Induced Settlement Reduction of Adjacent Masonry Building in Residential Constructions

Abolfazl Mohafezatkar Sereshkeh [a*], Reza Jamshidi Chenari [b]

[a] M.Sc., Faculty of Engineering, University of Guilan, Rasht, Iran.

[b] Associate Professor, Faculty of Engineering, University of Guilan, Rasht, Guilan, Iran.

Abstract

Many buildings and heritages are yearly damaged due to new construction plans in vicinity of them. Current engineering practice in Iran lacks unfortunately regulations to enforce the designers of new buildings to re-evaluate the structural integrity of adjacent old buildings which are prone to unacceptable induced settlement and distortions. To damage assessment of old building, deflection ratio was used for unreinforced load-bearing wall (masonry) building. In this paper some practical methods like story limits for the new buildings according to the specification of old structure, improvement of shallow foundations and increasing the embedment depth of new foundations have been studied in order to decrease the settlement and undesirable effects of adjacent constructions. Parametric studies using numerical analysis, Flac3D, have paved the way how above mentioned methods can remedy the problem. So induced consolidation settlements due to new construction in adjacent building were studied. In conclusion, increase of admissible story of new building up to one floor by increase of embedment depth as much as one meter and three floors by using of mat foundation instead of single footing were highlighted these methods.

Keywords: Induced Settlement; Forensic Analysis; Adjacent Building; Embedded Depth; Shallow Foundation; Consolidation Settlement.

1. Introduction

Today with the increasing development of cities and high rise buildings in urban areas, it's necessary to keep an eye on the destructive effects of new constructions on the existing old buildings which are mainly small and masonry. Lodging many complaints and appeals to the municipalities and local courts in a yearly basis regarding the disruptive events due to new constructions in highly populated zones reflects the dissatisfaction of the citizens from the existing design and construction practice and the lack of mutual consideration when designing a new building.

Votyakov [1] studied the additional settlement of a building due to the foundation of an adjacent building. It is known that the bases of two adjacent structures in zones of the superposition of stresses undergo increased deformations.

Murthy [2] studied the interference effect of surface footings on sand, but both the footings were not loaded simultaneously, i.e. one of the two footings was first loaded to its safe bearing capacity and the load on the other adjacent footing was then increased up to the ultimate load.

Selvadurai [3] examined the problem of the interaction between a loaded rigid circular foundation resting in smooth contact with an isotropic elastic half-space and a distributed loading which acts at an exterior point on the surface of the half-space. His studies were showed that the settlement of the rigid circular foundation due to an externally placed concentrated force can be evaluated in exact closed form.

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* Corresponding author: abmo1985a@gmail.com

Amir [4] and Saran and Amir [5] extended drawing pressure-settlement characteristics of isolated footing for the interfering strip foundations by consideration of hyperbola constitutive law for sand.

The investigation by Ahmed et al. [6] was showed the magnitude of settlement and tilt of the interfering footings is affected by ratio of spacing of footing to width one. Therefore, proportioning of interfering footings should be carried out by actual estimation of settlement and tilt.

A study on 225 building failure in United States from 1989 to 2000 shows that failures of low-rise buildings constitute about 63% of all cases and 25% of them was reported due to construction procedure [7].

Zdravkovic and Neo [8] presented the results of finite element analyses performed to investigate the effect of spacing on the bearing capacity and deformation of rough, rigid strip surface footings. The analyses show that the reduction in bearing capacity for spacings of B and 0.5B is less than 3% and a significant effect is again observed only at close spacings of 0.5B and B, with all the settlement components increasing by up to 40% as compared to the settlement of a single footing.

the experimental study by conducting a number of laboratory scaled model tests on the effect of interference between two adjacent surface strip footings was on reinforced sand was carried out by Ghosh and Kumar [9]. Their investigation showed that the ultimate bearing capacity and settlement of footing generally becomes maximum in terms of efficiency factors ($\xi\gamma$ and $\xi\delta$) at a certain critical spacing between the footings.

López Gayarre et al. [10] researched on pile foundation failure in the set of building in the Gijon (NW of Spain). By considering of some hypothesis of the failure they concluded exposing and rotting the top of wooden pile due to decreasing in the groundwater level causing by pumping in adjacent excavation of new building was a reasonable of existing crack in block.

Ghosh and Kumar [11] carried out a number of model tests to verifying the effect of interfering footings on cohesionless layered soil with experimental observation and theoretical result. The effect of centre to centre spacing (S) between two adjacent footings on their bearing capacity and settlement at failure was focused by authors. The results are presented in terms of efficiency factors ($\xi\gamma$, $\xi\delta$) and their variation was obtained with the change in S.

Nainegali et al. [12] provided the 2-D and 3-D finite element code to analysis of two closely spaced footings by considering linearly varying of elastic modules of soil. Influence between the load-settlement of footing and various parameters like width, spacing between the footings, length to width ratio, modulus of elasticity were highlighted in this research.

Alimardani Lavasan and Ghazavi [13] conducted an experimental investigation to evaluate the ultimate bearing capacity, the settlement and the tilt of two types closely spaced footings, one having square shapes and the other having circular shapes, on unreinforced and reinforced soil. The ultimate bearing capacity of the interfering footings increased by about 25–40%, whereas the settlement of the interfering footings at the ultimate load increased in the range of 60–100%. However, the closely spaced footings tilted by approximately 45% and 75% for reinforced sand with one and two layers of geogrid, respectively.

The research conducted was by Saibaba Reddy et al. [14] on the results of series of model tests in which two adjacently placed rough-placed footing resting on sand were loaded simultaneously in order to study the effect of footing size and spacing on the load settlement and failure behavior. The experimental results obtained from the model tests indicated that, the proximity of footings founded on sand enhances of foundations both in terms of settlement and ultimate bearing capacity. The interference effect is negligible when the spacing between the footings is greater than six times the footing size.

