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A Review of Factors Influencing Foundation Stability of Tall Structures

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Abstract

This paper reviews the issue of stability of tall structures and the influencing factors. Depending upon location and type of tall structures, magnitude and direction of forces induced, ground conditions, presence of adjacent structures, appropriate stabilization techniques are required to be adopted. Length, diameter, inclination etc. of piles plays important role as far as local and global stability of the tall structures is concerned. This review paper will help the designers to carefully select these parameters and provide stable foundation for the tall structures.

Keywords — *foundation, tall structure, pile foundation, shear wall, global stability, pile centre, micropiles.*

I. INTRODUCTION

Urban population is growing day by day at faster rate of pace, thereby creating shortage of available space for construction of residential and commercial complexes. Also the prices of available spaces have reached extreme highs since last decade. Therefore in order to meet growing demands, a construction of multistoried buildings utilizing vertical space is the only solution.

This vertical growth of the structures has created need for careful and stable foundation design in order to avoid catastrophic failures; in the events of settlements, earthquakes and wind pressures. Foundation design is very important aspect as it provides sufficient capacity to transfer loads into the soil thereby providing stability to the tall structures.

As per the building code of Hyderabad, tall building is one having more than 04 floors or 15 m height [1]. A high-rise building as a building more than 75ft (22.5m) in height where the building height is measured from the lowest level of fire department vehicle access to the floor of the highest occupiable story [2].

This paper discusses the influential factors affecting the stability of tall structures and the requirements for stable foundation design through in depth review of the recent and relevant literature.

II. STABILIZATION

Stabilization of individual structures as well as the group of all adjoining structures as a whole is an important aspect. When stability of a single structure is considered, it is termed as local stability whereas group stability is called global stability.

Tall structures may be subjected to lateral forces due to wind loading, seismic forces induced lateral motions in the ground, unequal settlements due to non-uniform loading of superstructures and non-uniform ultimate bearing capacity of the soil.

Also, tall structures can be considered as cantilever columns undergoing bending deformation, or shear deformation or combination of these two [3]. For slender structures, bending deformation is considered more vital than shear deformation. Transverse, as well as torsional buckling might include both bending and shear contribution. Rotation at the foundation as well contributes to global instability [4].

Depending upon location and type of tall structures, magnitude and forces induced, ground conditions, presence of adjacent structures, appropriate stabilization techniques are required to be adopted [5].

Piled foundation, raft foundation, and their combinations along with shear walls are the commonly used methods for providing stability where the vertical and lateral loading on the foundation are considerable.

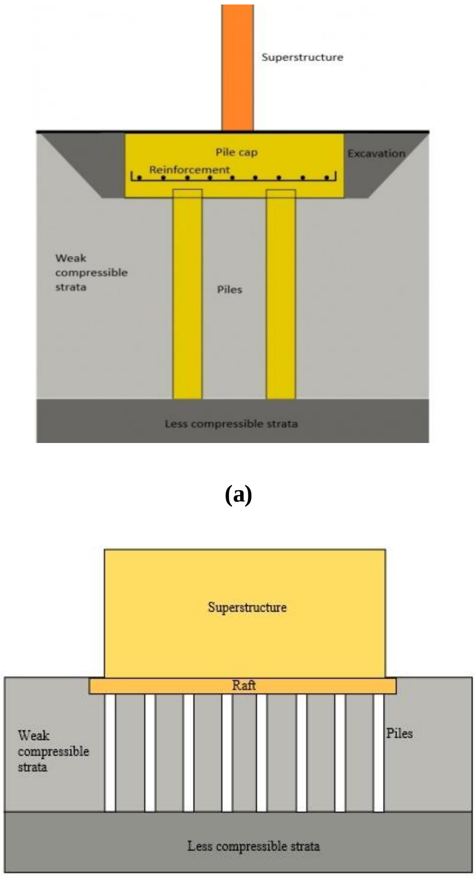
A. Pile Foundation:

Pile foundation as shown in Figure 1(a), a kind of deep foundation, is actually a slender column or long cylinder made of materials such as concrete or steel which are used to support the structure and transfer the load at desired depth either by end bearing or skin friction. A foundation is described as 'piled' when its depth is more than three times its breadth [6].

Pile foundations are principally used to transfer the loads from superstructures, through weak, compressible strata or water onto stronger, more compact, less compressible and stiffer soil or rock at depth, increasing the effective size of a foundation and resisting horizontal loads. They are typically used for large structures and in situations where soil is not suitable to prevent excessive settlement.

