyptian code of soil mechanics and foundation 2005. The seismic analysis was carried out by the response spectrum method and seismic loads due to a ground acceleration g = 0.15g m/s^2.
The foundation of each model is a piled raft resting on non-homogeneous soil medium (Port Said subsoil) and is analysed considering the soil-structure interaction by ELPLA. The raft dimensions are 30 m × 30 m, and the thickness is 2.5 m.

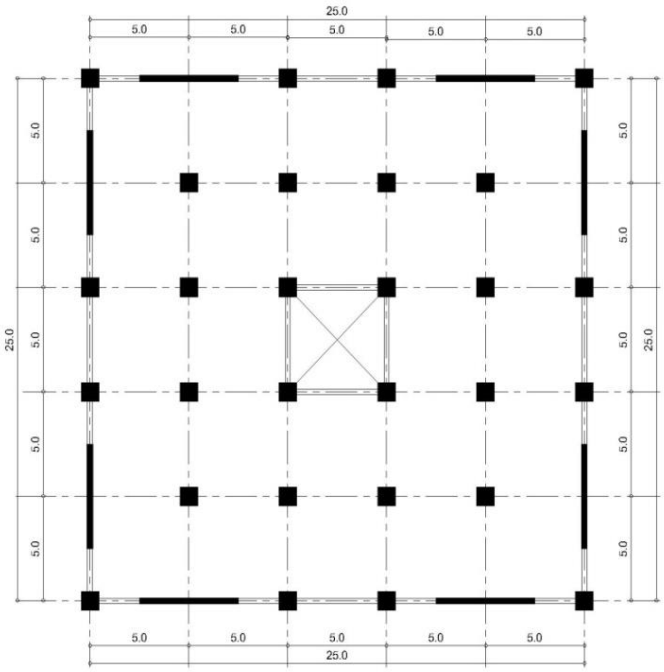


Figure 5. Plane of the studied building.

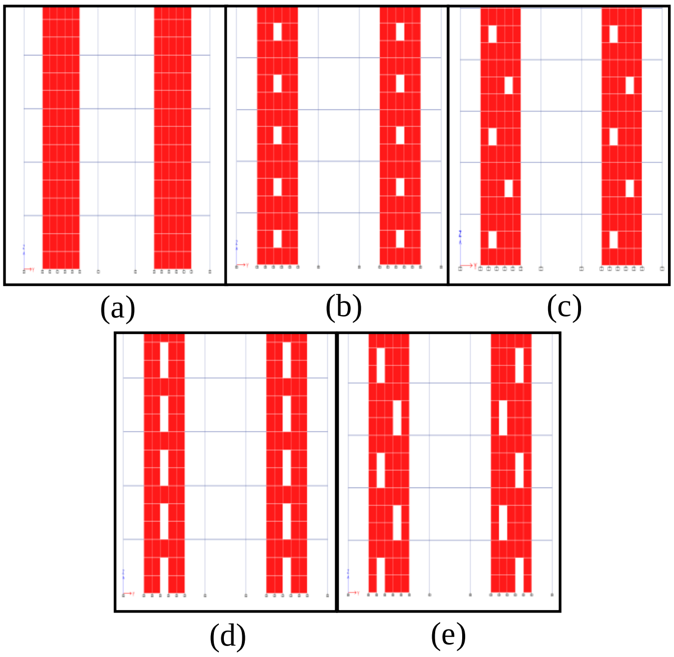


Figure 6. Elevation of different shear wall cases (first five floors seen).

2.5.1 *Material Properties*

- Concrete Material Properties:

Slabs, columns, and shear walls have the following material parameters:
  - Young's modulus $E = 2.5 * 10^7$ [kN/m^2]
  - Poisson's ratio $\nu = 0.2$
  - Unit weight $\gamma = 25$ [kN/m^3]
- Piles have the following material parameters:
  - Young's modulus E_b = $3.14 * 10^7$ [kN/m^2]
  - Unit weight γ_b = 0 [kN/m^3]

2.5.2 *Studied Parameters*

In the current study, five different cases of a shear walls were considered as given in Figure 6. Each case was studied for different floor numbers: 20, 25, and 30 storeys. The max displacement, drift ratio, shear stress and the settlement in the piled raft are investigated. Parametric study (1) is shown in Figure 7.

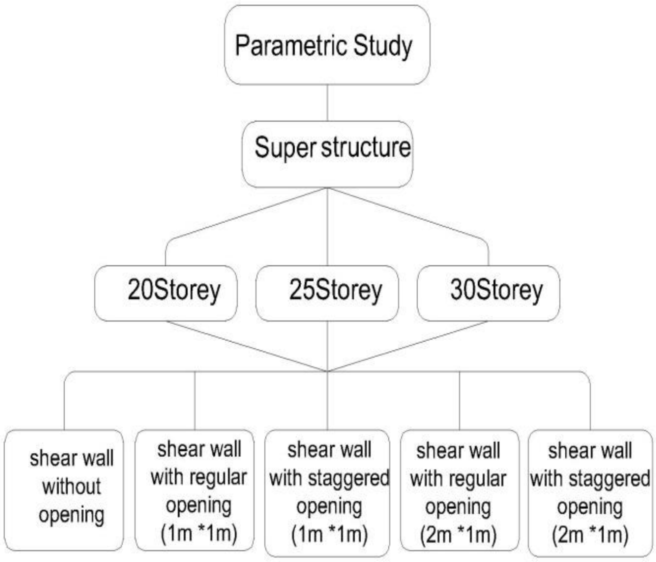


Figure 7. Flow chart of super structure, Parametric Study (1).

