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Case Study

Case Study of Detailed Settlement Analysis of an Old Residential Building within Lahore Fort, Pakistan

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Abstract: This study deals with settlement analysis of a single story old residential building constructed inside the Lahore fort, Pakistan. It was constructed on non-engineering fill and it exhibited major differential settlement. The building started to exhibit cracking and was rendered unserviceable in 2009. The building has to be demolished for the new proposed structure. Crack mapping was performed to get an idea about the prevailing structural condition of the building. Precise leveling was carried out to determine the exact amount of differential settlement in various parts of the building and its surrounding area. Soil investigation was carried out to determine the depth of the non-engineering fill and any other factors that contributed to the excessive settlement of the building. The engineering properties of the associated soil samples were determined. Finite element analysis was carried out using computer aided software to suggest different foundation solutions for the site. A cost analysis was also carried out for the decided remedy.

Keywords: Settlement, Soil investigation, Non-engineering fill, Foundation, Shear cracks, Lahore Fort-Pakistan

1. INTRODUCTION

The work presented in this research paper originates from an investigation of a building undergoing excessive settlement and being rendered unserviceable. This building is situated inside a historical fort, located in the most elevated region in the city of Lahore, Pakistan. The reason for its elevation is due to the succeeding empires which were building their strongholds right above the ruins of their predecessors without clearing the area. It has resulted in construction of buildings over a non-engineering fill. The investigated building exhibits numerous shear cracks and visible deformations. Similarly, a considerable number of buildings in the region have undergone significant differential settlement, and some of these even had to be demolished.

An early assessment made during the initial visual inspection at the site has concluded that the underlying soil and drainage issues were the primary causes of settlement in the building. This assessment was further supported by the fact that the massive structure surrounding the building, the Lahore Fort, had not undergone any similar settlement or deformations due to having deep foundations that are beyond the depth of the non-engineering fill. Researchers have proposed methods for assessment of vertical deformation of the structures. The settlement can be estimated using probabilistic approach [1], laboratory experiments [2] or by using numerical approaches. The settlement data obtained from the leveling equipments can be used to plot 2D or 3D displacement maps [3]. Geodetic leveling is considered as one of the techniques for investigationg the vertical deformation of the structures. This technique was used for monitoting of vertical deformation at Arenoso dam [4]. The subsidence of Cathedral and the Ghirlandina Tower at UNESCO site of Modena was also monitored with conventional leveling techniques [5]. The procedure used in this study was based on the actual measurement of settlement using survey equipments.

The scope of this study is to determine the extent of settlement throughout the building by leveling and ascertain the causes of said settlement by drilling three boreholes at strategic locations.

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The field and laboratory tests were performed to propose the most viable solution of the site for future construction.

2. MATERIALS AND METHODS

2.1 Project Description

The residential building is a single story masonry structure of dimensions 64 x 11m, with an additional 3m of verandas going along the length of the building on both sides. The building has been constructed using standard 229 x 114 x 75mm bricks. The layout of the building, as well as the location of each borehole drilled for the investigation, is given in Fig. 1.

