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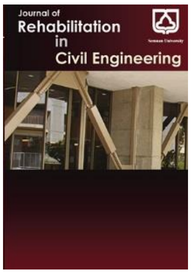


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# An Investigation into the Performance of Excavation with Inclined Struts Connected to Adjacent Buildings

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## ABSTRACT

One practical excavation support system is the inclined struts connected to adjacent buildings. This method is very common in small excavations, because of simplicity and minimum cost, when soil is cohesive and depth of excavation is less than stability depth (Hcr) but adjacent structures is at risk of damage due to weakness, old age or lack of proper skeleton frame. Although this method has been used in many small excavations, it is not entirely investigated. This study describes the performance of struts based on field observations and the results of numerical analysis. A small strain constitutive model (Duncan-Chang) was used for analysis. The efficiency of struts was evaluated by comparing the movements of the real case of excavation with struts and the same case but without struts. The results indicate that movements are decreased substantially using struts. A mechanism of struts during excavation is proposed and the effect of installation of the inclined strut on deformation patterns is discussed. The study introduces simple instrumentation designed in the course of the study that can be used in common engineering practice for small to medium-sized excavations.

## 1. Introduction

With the development of urban construction, excavations adjacent buildings have increased. With large changes in stress distribution due to excavation, displacements may occur in the buildings and the soil. Lateral displacement of the excavation face and vertical displacement of the ground surface occur simultaneously. Boscardin and Cording, Burland and Finno et al found that the settlements and horizontal strain determine the level of damage in the structure [1-3]. In urban excavations, the control of displacements in soil and buildings has always been an important issue due to the risk of damages. An optimum design and safe operation of the supporting system

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require a full understanding of the load distribution and displacement patterns.

A simple method in protecting the excavation neighboring buildings is the use of inclined struts [4]. In the presented method struts are directly connected to adjacent buildings. Therefore it is supposed that struts can control the movements of the buildings and also may decrease the excavation face displacements. This method is very common in small to medium size excavations in Iran. Fig.1(a) schematically illustrates the method. This method is the subject of the presented paper and should not be mistaken by the common use of struts which are connected to soil retaining walls, Fig.1(b). In the mentioned method, the struts are directly connected to the building and soil is unprotected. This method is very common in small excavations, because of simplicity and minimum cost, when soil is cohesive and depth of excavation is less than stability depth ($H_{cr}$) but adjacent structures is at risk of damage due to weakness, old age or lack of proper skeleton frame. This method can be considered as a traditional support system in Iran and the main advantage of this method with respect to conventional embedded retaining walls propped by struts is the time and cost in small excavation and the ability of reuse the struts in other excavations.

The later method, as depicted in Fig.1(b), is mentioned in text books and also many researchers [5-13]. In this method, struts are required to avoid movement of the retaining wall with preventing rotation of the wall at its toe [14]. But in the method, which is the subject of this paper, struts are used to avoid deformation and damage of the structures [15].

Based on previous studies which are done on two mentioned types of support systems, Table 1 summarizes the comparative application of the methods [16,17]. But each of these methods may be best choice in condition of the project and it cannot be expressed which of methods are generally preferable.

Although the inclined struts connected to buildings have used in many small excavations in urban areas, are not fully investigated and the behavior in restraining movements is still not completely understood. It is necessary to investigate to determine its advantages and disadvantages as well as the limitations and the appropriate scope of its application.

Fig. 2 shows the stages of excavation of this method. In stage (i), the soil is excavated leaving a perimeter margin. In stage (ii), the perimeter margin is excavated in short spans to allow installation of the inclined struts and then struts are installed. In stage (iii), the remaining soil is removed.

Previously published studies provide a basic explanation of the performance of inclined struts. Fakher and Sadeghian found that optimal results for inclined strut installation could be obtained by connecting the strut to the foundation of the neighboring building [15]. They also found that the most effective inclination angle for the struts could be calculated as $L/H = 0.45$ in which $L$ is the distance of the struts from the bottom of the excavation face and $H$ is the depth of the excavation. This value corresponds to an inclination angle of 65° from the horizontal. Sabzi and Fakher suggested an appropriate area of application for this method based on soil type, excavation depth and adjacent building conditions [17].