B. Compensated Raft Foundation

Where soil is compressible, a raft foundation may be formed as a compensated foundation. In this case, the raft slab is provided to a depth that the weight of the excavated soil is equal to the raft slab weight plus that of the structure to be supported. This can be appropriate when constructing buildings on soft clay or loose sand, as settlement can be significantly reduced. Compensated foundations normally comprise a deep basement and/or are used to support tall buildings or swimming pools, where a very large amount of material is excavated. The relief of stress due to the excavation is approximately balanced by the applied stress of the foundation, resulting in a negligible net stress. As a result there may be little consolidation settlement experienced.



(a)

(b)

Fig. 1 : Schematic presentation of (a) pile foundation (b) piled raft foundation [7]

C. Piled Raft Foundation

Where a conventional raft foundation does not provide adequate support, it can be enhanced by the addition of piles, creating what is known as a piled raft foundation, as shown in Figure 1(b). The addition of piles to a raft increases the effective size of a foundation and can help to resist horizontal loads. This can improve the performance of the foundation in reducing the amount of settlement and differential settlement, as well as improving the ultimate load capacity. Piled raft foundations are typically used for large structures and in situations where soil is not suitable to prevent excessive settlement. They are popular choice for tall buildings.

D. Shear Wall

A shear wall, as shown in Figure 2, is a vertical element of a seismic force resisting system that is designed to resist in-plane lateral forces, typically wind and seismic loads. A shear wall resists loads parallel to the plane of the wall. Collectors also known as drag members; transfer the diaphragm shear to shear walls and other vertical elements of the seismic force resisting system. Shear walls are typically light-framed or braced wooden walls with shear panels, reinforced concrete walls, reinforced masonry walls, or steel plates.

Shear walls generally start at foundation and are continuous throughout the building height. The walls provide large strength and stiffness to buildings in the direction of their orientation, mostly due to its large cross-section area that provide great moment of inertia, which significantly reduces lateral sway of the building.

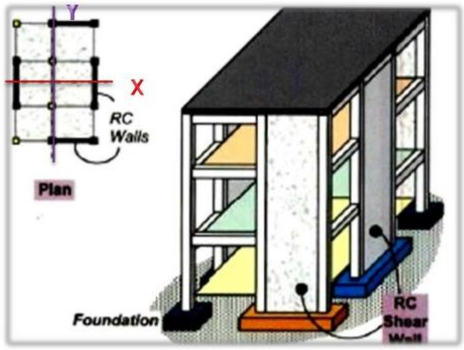


Fig. 2: Reinforced concrete shear wall [8]

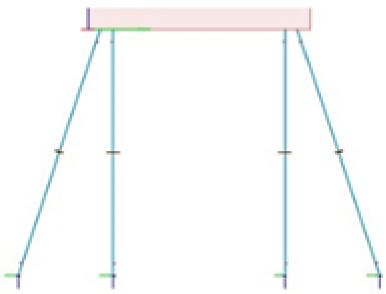
III. Factors Influencing Local and Global Stability of Structures

A. Length and Diameter of piles:

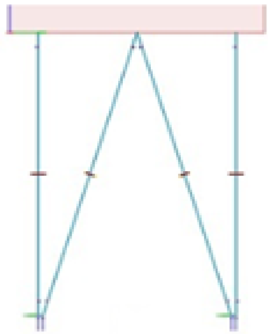
In the analysis of a case study, Talikoti & Lodha [11] studied the effect of pile diameter and length of piles on the settlement of the soil. A case of piled raft for displacement limiting criterion was undertaken for study. The number of piles required, length and diameter of piles required were obtained numerically. The approximate settlement of piled raft under point load was estimated by theoretical formulae. Using three dimensional analysis in FEA software, the problem was further analysed under uniformly distributed load and point load. From the FEA, it was found that the settlement was nearly same as that of theoretically calculated one. Also, it was concluded that, settlement was reduced considerably with increase in the pile diameter. Also, as the length of pile increased, settlement was reduced. Combined piled Raft Foundation method, thus used was found to be suitable in clay soil.