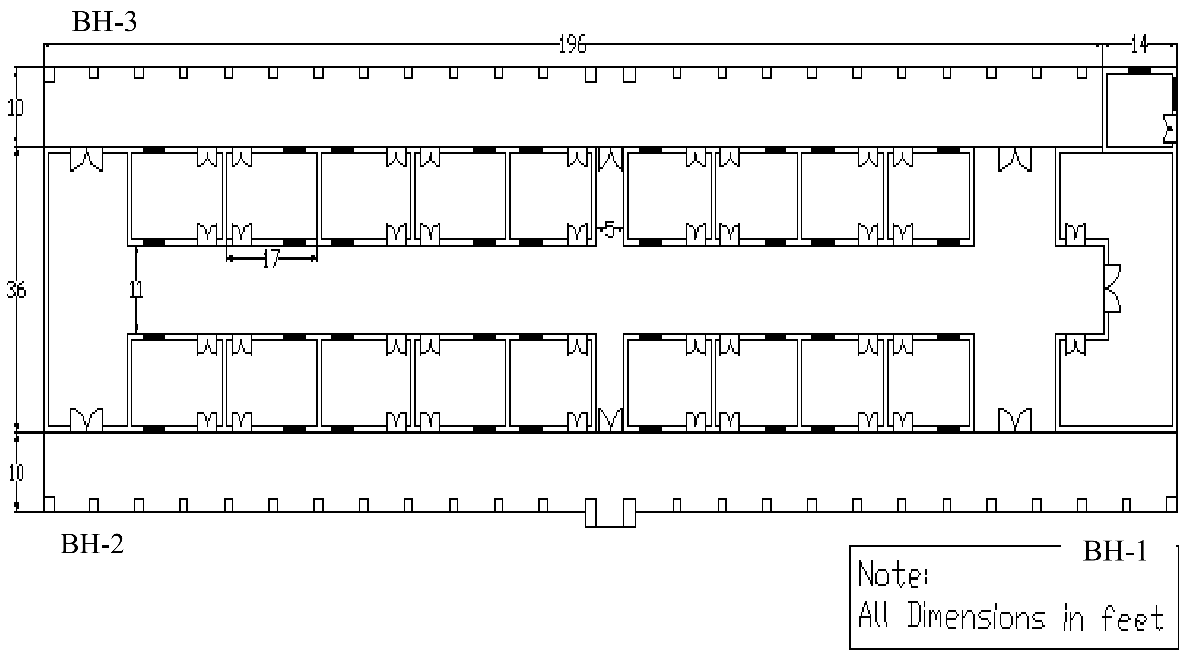

Fig. 1. Building layout

Very little information about the building in question could be found and it was discovered that 1.2m wide and 1.2m deep stepped brick foundation with the concrete slab at the base of the foundation was used. The building was constructed in 1994. Cracking started to be observed in 2001, however it was ignored until 2005, when a huge Earthquake struck Pakistan. After that, the North East half of the building was abandoned but the remaining portion of the building was in use. By 2009, the severe cracking and deformations in the building resulted in jamming of the doors, and the entire building was rendered unserviceable.

2.2 Crack Measurements

Initially, the numerous shear cracks in walls across the building were examined and their features were noted as shown in Fig. 2 and Fig. 3. The cracks on the inside face of the walls were of greater severity as compared to those on the exterior face. The width of the cracks on the exterior side was observed as less than 25mm, whereas majority of the interior cracks easily fall within the range of 50-75mm width.

Fig. 2. View of Exterior cracks

Fig. 3. View of Interior cracks

Fig. 4. View of Brick column

Additionally, the cracks angles were in the ranges between 45-60°. The residents of the building had erected several brick columns throughout the structure in order to prevent it from collapse or further damage. None of these columns served any structural purpose as they were not rigidly connected to the building and no loads or moments were being transferred to them from the building. Such actions of the residents only resulted in additional loads acting on the foundation. One of the columns mentioned above can be seen in Fig. 4.

2.3 Settlement Measurements

Leveling was performed on the site throughout a grid comprising of nearly two hundred points, as shown in Fig. 5. The precise leveling staff offers a least count of 0.1mm in comparison to the 5mm least count of an ordinary leveling staff. Therefore, it was intended to perform precise leveling throughout the grid in order to obtain more accurate results. Unfortunately, the ceiling height of the roofed porches, also known as verandas, on both sides of the building was 2.5m, which was not sufficient enough for the 3m precise leveling staff to be vertically fit. Due to this limitation in the equipment, precise leveling was only performed on the exterior perimeter of the building, while ordinary leveling was done in the verandas.

The rise and fall method was employed throughout the entire grid. In this method, the difference in elevation is determined by comparing each forward staff reading with each preceding staff reading. A rise is said to have occurred if the forward reading is lesser in value than the preceding reading, and a fall occurs if the forward reading is greater in value than the preceding reading. These rises and falls are then added to a Reduced Level (RL). The results obtained from the leveling of the building site were then entered into MATLAB to create a 3-D model of the settlement the building, that can be seen in Fig. 6. It can be seen that the building has undergone massive differential settlement.

The results of the leveling confirmed the initial estimation of the building's settlement lying within the range of 0.3m. However, one portion in the corner of the building had undergone excessive settlement to about 0.6m. The reason for such an anomaly was discovered to be a running cracked sewer line beneath that portion. The seeping water has washed away soil particles, resulted in collapse of the soil beneath the structure. The settlement problem resulting from groundwater extraction in city of Bologna was also reported [6]

2.4 Soil Investigation

Standard Penetration Test was performed into the drilled boreholes according to ASTM specifications [7]. Standard Penetration Test is the most practiced soil investigation method in Pakistan because it is the most economical method. Furthermore, the number of blows (N) against standard penetration can be used in empirical relations [8] to estimate soil properties such as expected settlement and bearing capacity.