Panjalizadeh Marseh et al. [15] studied on negative effects of adjacent building construction in a case and various solutions were offered to reduce its adverse effects.

Hefdhallah [16] presented a case history that shows effect of neighboring footings on single footing settlement. The case history in hand consists of 28 auxiliary buildings of an Electrical Power plant near Cairo, Egypt. Settlement analysis was carried out by computing a profile of elastic stress increase due to all loaded areas at the foundation level. The results of the analysis suggested that the effect neighboring footings could be important to the extent that necessitates the change of the foundation system from isolated footings to raft foundation in the light of the maximum allowable settlement of each foundation system.

The forensic analysis was under taken on a 5-storey RC building in Athens by Anastasopoulos [17]. For more than 30 years, no damage had been observed in this building. In 1999, construction of an adjacent 5-storey RC building begun, and shear cracks in old building started appearing. In order to assess the relative importance of the two factors (construction of the adjacent structure vs. construction defects), numerical analyses were conducted modeling both buildings in detail. Results showed that almost 70% (3.5 cm) of the differential settlement had already taken place before construction of the adjacent building. Neighboring building induced Just 1.5 cm of the differential settlement.

Alimardani Lavasan and Ghazavi [18] studied the variation of ultimate bearing capacity, failure mechanism and deformation pattern of soil beneath two closely square footings. The presented numerical analyses are based on explicit-finite-difference code, Flac3D. The results of numerical modeling of interfering square footings show that the interference causes significant increase in the ultimate bearing capacity up to 1.5 times than that obtained for an isolated identical footing.

An investigated by experimental work on the bearing capacity and settlement of two closely spaced squared footings was conducted by Dhatrak and Awachat [19]. The parameters were spacing of footings, reinforcement layer and magnitude of prestressing force. The spacing between footings was varied from 1B to 3B along the width for both left and right footings. The prestressed reinforcement results in increasing bearing capacity and reduction in settlement behavior of the soil.

Impact of adjacent footings on immediate settlement of shallow footings was studied by Aytekin [20]. In the estimation of elastic (immediate) settlement, the Schmertmann's method was employed. The results show that settlement of an isolated footing with adjacent footings is always larger than one with no adjacent footing. The effect of adjacent footings on settlement of main footing is increased linearly with the number of adjacent footing.

Aghahadi Forushani and Mehrnahad [21] conducted a case study using of Pile to reduce induced settlement in existing adjacent building following construction of new building. Results revealed that proper arrangement of piles in the first row of piling and with axis-axis spacing of 3 m and length of 15 m next to the old building can rule out structure cracks.

As prevention is always better than retrofitting, checking for potential failure mechanisms and seeking methods to avert uncalled-for situations by revising the current regulations so as to allow for prevention of such effects is conceived to be effective.

Tall buildings construction induces significant stresses to the ground which not only spreads in depth, but also distributes laterally. Increments of stress transferred to underneath the existing foundations, induces ground deformation that may affect existing structures.

Although the resulting ground settlements rarely cause major structural damage to buildings, aesthetic and serviceability damage may occur. Structures adjacent to a new building, in particular old masonry buildings, may suffer damage resulting in costly repairs or require expensive protective measures, such as underpinning or compensation grouting [22].

This paper describes some case studies and the potential preventive measures to control the angular distortion of the adjacent building due to construction in neighborhood. 3-Dimensional finite difference is used to investigate some measure numerically.

2. Case Studies

The motivation for this study was raised by getting involved in forensic analysis for some failure cases in Guilan province located in northern Iran. The first case is related to a cottage house failure adjacent to a five-story building located in city of Rasht. After construction of five-story building in vicinity of it, some cracks in facade were founded (Figure 1). This large vertical crack was around 2 cm wide at first, subsequently increasing markedly until reaching some 10 cm in width. This conclusion was included in the sentence of the Court of Justice of Rasht, which rules that "there exists necessary causal link between the construction of the new construction and the damage to the masonry building''.

Figure 1. Adjacent building failure case I located in Rasht, Guilan (a) location of two building (b) and details of facade failure

The second case refers to the failure of a two-story building induced by the additional settlement due to a new construction nearby. Figure 2. shows one of the cracks that occurred in the interior partitions of this building due to adjacent construction of new six-story structure. The rupture can be seen by following the joints of the bricks, where the mortar shows less resistance. This cracks caused by differential settlement of existing foundation due to induced settlement of new building.
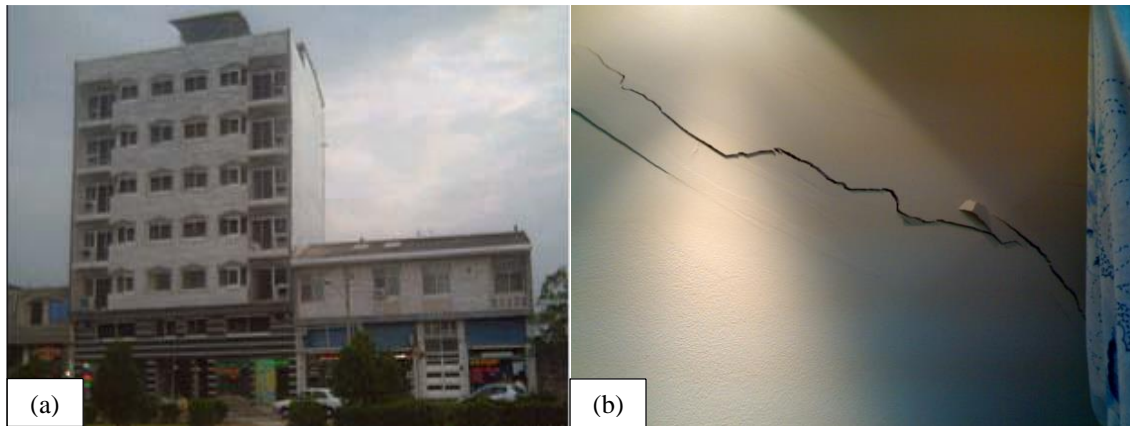

Figure 2. Adjacent building failure case II located in Somesara, Guilan (a) location of two building and (b) cracks in the walls due to differential settlement

There are quite a few other cases suffering additional settlement-induced failure in Guilan province which are out of the scope of this paper. This study has just exemplified the failure phenomena by bringing some real cases. The balance of the study only focuses on the general causes of similar failure by conducting some numerical parametric studies.