B. Pile Centre and Angle of Inclination of piles:

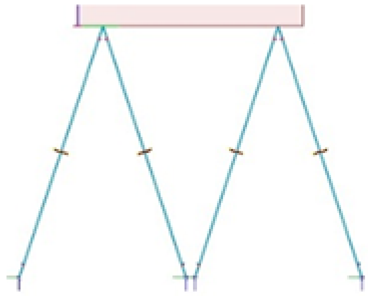
Dhorajiwala [4] investigated the influence of foundation on piles on global stability of superstructure and also investigated analytical methods to asses global buckling. The analysis involved parametric study of various factors influencing global stability with the help of FEM software. In the parametric study, a stabilizing concrete wall, supported by piles with different configurations was modelled in FEM Strusoft AB. The parametric study was conducted by considering different lengths of piles (10, 20 and 30 m) and different inclination of piles (3:1 and 4:1) Three different cases were analysed for different configurations of piles as shown in figure. In Case 1, inclined piles were situated at the edges. In Case 2, inclined piles were situated at the middle of the wall and in the Case 3, four inclined piles were situated at the edges. The structure was subjected to a horizontal distributed load along the height of the wall and vertical line load acting at the centre of the wall. For Case 2 and 3 the analysis was done only for pile length of 10 meter, whereas for Case 1 for 10, 20 and 30 meter.



(a) Case 1



(b) Case 2



(b) Case 3

Fig. 3: Pile Configurations [4] used in the case studies

The stability analysis was conducted for wind and line load separately. The analytical obtained results for the vertical buckling were compared to results from FE software. Stability analysis for horizontal load was done to investigate how the stability changes for different configurations.

The influence of the stiffness of the piles was investigated for different bending stiffness of pile groups for the structure. Safety factors extracted from FEM-Design software for walls subjected to vertical loading were compared to each other in order to see how the decrease in stiffness of piles influence global stability.

Safety factors received from FEM design were compared with the one received from methods that Equivalent stiffness method (ESM) and Combined flexural and rotational buckling (F&R).

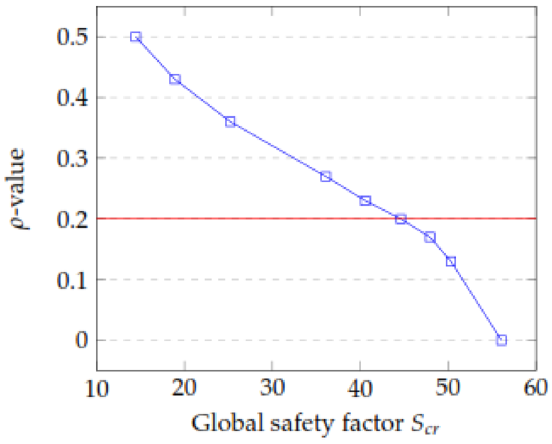


Fig. 4: Global Safety Factors

It was found that walls with 3:1 compared to 4:1 inclination of piles having the same pile length and height of wall had bigger global safety. Furthermore, the longer the piles were the lower was the global safety

***Table 1*: Comparison of Global Safety Factors**

ρ	Ratio between F&R and FEM	Ratio between ESM & FEM	ρ	Ratio between F&R and FEM	Ratio between ESM & FEM
0.5	9.54	4.14	0.20	1.18	1.57
0.43	2.82	3.48	0.17	1.10	1.43
0.36	2.10	2.77	0.13	1.04	1.32
0.27	1.46	1.99	0.00	0.98	0.99
0.23	1.23	1.76			

ρ	$S_{cr,10}$	$S_{cr,20}$	Ratio between S_{cr10} & $S_{cr,20}$
0.50	14.45	15.58	1.08
0.43	18.91	19.83	1.05
0.36	25.23	25.19	1.00
0.27	36.08	31.71	0.88
0.23	40.57	34.80	0.86
0.20	44.61	36.78	0.82
0.17	47.92	38.28	0.80
0.13	50.32	39.41	0.78
0.00	61.08	45.95	0.75

C. Depth of excavations:

Srivastava et al. [14] analysed stability of foundation for deep excavation of 18 m depth using micro piles for a multi-storey basement structure for a shopping mall. Stability analysis was performed by considering in situ soil following Mohr Coulomb constitutive behaviour and modelling micro piles as plate elements in FEA. Global factor of safety of the deep excavation problem was evaluated and estimated deformation values were found to confirm the foundation stability.

Micro piles are found to be suitable to replace deteriorating foundation systems, to provide extra support for structures during renovation and to provide pile foundations where access, geology or environment prevents the use of other methods.