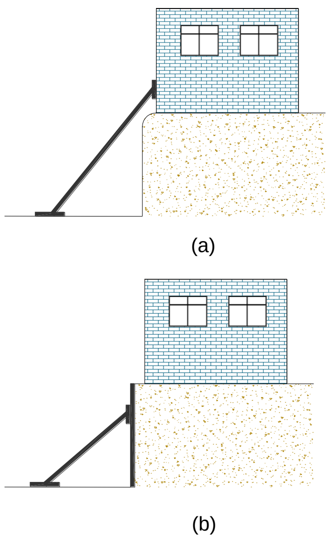



**Fig. 1.** Schematic comparison of two methods of using struts, (a) struts connected to the building as investigated in the presented research, (b) struts connected to the retaining wall.

**Table 1.** Typical applications of two retaining systems shown in Fig. 1.

| | Struts connected to building Fig.1(a) | Struts connected to retaining wall Fig.1(b) |
|---|---|---|
| Excavation depth | Small to medium excavations | Small to deep excavations |
| Soil type | Cohesive soils (c>25 kPa) | Possible in all types of soils |
| Time for excavation | Fast | Slow |
| Primary function of struts | Control of the building deflections and damage level | Control of the wall movements |

In previous studies a performance-based design approach was presented that is used to design struts based on the deformation limits [18]. But currently, there are only very limited field data regarding deflections caused by excavation, using struts connected to building, available in the literature.

The effects of excavation on the neighboring structures can be examined through the monitoring of the buildings, excavation and the struts. Using the monitoring, it would be possible to comment on the performance of the struts. The presented research study is aimed to experimentally and analytically examine the mechanism of struts. In addition a simple monitoring tool is designed to be used for small to medium-sized excavations.

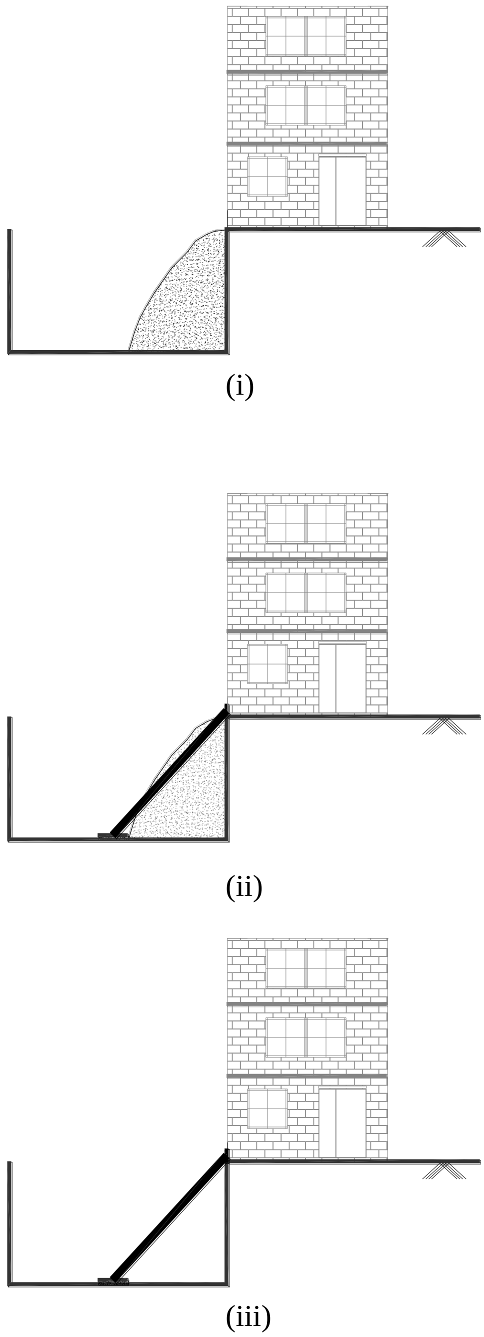
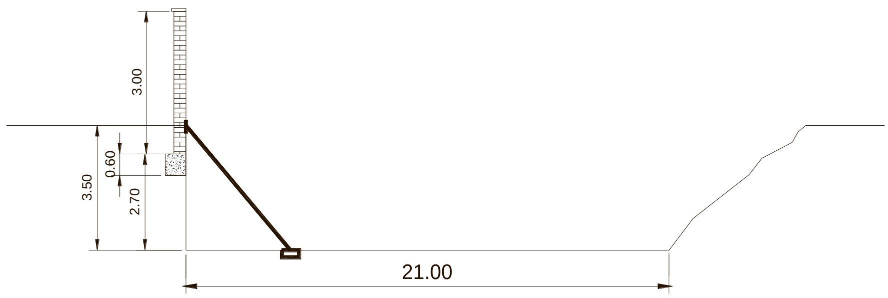