The parameters of the pile are as follows:

- Pile diameter

Each structural model with pile raft was analysed three times with varying pile diameters of 1.0 m, 1.2 m, and 1.4 m. The pile length is taken constant (L=32m) for all diameters.

- Pile length

Each structural model with pile raft is analysed three times with varying pile length of 30.0 m, 32.0 m, and 34.0 m. The pile diameter is taken constant (d=1.2 m) for all lengths. In all cases, the square raft was 30 m x 30 m with a thickness of 2.5 m for working and maximum dynamic earthquake. Parametric study (2) is shown in Figure 8.

Two different groups of piled raft for 25 stories were analysed considering variable pile spacing S = 5 m for group (1) and S = 2~5 m for group (2) as shown in Figure 9.

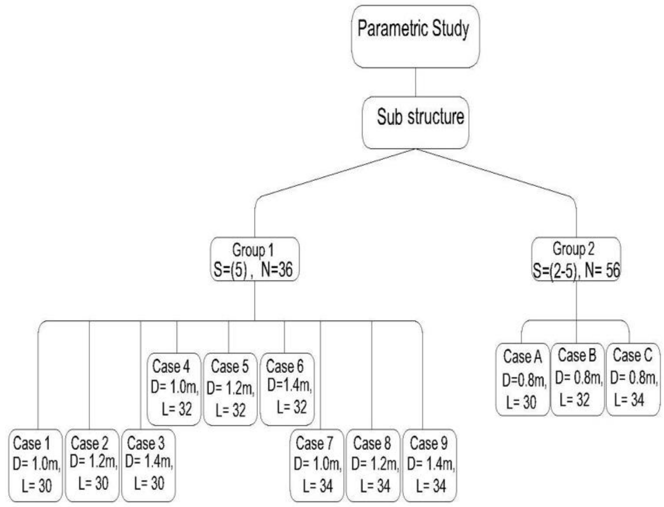


Figure 8. Flow chart of sub structure, Parametric Study (2).

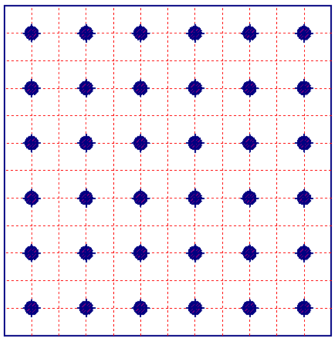
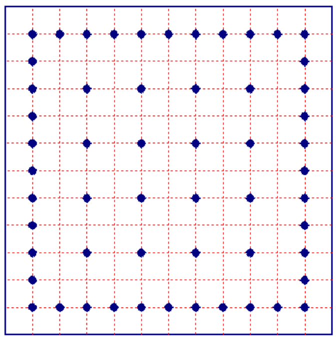
Group No.	Group arrangement
Group 1 S = 5 m	
Group 2 S = 2 ~ 5 m	

Figure 9. Different groups of piled raft.

3 RESULTS

3.1 *Building Displacement*

The storey displacement refers to the absolute value of displacement of the storey under action of the lateral forces. The displacements for 20, 25 and 30 storeys are shown in Figures 10, 11, and 12, respectively. The figures show the storey displacement for shear wall without openings, shear wall with regular openings (1m×1m), shear wall with staggered openings (1m×1m), shear wall with regular openings (2m×1m), and shear wall with staggered openings (2m×1m). It can be seen from these figures that the increase of displacement of shear wall with regular openings compared to shear wall with staggered openings are almost as close. The max percentage of displacement of shear wall with regular opening to staggered opening is 1.29 %, 1.41 %, and 1.65 %, for 20, 25, and 30 storeys, respectively.

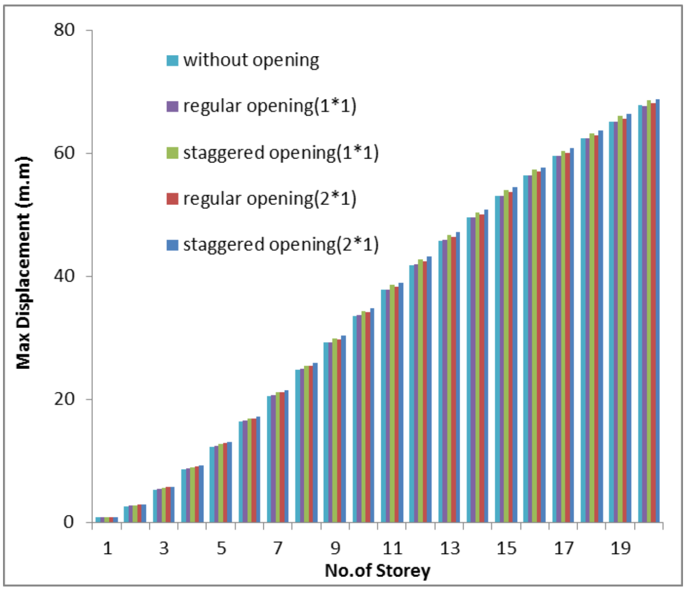


Figure 10. Displacement of 20-storey.