3. Mechanism of Foundation Damage

When a new building construction happens in vicinity of another building, in view of geotechnical concerns two major risks arise:

1. Soil rupturing and sliding in vicinity or underneath the existing foundation caused by excavation of a new foundation. Figure 3b. shows displacement of an existing footing caused by excavation for new footing [23]. Excavation wall can face rupture and slide or by removing the lateral support it will face lateral deformation called "Bulging".
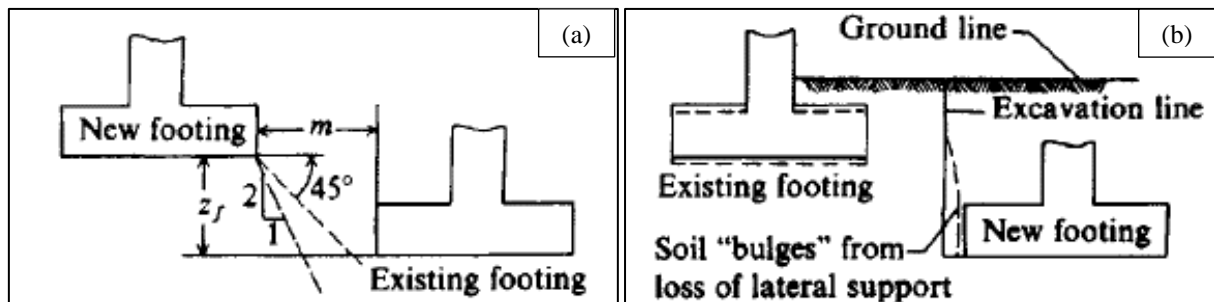

Figure 3. Location considerations for spread footings; (a) An approximation for the spacing of footings to avoid interference between old and new footings. If the "new" footing is in the relative position of the "existing" footing of this figure, interchange the words "existing" and "new." Make m > z_f; (b) Possible settlement of "existing" footing because of loss of lateral support of soil wedge beneath existing footing [23]

2. Differential settlement between existing foundations induced by stress increments from the new construction. New structure is often built at one side of old structure introducing increments of stresses in adjacent side. So foundations or those parts of foundations that are closer to the new structure will face more settlement compared to those that are farther. This process will lead to the so-called angular distortion in old building shown schematically in Figure 4.
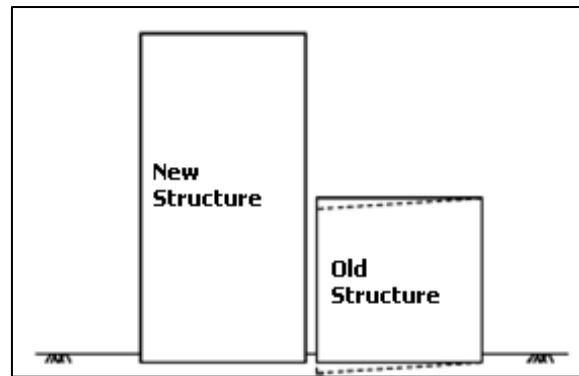
Figure 4. Angular distortion in old structure

According to the position of two foundations it is recommended [23]:

a) If the new footing is upper than the existing footing. When footings are to be placed adjacent to an existing structure, as indicated in Figure 3a, the line from the base of the new footing to the bottom edge of the existing footing should be 45° or less with the horizontal plane. From this requirement it follows that the distance m of Figure 3a. should be greater than the difference in elevation of the two footings z_f.

b) If the new footing is lower than the existing footing. Figure 3b. indicates that there is a possibility that the soil may flow laterally from beneath the existing footing. This may increase the amount of excavation somewhat but, more importantly, may result in settlement cracks in the existing building. This problem is difficult to analyze; however, an approximation of the safe depth z_f may be made for a ϕ-c soil since $\sigma_3 = 0$ on the vertical face of the excavation. The vertical pressure σ1 would include the pressure from the existing footing. This analysis is as follows:

$$\sigma_1 \approx \gamma z_f + q_0 \tag{1}$$

$$\sigma_3 = 0 = \sigma_1 K - 2c\sqrt{K} = \gamma z_f K + q_0 K - 2c\sqrt{K} \tag{2}$$

Solving for excavation depth, z_f (and using a safety factor, SF), is obtains:

$$z_f = \frac{2c}{(SF)\gamma\sqrt{K}} = \frac{q_0}{(SF)\gamma} \tag{3}$$

It is difficult to compute how close one may excavate to existing footings such as those of Figure 3. before the adjacent structure is distressed. The problem may be avoided by constructing a wall (sheet pile or other material) to retain the soil [23].

4. Regulatory Limits

Regulations limits for the settlement are divided to total and differential settlement. There is a structural damage if differential settlement exceeds limiting value. Common limitations are shown in Table 1. to control the settlements in urban buildings.