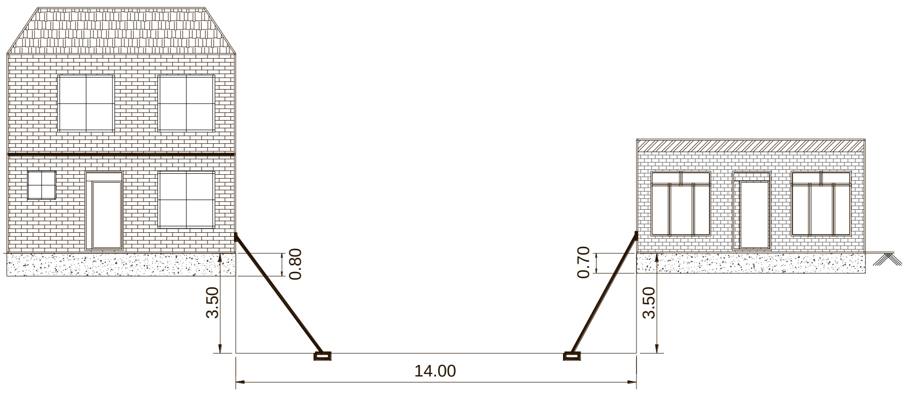

**Fig. 2.** Excavation stages for the strut installation

## 2. Project Description

In the presented paper, an excavation has been studied. The site area was 14 × 21 $m^2$ and a depth of 3.5 m below the surface. There was a one story old concrete building on the east side and a weak brick wall (3m height, 0.35m thickness) on the north side. In addition, a two-story concrete residential building was on the west side. To better understanding the problem layout, two vertical sections of site are provided in Fig.3. To ensure the safety, adjacent buildings were monitored and no structural damage, cracking and tilt were observed on the interior of the buildings during and after the excavation. It should be noted that east and north sides of excavation were at greater risk due to structure and brick wall condition.




(a)




(b)

**Fig. 3.** Vertical sections of excavation area (a) North-South section, (b) East-West section.

Site investigations indicated that the subsurface soil contained high-density coarse grained soil described as SP and GP with a maximum diameter of 50 mm. The fine content (clay and silt) of the soil was about 40% and was very stiff so it creates a strong cementation and high cohesion. No evaluation of the relative density of the granular soils was undertaken because of the high percentage of clay and silt. Standard penetration tests (SPT) were performed and was more than 50 in all depths. No groundwater table was detected in the excavation zone.

The supporting system was inclined struts connected to the adjacent buildings. The struts were box 140 × 140 × 7 mm. Strut's concrete foundations were 500 ×500 $mm^2$ with 400 mm thickness.

## 3. Planning and Execution of Monitoring System

The displacement and strut loads were measured using instrumentation placed around the site. The instruments used were optical surveying points placed on three sides of the excavation and strain gauges on the struts. Fig. 4 shows a real picture of site, a plan of the instrumented. The excavation stages and strut installation procedures are presented in Table 2 and followed the general procedures shown in Fig. 2.

Operators at small projects prefer the use of simple mechanical devices that can be operated by unskilled workers. Electronic devices are very sensitive and easily deviate from the calibration and require trained operators. In this study, aside from the use of strain gauges, new mechanical devices that do not require skilled operators were designed and implemented.