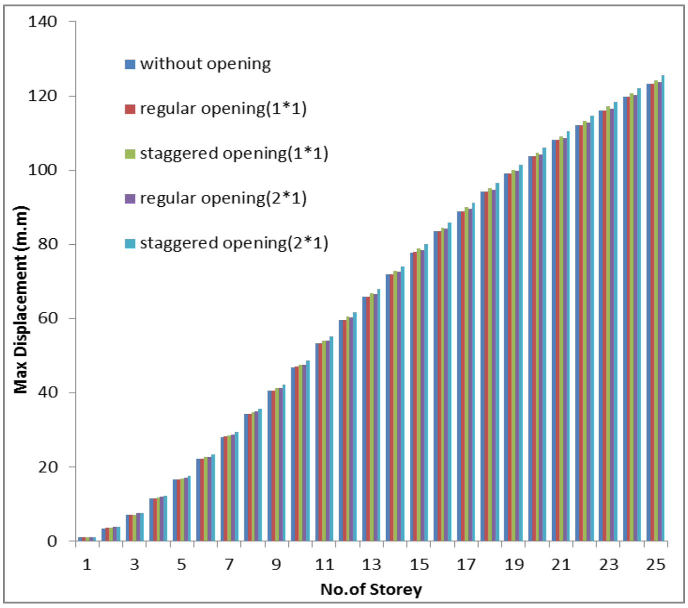


Figure 11. Displacement of 25-storey.

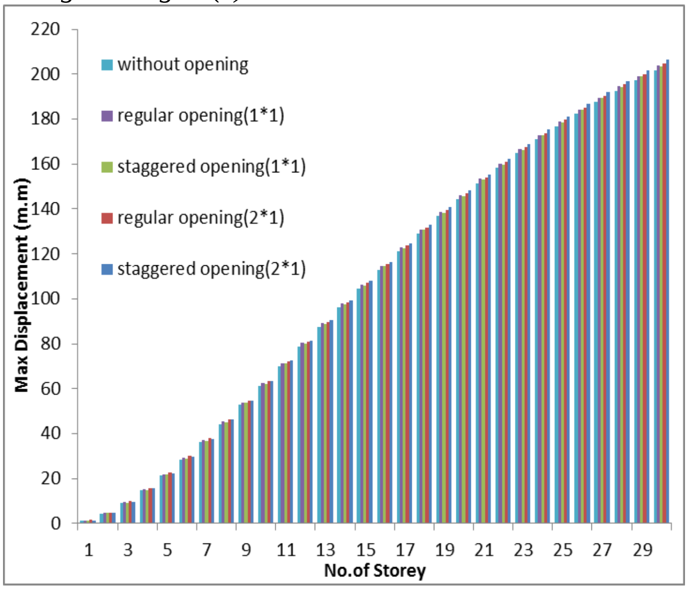


Figure 12. Displacement of 30-storey.

3.2 *Inter-storey drift*

Storey drift is defined as the displacement of one level relative to the other level above or below. The drift for 20, 25, and 30 storeys is shown in Figures 13, 14 and 15, respectively. The figures show storey drift for shear wall without openings, shear wall with regular openings (1m×1m), shear wall with staggered openings (1m×1m), shear wall with regular openings (2m×1m), and shear wall with staggered openings (2m×1m). It can be seen from these figures that the increase of drift of shear wall with regular openings compared to shear wall with staggered openings is big for low floors number and low for large floors numbers. The max percentage of storey drift from the regular opening to staggered opening is 0.79, 0.98 %, and 1.14 % for 20, 25, and 30 storeys, respectively.

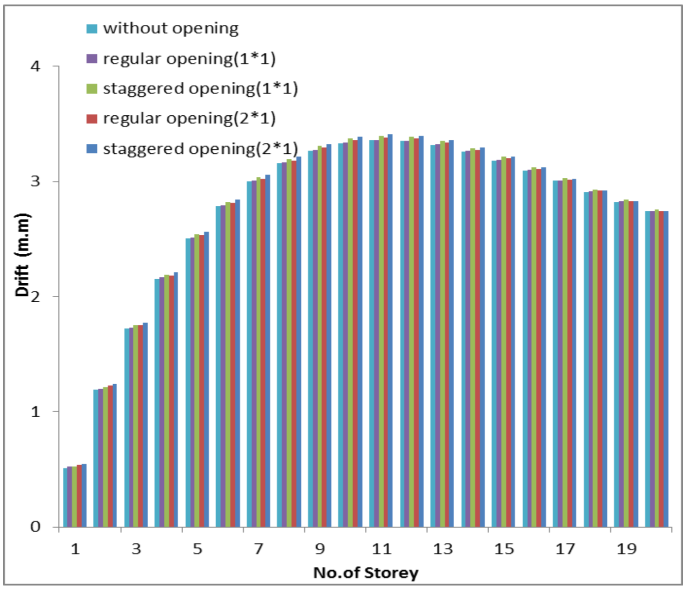


Figure 13. Drift for different size of openings in 20-storey.