Table 1. Limitations of total and differential settlement in urban buildings [24]

Type of Damage	Criterion	Limiting Value
Structural damage	Angular distortion	1/150 - 1/250
Cracking in walls and partitions	Angular distortion	1/500 1/1000 - 1/1400: end bays
Visual appearance	Tilt	1/300
Connection to services	Total settlement	50 - 75 mm: sands 50 -135 mm: clays
Cracking by relative sag *	Deflection ratio	1/2500: wall length/height=1 1/1250: wall length/height=5
Cracking by relative hog *	Deflection ratio	1/5000: wall length/height=l 1/2500: wall length/height=5

* For unreinforced load bearing walls

The most meaningful distortion parameter in the context of cracking walls in masonry building is the deflection ratio, which is defined as the maximum vertical displacement (Δ) relative to the straight line connecting two points divided by the length (L) between those two points [25].
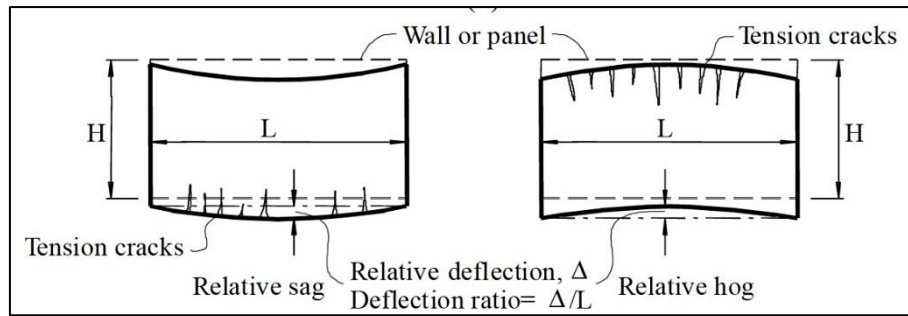

Figure 5. Definitions of deflection ratio load-bearing wall structures [25]

5. Damage Reduction Measures

Practical measures to prevent damage to the existing building after new construction nearby can mentioned as follows:

- Restriction of the number of story for new constructions.
- Increasing the embedment depth of new foundations.
- Proper choose of shallow foundations.
- Provision of deep foundations.
- Improving the load bearing characteristics of subsoil underneath both old and new buildings.

A combination of the above listed measures can be adopted for a construction project so as to minimize the side effect of the new building construction on the adjacent building. Current study will focuses on the first three methods by conduction a numerical study.

6. Numerical Modeling

In Rasht city, there are a lot of Masonry buildings with one or two floors. The most masonry buildings have been constructed by cement blocks and their structure system is unreinforced load bearing wall. Because not having qualified structural system and proper foundation; these old masonry buildings are sensitive to additional settlement. Due to the economic development and population growth, new buildings are built in the form of tall buildings and this may be located nearby the buildings with low floors. The majorities of new structures have frame system and are constructed more than four floors. So, to designing such buildings, in addition to the soil properties which must be carefully evaluated, it is necessary to consider the status of adjacent structures.

The Flac3D software was used to numerically investigate the effect of adjacent building construction based on finite difference method. In order to set up the numerical model and to carry out simulations, three fundamental components of finite difference approach including grid geometry, boundary and initial condition and constitutive behavior should be specified.

Artificial boundaries fall into two categories: planes of symmetry and planes of truncation. The model was created the one half-symmetry model to takes advantage of the fact that the geometry and loading in a system are symmetrical about one plane.

The grid can be defined from the geometry of model as shown in Figure 6. The procedure of geometric modeling was simplified using 'Primitive Shape' zones. 'Radial Tunnel' and 'Brick' elements were used to define geometry of soil and foundation respectively.

The boundary conditions applied to numerical models consist of roller boundaries provided in outside and bottom planes. Geometry dimension and boundary condition of model has shown in Table 2.

Table 2. Information of Modeling

Modeling Dimension	Meshing		Boundary Condition		
length x Width x height $(m \times m \times m)$	Min. Size $(m \times m \times m)$	Max. Size $(m \times m \times m)$	Top	Side	Bottom
$160 \times 50 \times 50$	$1 \times 1 \times 1$	$6.67 \times 5 \times 2$	Free	Roller Boundary	Roller Boundary

Flac3D offers a variety of material models. The Mohr-Coulomb material model which allows for plastic deformation after meeting the failure criterion (strength) is used for soil elements which employs a linearly elastic-perfectly plastic stress-strain response. The Consolidation analysis is used for calculation of settlement. The formulation of coupled deformation-diffusion processes in Flac3D is done within the framework of the quasi-static Biot theory, and can be applied to problems involving single-phase Darcy flow in a porous medium. In this research, geotechnical parameters of Rasht soil (Southern area of Caspian Sea) are considered. Sekhavatian [26] investigated on general soil profile and geotechnical properties of Rasht clayey soil. Properties of the clay materials according to Sekhavatian's studies are summarized in Table 3.

Table 3. Properties of chosen clay

Wet Density (kg/m³)	Drained Cohesion (kPa)	Drained Friction Angle (degrees)	Elastic Modulus (MPa)	Drained Poisson's Ratio	Permeability (m/s)
1900	8	25	16	0.2	10^{-9}

Overall dimensions of the model are normally dependent on the foundation width; B. boundaries should be far enough so as not to be affected by the stress bulbs beneath the foundation.
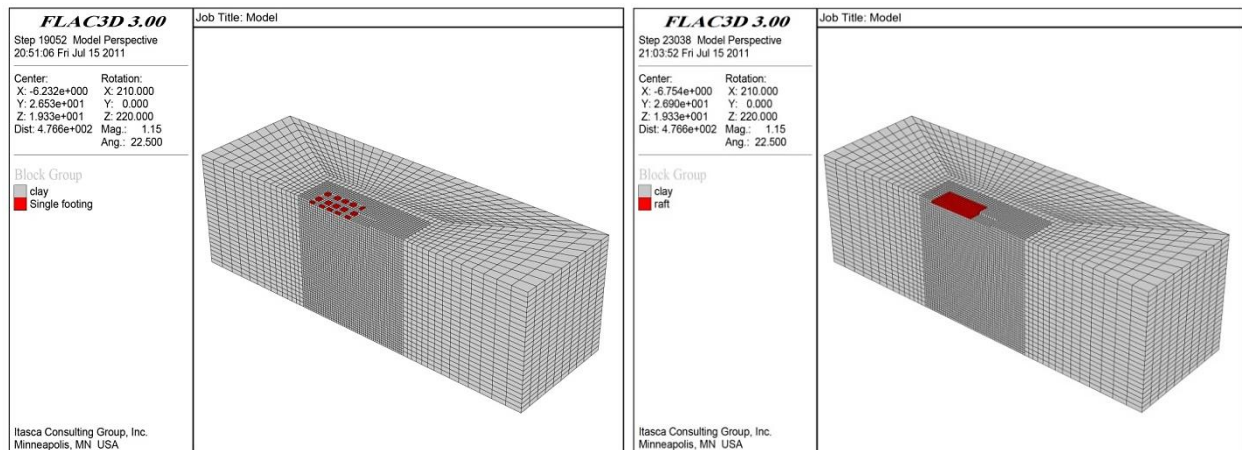