Three boreholdes were drilled at selective areas. The first hole was drilled in area having noticeable

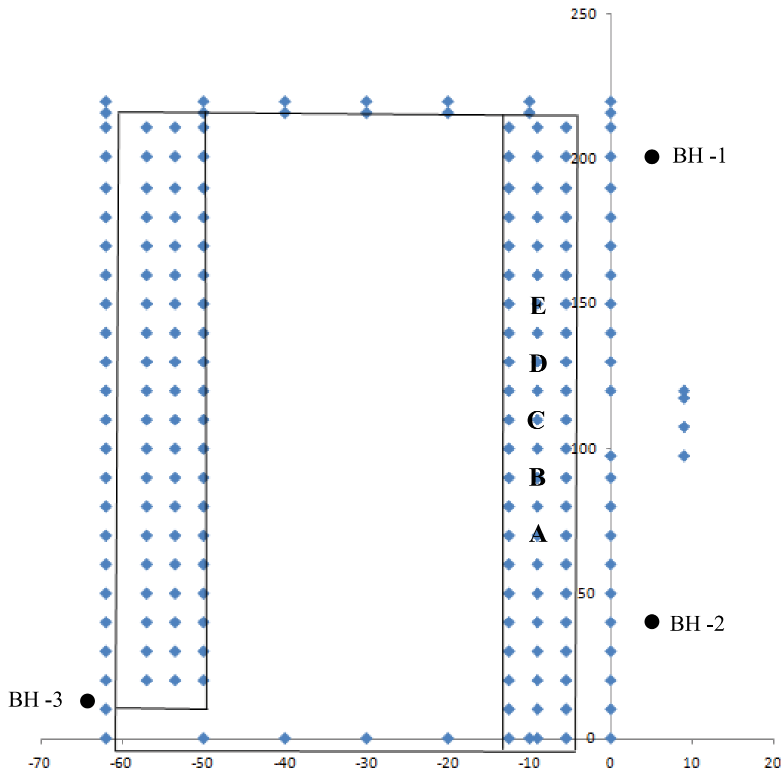

Fig. 5. Surveying grid (ft) showing location of Bore Holes (BH)

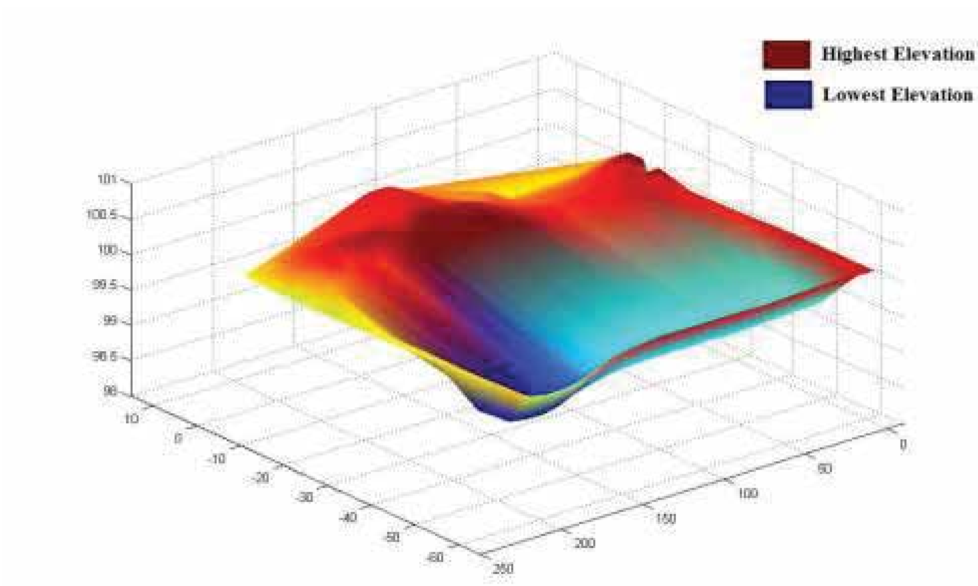

Fig. 6. 3-D Settlement model (ft)

average settlement, and the second where the soil seemed to have heaved outwards. The third borehole was drilled in area where execessive settlement had occurred. Each borehole was drilled up to a depth of 9m, and the number of blows (N) was recorded and soil samples were also collected. The N values obtained by the Standard Penetration Test had to be discarded as false values were obtained due to the interference of the non-engineering fill. The presence of multiple layers of brick ballast in the soil strata resulted in an outrageous number of blows. Images of the samples obtained from bore holes can be seen in Fig. 7. The borehole log of BH-3 is shown in Fig. 8.