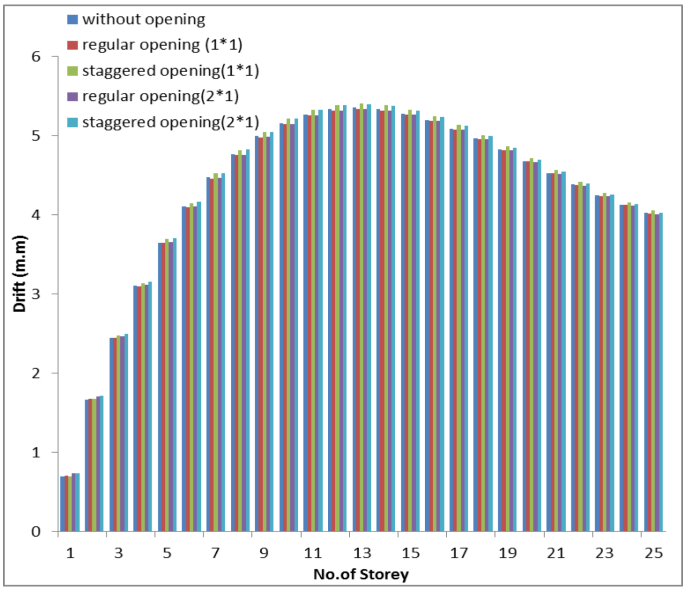


Figure 14. Drift for different size of openings in 25-storey.

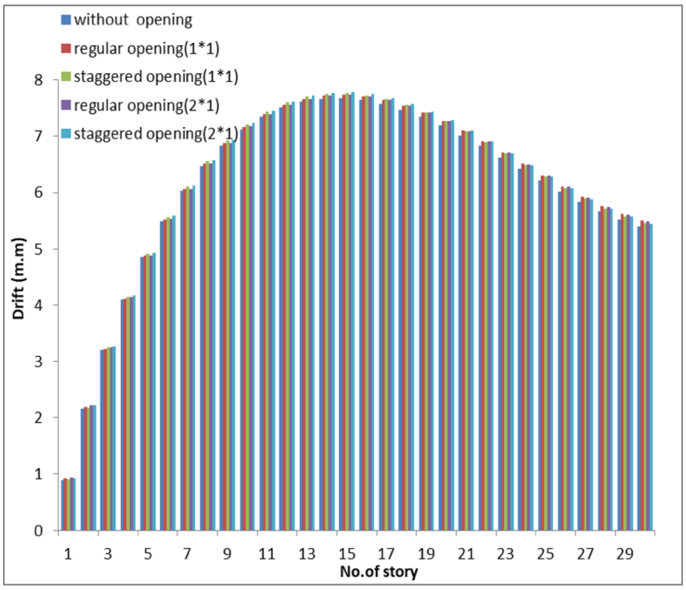


Figure 15. Drift for different size of openings in 30-storey.

3.3 *Stress Distribution*

The stress distribution of the shear wall with regular openings and with staggered openings was studied to recognize the effect of soil structure interaction on stress pattern in shear walls. The stress distribution for shear wall with regular openings (1m×1m), shear wall with staggered openings (1m×1m), shear wall with regular openings (2m×1m), and shear wall with staggered openings (2m×1m) is shown in Figures 16, 17, 18, and 19, respectively. It can be clearly defined that the stress in shear wall around the staggered openings is lesser than the stress pattern around the shear wall with regular openings.

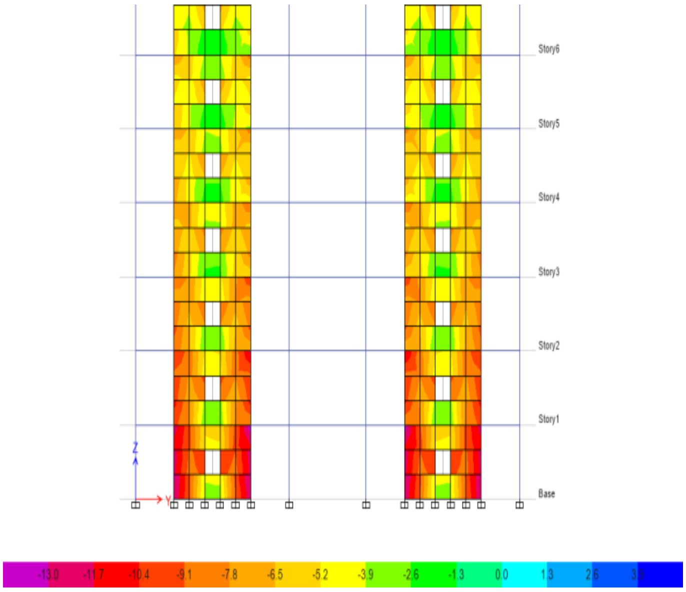


Figure 16. Stress distribution in shear wall with regular opening (1m×1m).