Figure 6. Mesh discretization for the soil model in Flac3D: Types of new foundation: (a) Single footing; (b) Mat foundation

For parameter study of induced settlement, the old and new foundations have modeled separated from their structures. In order to damage assessment of old building, induced deflection ratio is traced in old foundation. The definition and limited value of deflection ratio have discussed in clause 4.

The dimensions of foundation for new building are assumed $20\ m \times 20\ m$ in plan and for the adjacent building are $10\ m \times 10\ m$. The overall dimension of the model was then chosen to be $160\ m$ in length, $50\ m$ in breadth and $50\ m$ in height. Due to the Iranian building loading manual, the total dead and live loads were summed at $1000\ kg\ /\ m^2$ for each story of the building.

Before applying the load to the system, the model was brought to equilibrium under initial state to simulate this condition; the model was simulated under initial stresses caused by gravity of soil.

Two different foundation systems were adopted on this study as demonstrated in Figure 7. Single footing and mat foundations were chosen for the new building in order to study the effect of foundation type.
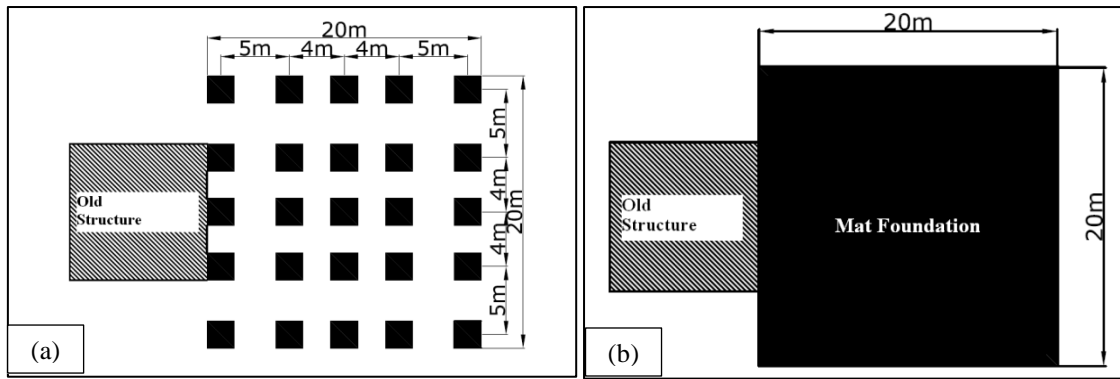
Figure 7. Types of new foundation, (a) Single footing; (b) Mat foundation

7. Parametric Studies

As stated before, three measures, namely the story limits for the new buildings, increasing the embedment depth of new foundations and the proper choose of the shallow foundations for the new building are typical methods to reduce damage imposed on the adjacent old building. Old building distortion threshold limit was taken 1/5000 for cracking by relative hog and 1/2500 for cracking by relative sag which is compared with the deflection ratio in old building due to construction in the vicinity of it.

The induced deflection ratio in adjacent old building was calculated for every story increment in new building. Results of such calculations are provided in Figure 8. for different foundation systems in new building. It's assumed old building has one story.

With increasing in number of stories in the new building, deflection ratio of the old building increases.

As expected, the improvement of shallow foundation system will lead to an increase in the story limits for the new building.
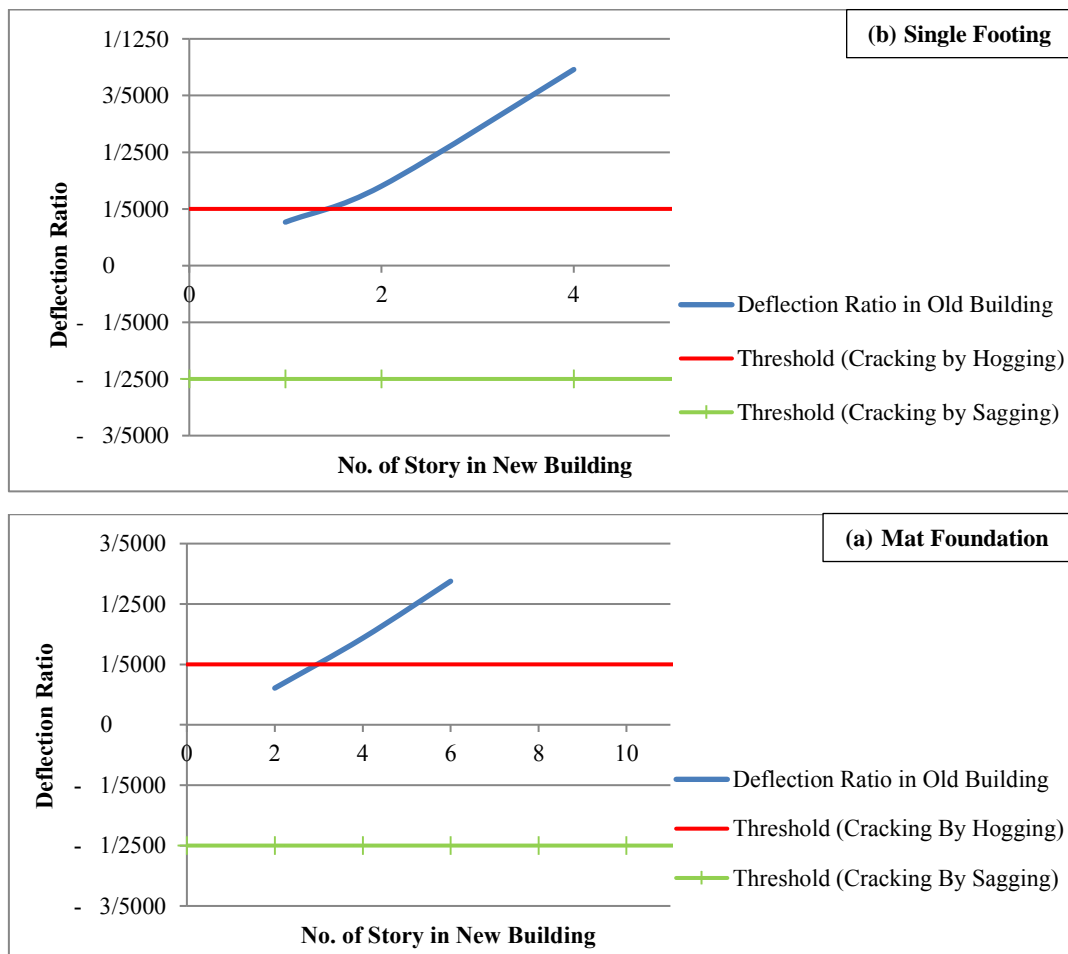