(a)

(b)

Fig. 7. Soil Sample obtained from BH-3 at (a) 1.8m and (b) 7.6m depth

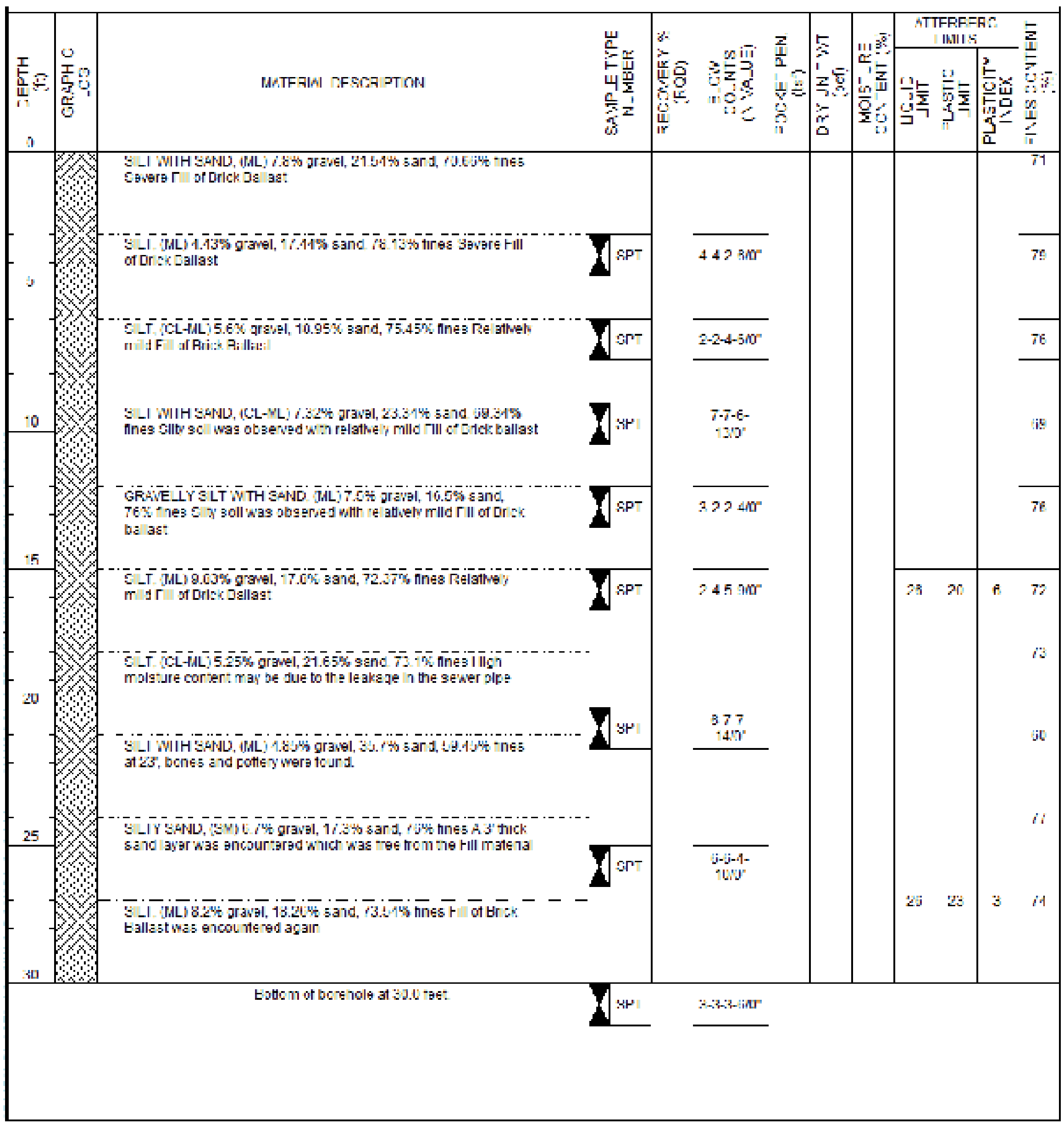

Fig. 8. Borehole log, BH-3

2.5 Soil Testing

The soil samples obtained from the boreholes were taken to the laboratory for testing. From each borehole, samples were used from the depths of 4.5m and 9.0m. The soil samples taken to the laboratory were pulverized, dried and then placed in separate containers for the different types of testing, such as particle size analysis, Atterburg limits [10], shear strength parameters First of all, each of the soil samples was put through sieve analysis to ascertain the particle size distribution. This was carried out according to ASTM procedure [9] as shown in Fig. 9. The Atterberg limits [10] of the soil (the Liquid Limits and Plastic Limits) of the soil were measured using ASTM- D4381 method and samples are given in Table 1. Increasing trend with depth was in general observed in laboaratory estimated values for liquid limit, plastic limit and plasticity index. The collected soil samples were classified in accordance with the [11] specifications and are shown in Table 2. Th soil samples are mostly classified as low plastic clay and silty sand.

Direct Shear test was performed on the soil samples in both saturated and dry conditions in order to determine their shear strength parameters (soil cohesion 'C' and their angle of internal friction 'f'). This test was also performed according to standard [12] specifications and the results are given in Table 3. The soil samples exhibits little to no cohesion with average angle of internal friction as 31 degrees.

Table 1. Atterberg limits (ASTM-D4381 Method)

Borehole	Depth m	Liquid Limit %	Plastic Limit %	Plasticity Index %
1	4.5	24.99	9.75	15.24
	9	33.27	10.1	23.17
2	4.5	29.78	13	16.78
	9	31.77	12.5	19.27
3	4.5	26.29	20	6.29
	9	25.56	22.98	2.58

Table 2. USCS Soil Classification (ASTM-D2487 Method)

Borehole	Depth m	USCS Classification
1	4.5	CL
	9	CL
2	4.5	CL
	9	CL
3	4.5	CL-ML
	9	ML

3. RESULTS

The finite element analysis was carried out on GeoStudio. The non-engineering fill was a heterogeneous material and the soil properties were not evenly distributed throughout it. Therefore, the average of the determined soil parameters were used. The empirical relations based on modulus elasticity were used for determination of unknown parameters. Linear Elastic model is used to model the soil behavior. The parameters used for analysis of original soil consist of C = 0, $\phi = 30°$, $\gamma = 14$ kN/m^3 and Elastic Modulus = 5MPa The simulations were run on the software to recreate the settlement in the range of what the building had undergone. For a building load of 25kPa, a settlement of 180mm was produced when an elastic modulus of 5MPa was used. The details of the settlement analysis can be seen in Fig. 10.

It was concluded that the existing soil conditions beneath the surface were insufficient for any form of

Table 3. Soil shear strength analysis (ASTM-D3080 Method)

Borehole	Depth m	Soil Condition	C (kPa)	ϕ (degrees)
1	6	Dry	5.84	30.17
	6	Saturated	0	33.1
	9	Dry	0	42
	9	Saturated	0	32.95
2	4.5	Dry	0	32.8
	4.5	Saturated	3.13	20.26
	9	Dry	0	34.52
	9	Saturated	3.97	12.54
3	4.5	Dry	0	32.28
	4.5	Saturated	0	31.69
	9	Dry	6.90	31.23
	9	Saturated	0	30.8