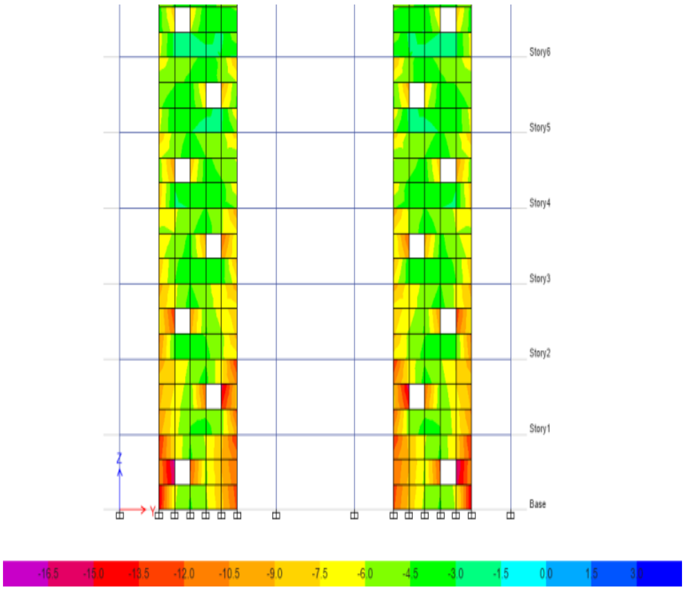


Figure 17. Stress distribution in shear wall with staggered opening (1m×1m).

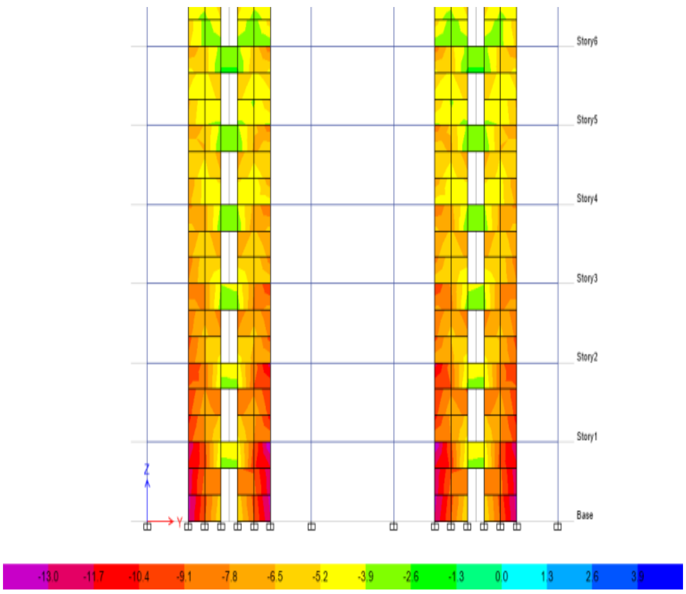


Figure 18. Stress distribution in shear wall with regular opening (2m×1m).

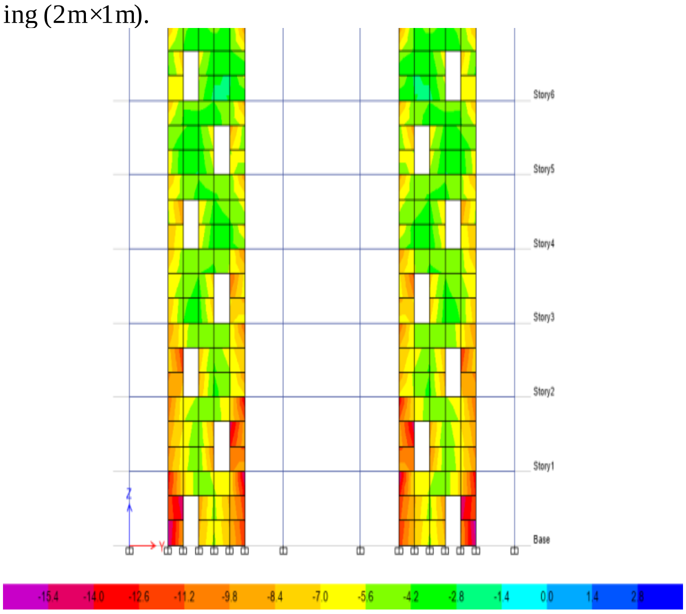


Figure 19. Stress distribution in shear wall with staggered opening (2m×1m).

3.4 *Settlement Comparison*

The settlement in piles raft for the five cases of shear wall in 25 storey is shown in Figure 20. When the pile diameter is 1.2 m, Pile length is 32 m, and raft thickness is 2.5 m.

The definition of shear walls (SW) in Figure (20) are as follows:

SW1= Shear wall without openings,
SW2= Shear wall with regular openings (1×1),
SW3= Shear wall with staggered openings (1×1),
SW4= Shear wall with regular openings (2×1),
SW5= Shear wall with staggered openings (2×1).

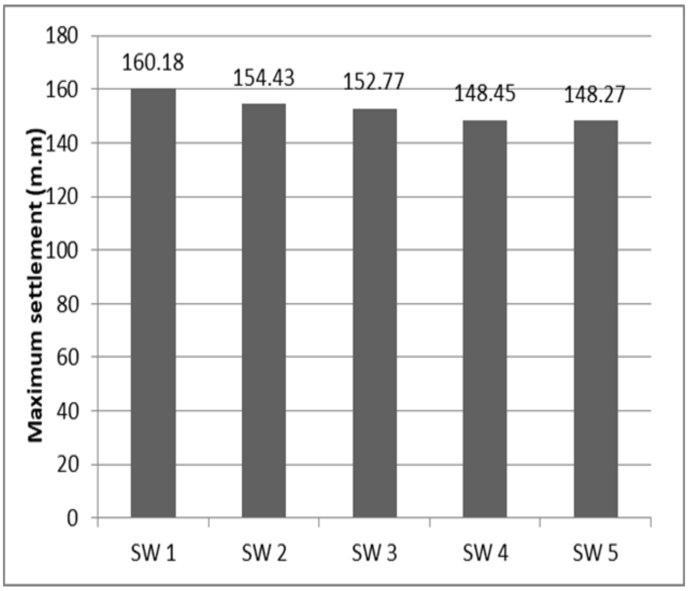


Figure 20. Settlement of SW cases for 25 storey building.