Figure 8. Story limits in the new building with Df = 1 for different type of the new foundation

Figure 9 to 13. demonstrates the deflection ratio induced in adjacent old building due to the new building constructing nearby for different foundation systems in new building when the embedment depth for new building is assumed to be Df =2 m to 5 m.
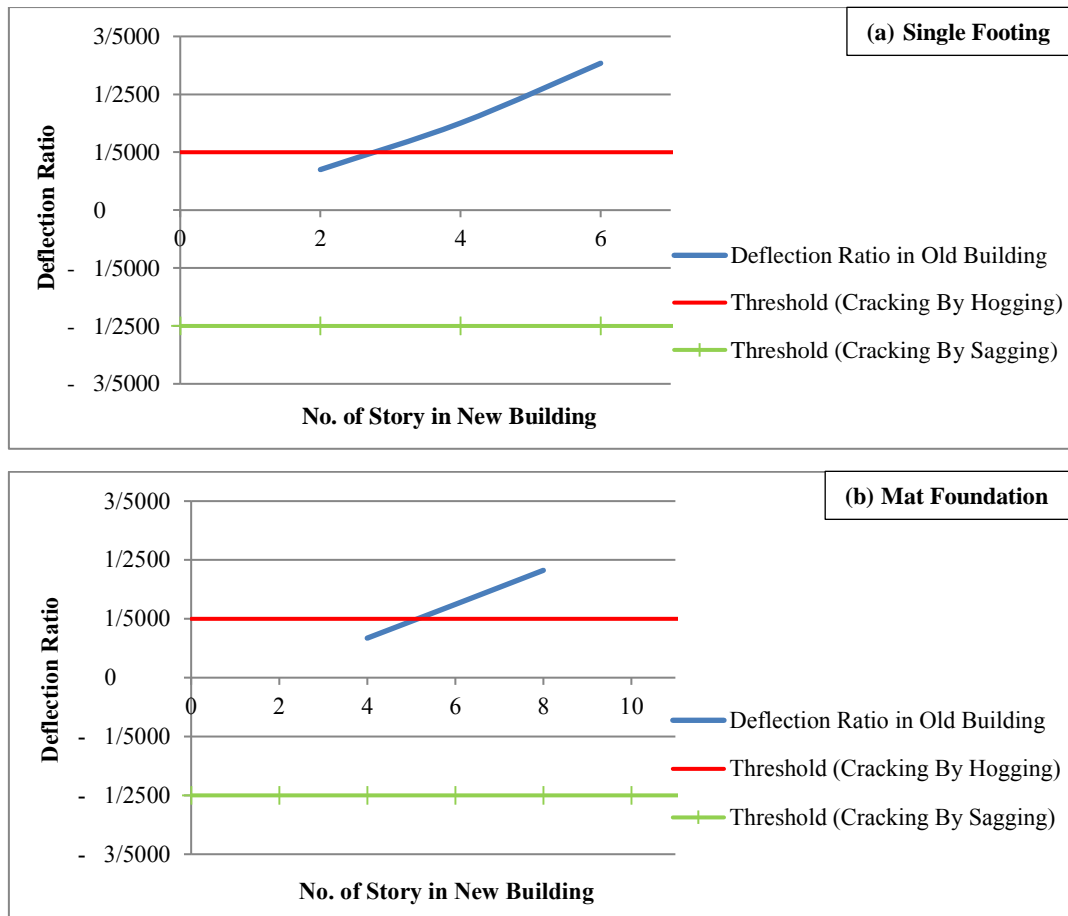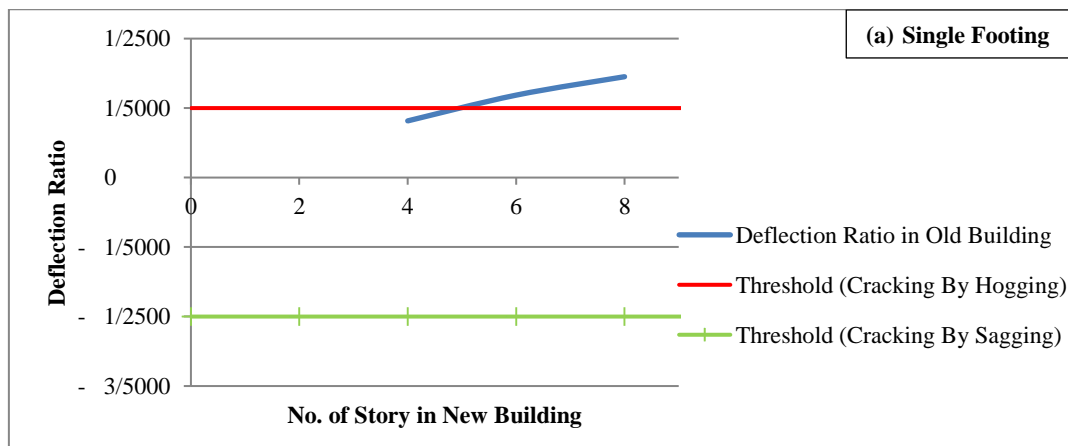