D. Orientation of shear walls:

Placement of shear walls is also an important aspect to provide overall stability [9]. Shear wall are located symmetrically to avoid ill effects of twisting. Symmetry can be maintained along one or both the directions [10]. Shear walls can be located at exterior or interior, but are more effective when located along exterior perimeter of the building. Figure 4, shows the appropriate locations for the shear wall in tall buildings.

E. Orientation towers and walls:

Stabilization with one stabilizing unit, for example tower is not appropriate, because the structure might be susceptible to torsional buckling. One tower can be sufficient if it is a central core with significant size compared to the size of the floor plan. The principles of stabilization require at least two towers, or one tower with a wall. If only walls are used, at least three have to be used and cannot be placed on the same extension line. And additionally two of walls have to be placed perpendicular to the longer side of the building. Examples of stabilizing systems that are unstable and stable are shown in Figure 5 (a) and (b) respectively.

If the plan of a structure is symmetrical in the direction of loading, except for eccentric wind load, the structure will not suffer from twisting. When a plan of structure is asymmetric in the direction of loading, the structure will twist and translate around rotation center.

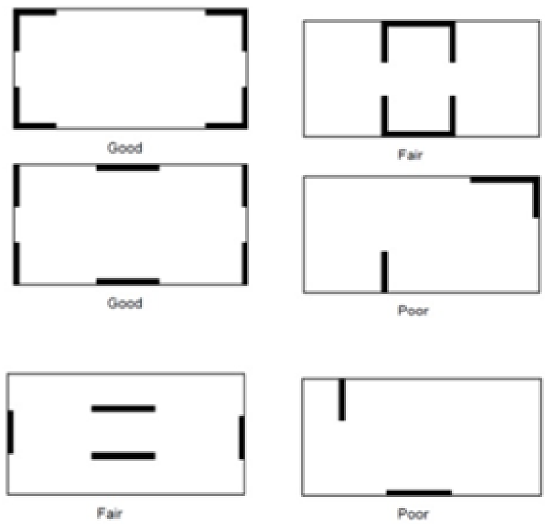


Fig. 5: Placement of shear wall [9, 10]

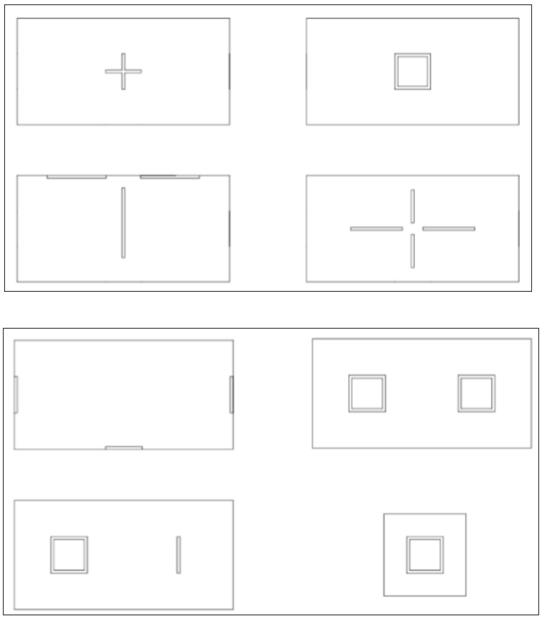


Figure 6 : (a) unstable and (b) stable systems [12, 13]

IV. CONCLUSION

From the review of the above literature and findings by the researchers regarding stability of tall structures, it can be concluded that depending upon location and type of tall structures, magnitude and direction of forces induced, ground conditions, presence of adjacent structures, appropriate stabilization techniques are required to be adopted. Length, diameter, inclination etc. of piles plays important role as far as local and global stability of the tall structures is concerned. In general, following inferences are drawn which will be helpful for the designers is assessing the stability issues concerned with tall structures and their foundations.

1. As pile diameter increases, settlement reduces considerably.
2. As pile length increases, settlement reduces and helps to improve local stability.
3. Compensated piled raft foundation is very effective foundation system in clay soil.
4. Pile centre has effect on global stability. Closer the pile centre is to the foundation on piles, the better the global stability of structure.
5. Longer the pile worse is the global stability because overall stiffness of a structure decreases and consequently the global stability.
6. Placement of shear walls and towers in symmetrical manner helps to improve the stability. Preferably, shear walls should be placed on the exterior perimeter.
7. In case of deep excavations and retrofitting works, micro piles can provide better stability.

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