Figure 20 shows the maximum settlement in the model. The shear wall stiffness has an effect on reducing settlements in all models. The decrease of stiffness of SW2 and SW3 to SW1 causes a reduction in settlement by about 3.59%, and 4.63%, respectively. The decrease of stiffness of SW4 and SW5 to SW1 causes a reduction in settlement by about 7.32%, and 7.44 %, respectively. It can be clearly shown that the shear wall with staggered opening gives less settlement than regular opening.

Figure 21 shows pile load ratio for 5 cases of the shear walls. The pile load ratio values are almost as close.

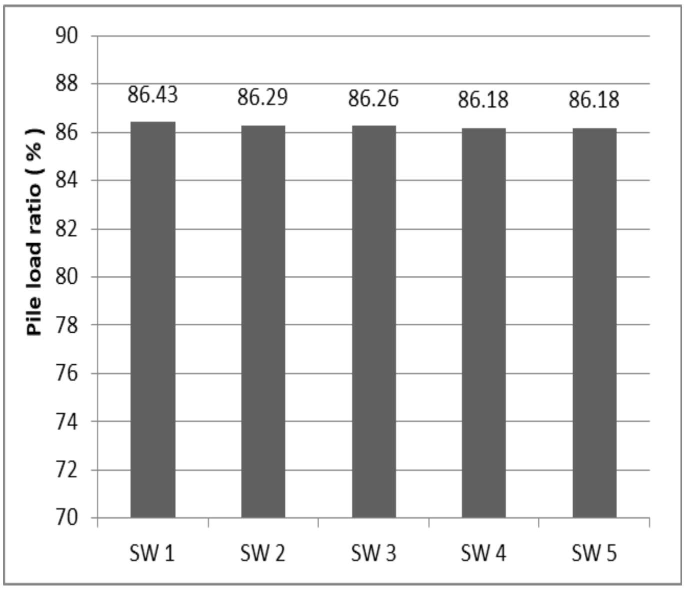


Figure 21. Pile load ratio of SW cases.

3.5 *Substructure Results*

3.5.1 *Effect of pile diameter (Group 1)*

Figure 22 shows the maximum settlement of 25-storey building with varying pile diameters of 1.0 m, 1.2 m, and 1.4 m. The pile length is taken constant (L= 32 m) for all cases. Each case of structure is analysed two times, the case of working and maximum earthquake case. The increment in pile diameter has an effect on reducing settlements in all models. The increase of pile diameter from 1.0 m to 1.40 m (40% increase) causes an average reduction in settlement by about 5.73%, and 15.49% for pile raft in working and pile raft max earthquake, respectively.

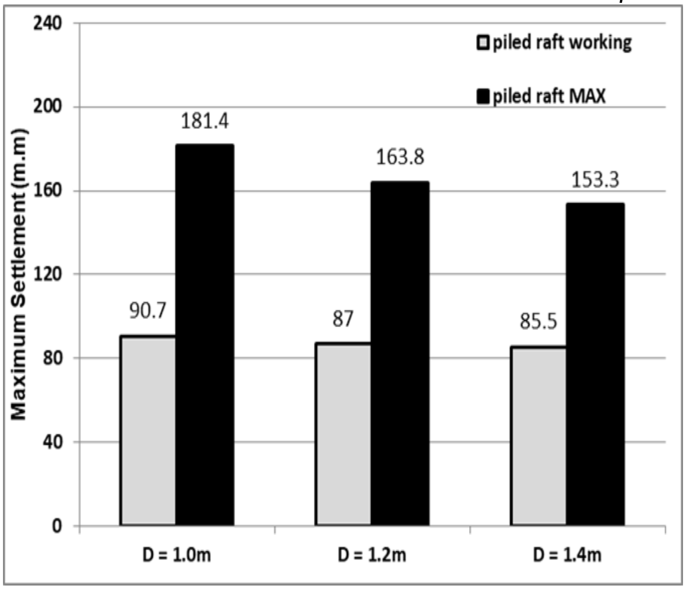


Figure 22. Settlement for different pile diameters (Group 1).

Figure 23 shows pile load ratio for different pile diameters. The increase of pile diameters from 1m to 1.4 m, causes an increase in pile load ratio by about 3.62%, and 3.98% for pile raft in working and pile raft max earthquake, respectively.