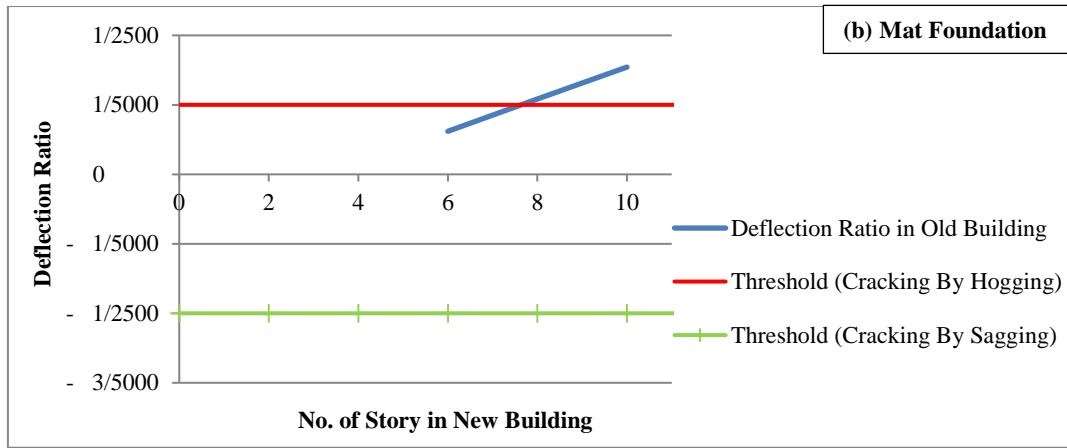**Figure 9. Story limits in the new building with Df = 2 for different type of the new foundation**

Figure 10. Story limits in the new building with Df = 3 for different type of the new foundation
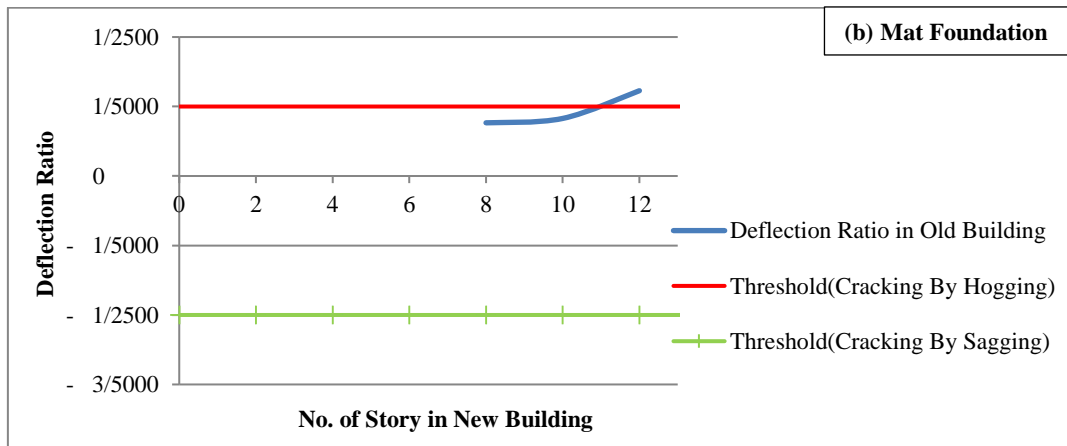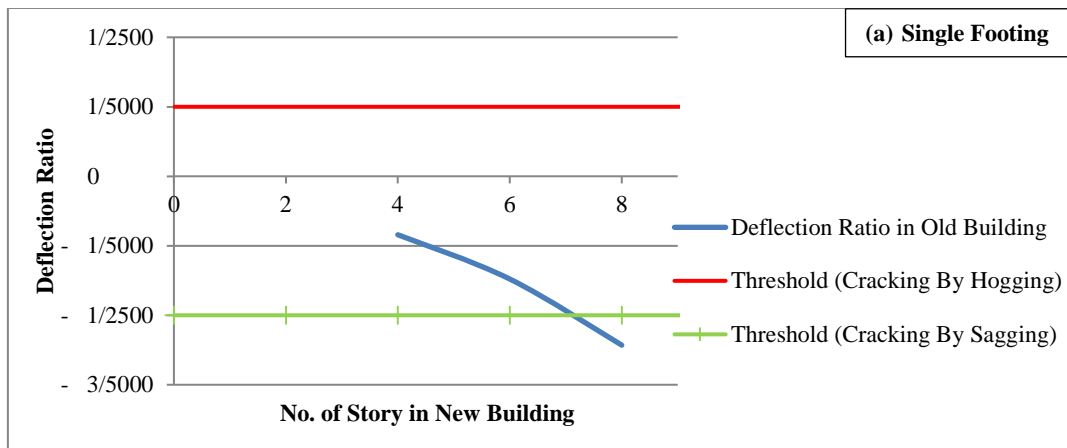