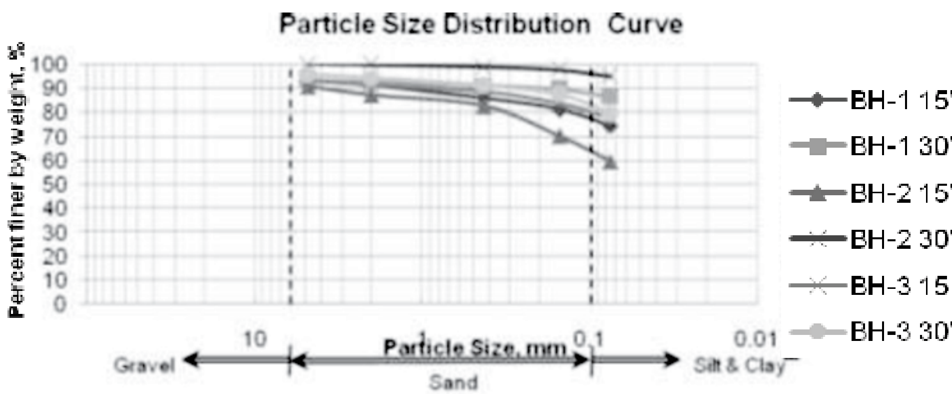

Fig. 9. Sieve analysis of soil samples recovered from boreholes (ASTM-D422-63 method)