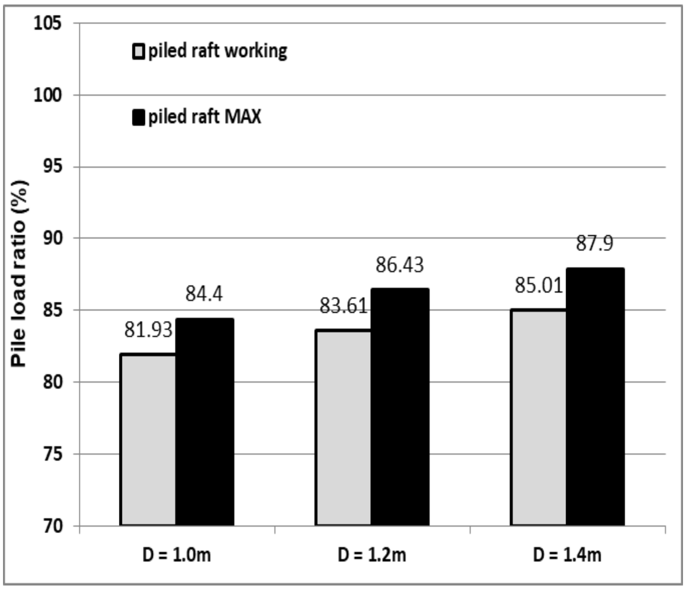


Figure 23. Pile load ratio of different pile diameter.

3.5.2 *Effect of pile length (Group 1)*

Figure 24 shows the maximum settlement of 25-storey with varying pile lengths of 30.0 m, 32.0 m, and 34.0 m. The pile diameter is taken constant (d = 1.2m) for all lengths. Each case of structure is analysed two times in working case and maximum earthquake case. The increase of pile length has a significant effect more than that of the pile diameter on reducing settlements. The increment of pile length from 30 m to 34 m (increase by 13%) causes an average reduction in settlement by about 54.42%, 55 %, for pile raft working and pile raft max earthquake, respectively. Figure 25 shows pile load ratio for different pile lengths. The increase of pile lengths from 30 m to 34 m (increase by 13%) causes an increase in pile load ratio by about 5.94 %, and 7.25% for pile raft working and pile raft max earthquake, respectively.

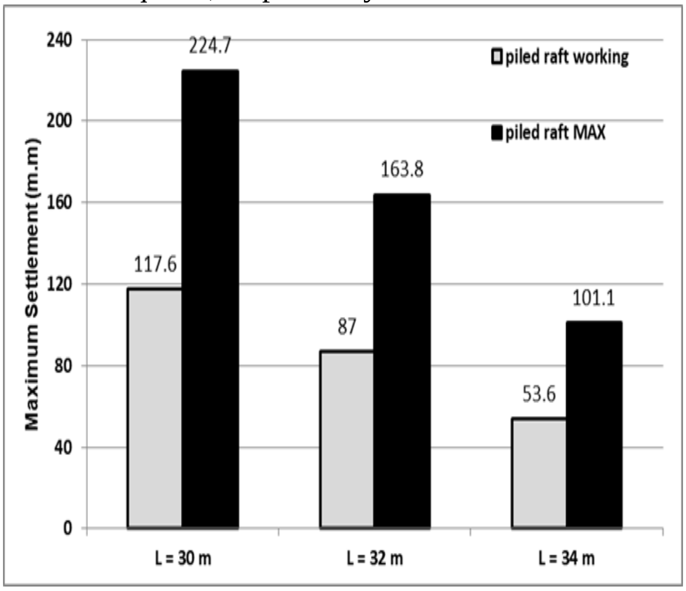


Figure 24. Settlement for different pile length (Group 1).

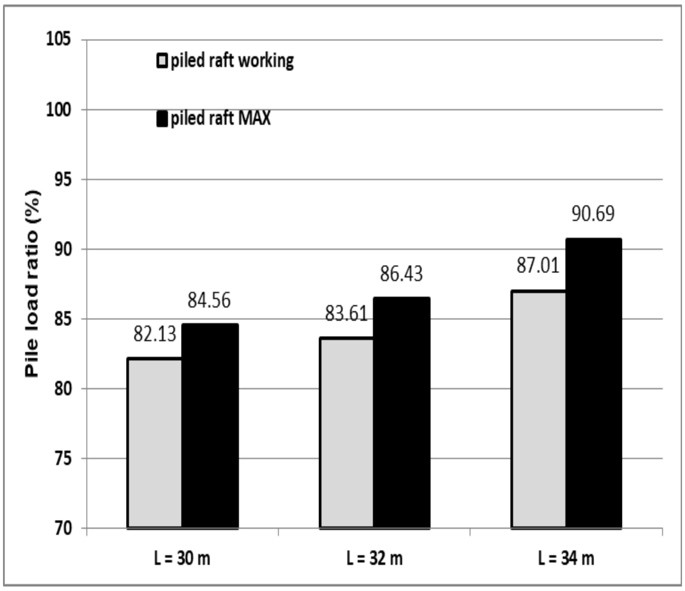


Figure 25. Pile load ratio of different pile length (Group 1).

3.5.3 *Effect of pile length (Group 2)*

Figure 26 shows the maximum settlement of 25-storey with varying pile lengths 30.0 m, 32.0 m, and 34.0 m. The pile diameter is taken constant (d= 0.8m) for all lengths with total number of piles N= 56 piles. Each case of structure is analysed two times, in working case and maximum earthquake case. The increment of pile lengths from 30 m to 34 m (increase by13%) causes an average reduction in settlement by about 52.45%, and 52.25 %, for pile raft in working and pile raft max earthquake, respectively. Figure 27 shows pile load ratio for different pile lengths. The increase of pile lengths from 30 m to 34 m causes an increase in pile load ratio by about 5.94 %, and 7.25%, for pile raft in working and pile raft max earthquake, respectively.