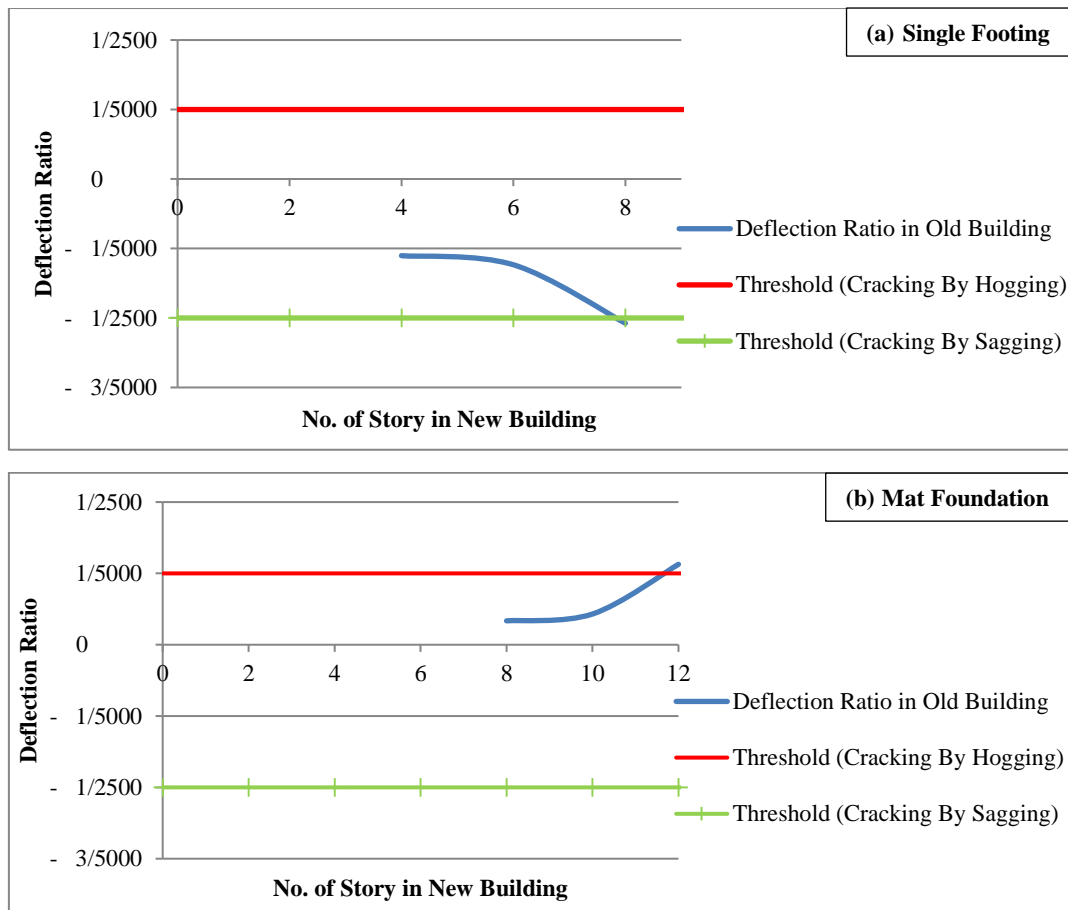**Figure 11. Story limits in the new building with Df = 4 for different type of the new foundation**

Figure 12. Story limits in the new building with Df = 5 for different type of the new foundation

Following the increment in embedment depth of new foundation, both for single and mat foundation type, the limiting number of story will increase in comparison to shallower constructions. This might be because the transfer of the pressure bubbles induced by the new construction distributes through deeper zones with more stiffness and finally to make the adjacent building less sensitive. However the increase of the depth of embedment depth will have an adverse effect when the vertical trench is left unsupported and the old adjacent building to experience failure.

Sheet pile or any other retaining structure could be an option for such a case so as to increase the safety against new constructions.

Figure 13. shows the Compression of the story limits of new building with two types of foundations. Above results were summarized in this chart.
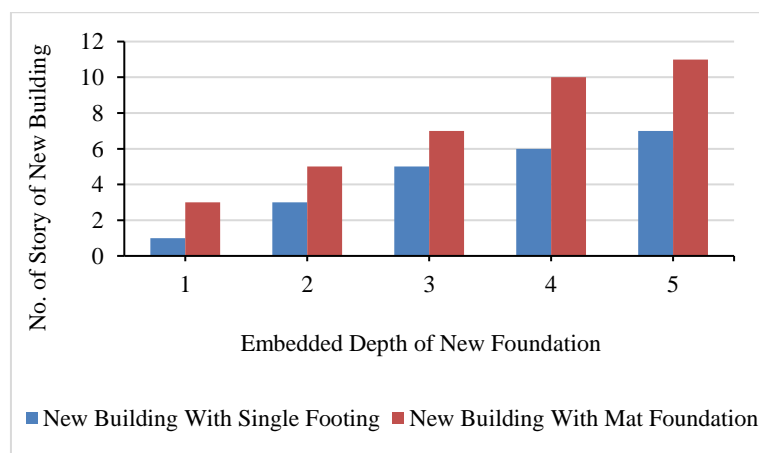

Figure 13. Story limits for the new building

8. Conclusion

This paper focused on the effect of new building construction on the deflection ratio of adjacent old building. For this aim three different measures were examined to be effective in urban building constructions. They are:

a) Story limits for the new buildings

b) Increasing the embedment depth of new foundation

c) Proper choose of shallow foundations for the new building

Flac3D is used for consolidation analysis of settlement calculation. After detailed numerical analyses, it was concluded to foundation type has a significant effect on this case. To be more specific, Mat foundation is an option when the adjacent old building is prune to excessive deflection ratio. Furthermore it was found the embedment depth will have paramount contribution by transferring the stress bulbs to the lower layers, so reducing the destructive effects.

If the trench keep supported it was found that the increment in embedment depth of new foundation, both for single and mat foundation type, the limiting number of story will increase in comparison to shallower constructions.

The study was shown with increasing of embedment depth of new foundation equal to one meter; story limits for the new building increase at least one story. In other words, height of building is increase 3 meter with incensing one meter of embedment depth of new foundation.

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