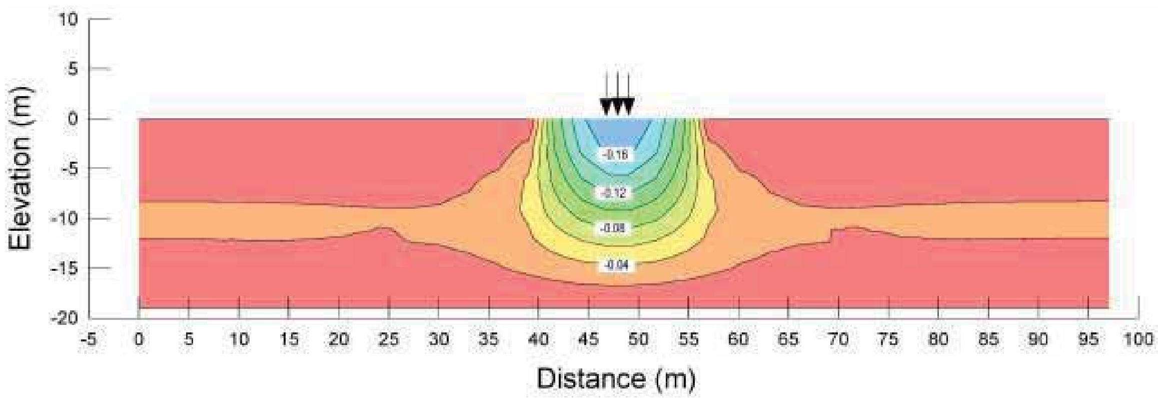

Fig. 10. Settlement analysis for existing soil beneath building

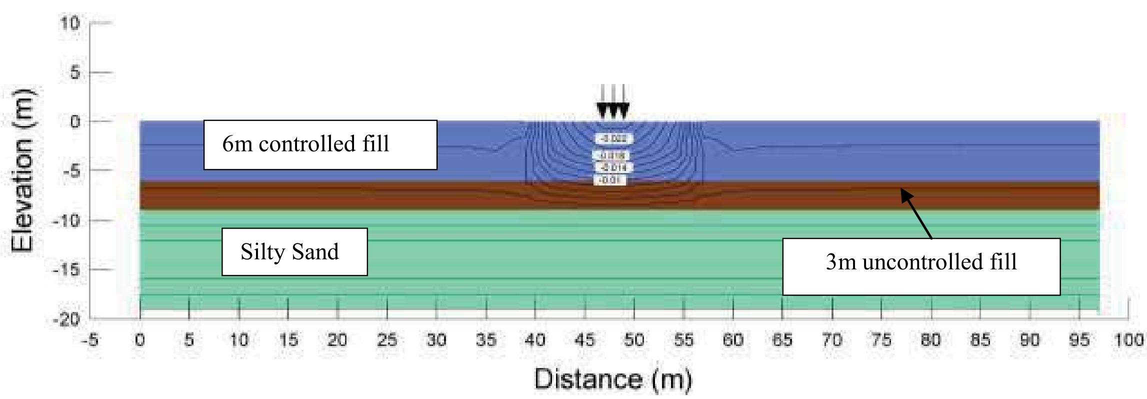

Fig. 11. Settlement analysis with recommended soil replacement of 6 m

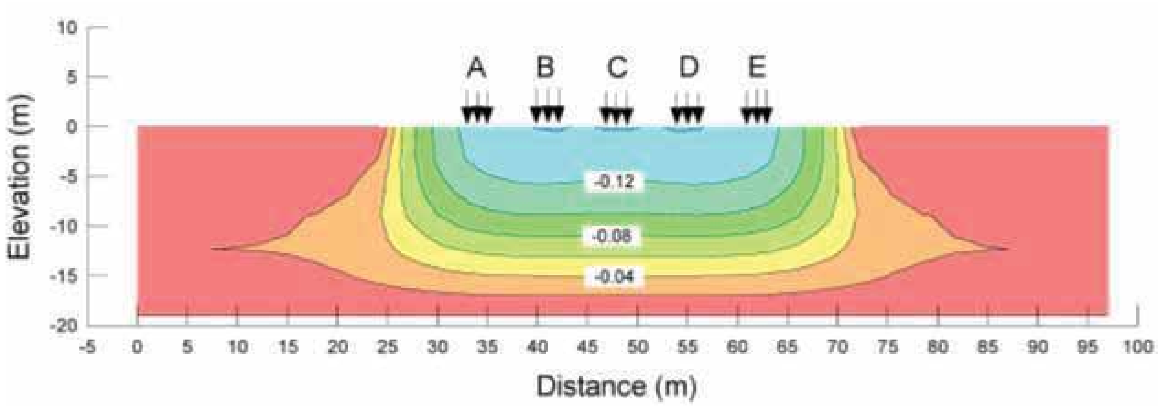

Fig. 12. Settlement analysis of five (5) footings with recommended soil replacement of 6 m

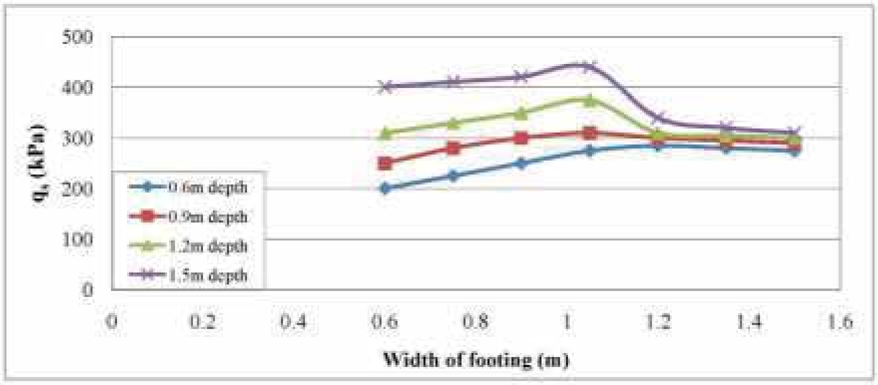

Fig. 13. Bearing capacity curves for soil

Table 5. Settlement comparison (Actual measured and by GeoStudio)

Location*	Settlement (mm)	
	Actual measured	**GeoStudio**
A	150	132
B	200	129
C	240	125
D	180	130
E	200	131

future construction. The (MRS) market rate systems rates [13] were used to evaluate the economically viable solution (and 1USD = 100PKR). The most economical solution (Table 4) would be to replace the soil beneath its zone of influence having more suitable properties. It would be suitable to use A-3 [14] soil with the properties of C = 0, $\phi = 33°$, $\gamma = 16$ kN/m^3, Elastic Modulus = 8MPa, Permeability = 10^{-5}m/s. The replaced soil should be compacted to 95% according to [15] specifications. The depth of replacement was decided by using GeoStudio, by replacing depths in trial and error until the settlement produced was within an acceptable range of 25mm. In the end, a settlement of 25mm was achieved with soil replacement of 6m as shown in Fig. 11. Buidling has undergone differential settlement. The settlement analysis considering the affect of 5 footings is shown in Fig. 12 and results are compared with actual measured settlement in Table 5. The difference in result is due to hydrogeneity of the problem. Furthermore, detailed manual calculations were also done for development of bearing capacity curves with regards to both shear and settlement [17]. The influence zone of each footing was taken to be four times its width. The bearing capacity curves are given in Fig. 13.

4. CONCLUSION

The historic site are very sensitive for new building construction. The situation becomes critical when excavation has to done adjacent to building of histroical nature. The 6m replacement can be achieved by first constructing soldier piles/ diaphragm wall with tie back anchors along the perimeter of the building to a sufficient depth. Instrumentation and other measures must be used to measure the reponse of the adjacent historic building to vibration, settlement, etc. during construction [16]. It is recommended to use a strip foundation for better and more uniform distribution of the building loads.

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