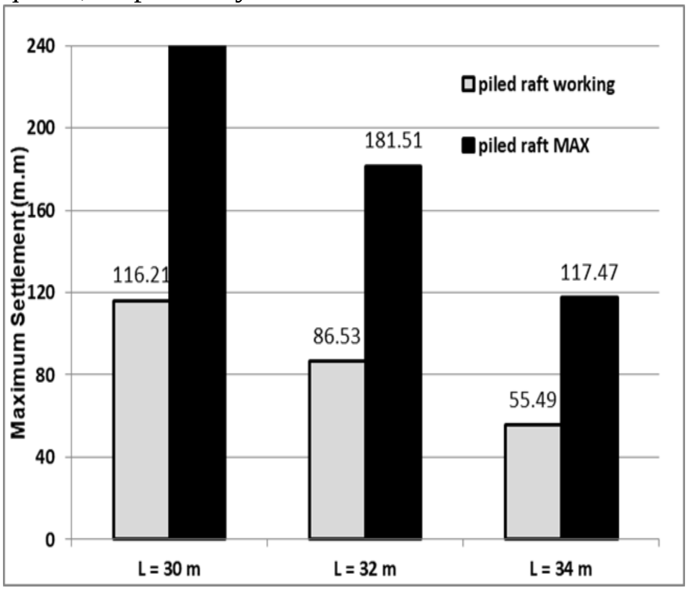


Figure 26. Settlement for different pile length (Group 2).

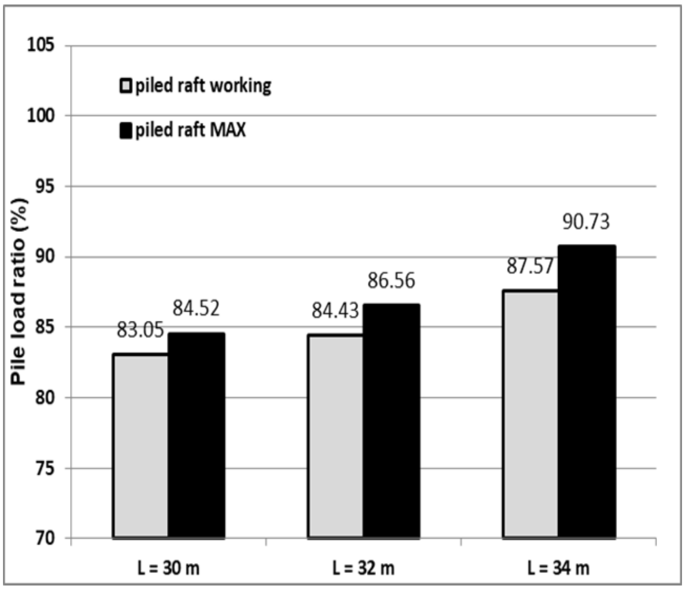


Figure 27. Pile load ratio of different pile length (Group 2).

4 CONCLUSIONS

A numerical analysis is carried out to analyse tall buildings with shear walls that having regular and staggered openings and resting on piles raft with different pile configurations under seismic action. The behaviour of soil-structure interaction on superstructures of 20, 25, and 30-storeys rested on a pile raft with weak soil properties was investigated. The study reveals that the displacement, drift, stress distribution on shear walls and the settlement is affected by the location of openings in shear wall. The analysis led to the following conclusions:

- The increase of displacement and drift from shear wall with regular openings compared to shear wall with staggered openings is almost close.
- The max percentage of displacement from the regular opening to staggered opening for 20, 25, and 30 storeys is 1.29 %, 1.41 %, and 1.65 %, respectively.
- The max percentage of drift from the regular opening compared to staggered opening for 20, 25, and 30 storeys is 0.79, 0.98 %, and 1.14 %, respectively.
- Staggered openings in shear wall proved to be highly advantageous and with less stresses in shear wall around the staggered openings than the stresses pattern around the shear wall with regular openings.
- The seismic behaviour of the building is not only depending on the location of openings but also on the size of openings.
- The shear walls with staggered openings needed much less reinforcement than the shear walls with vertical openings.
- The settlement for shear wall with staggered opening is less than the settlement of regular opening.
- The decrease of stiffness from shear wall without opening to shear wall with regular opening (1m×1m) and shear wall with staggered opening (1m×1m) causes a reduction in settlement by about 3.59%, 4.63%, respectively.
- The decrease of stiffness from shear wall without opening to shear wall with regular opening (2m×1m) and shear wall with staggered opening (2m×1m) causes a reduction in settlement by about 7.32%, 7.44 %, respectively.
- The effect of pile length in clay soil is greater than the pile diameter. The increment of pile length from 30 m to 34 m (13% increase) causes an average reduction in settlement by about 54.42%, and 55 %, for pile raft in working and pile raft max earthquake, respectively.
- The increase of pile diameter from 1.0 m to 1.40 m (40% increase) causes an average reduction in settlement by about 5.73%, 15.49%, for pile raft in working and pile raft max earthquake, respectively.
- The optimum design for pile raft in studied zone with clay soil is:
  Pile length = 32m, pile diameter = 1.2 m
  and spacing = 5m.

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