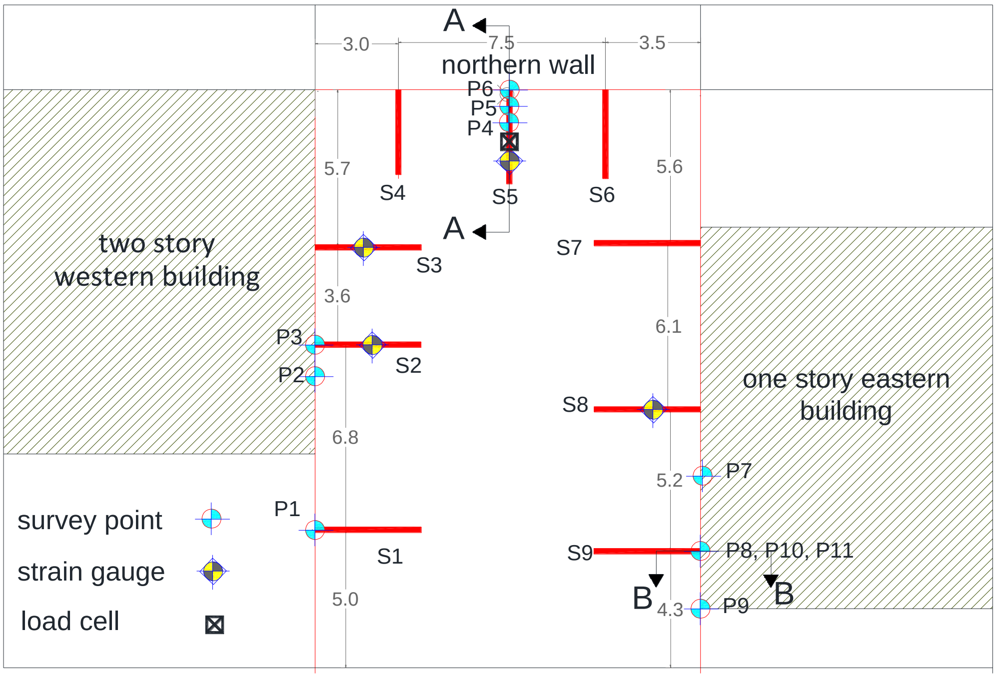
One goal of the present study was to develop a simple method for measuring the load of inclined struts for small projects. The instrument designed consists of a central coil placed inside two steel cylinder sheaths. To ensure the stability of the system, the two cylinders were connected by a steel rod welded to the lower cylinder threaded through the inside of the spring and the upper cylinder and fixed by a washer and nut. The central coil was loaded to 800 kg, compressed and the plates were connected by chains. The coil was steel with an outer diameter of 120 mm, 300 mm height and the rod diameter was 16 mm. Fig. 5 is a schematic of the fabricated tool.

The cell was loaded in laboratory and its stiffness curve was obtained. The load cell should be interposed in the strut to measure the axial load.

**Table 2.** Excavation stages of the project

| **Excavation stages** | **Excavation phase** |
|---|---|
| 1 | Excavate down to 3.5 m below the ground surface by sloping the sides of excavation |
| 2 | Installation of the inclined struts for 3 sides as shown in Fig.2. |
| 3 | Excavation of marginal soil in back of strut |

(a)




(b)

**Fig. 4.** (a) A picture of excavation looking to north side, (b) Plan view of site and instrumentation scheme.

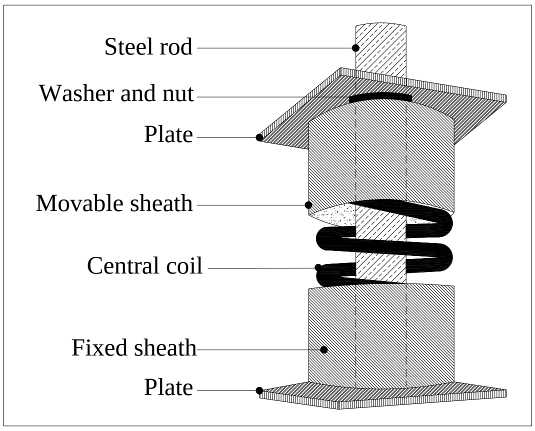



**Fig. 5.** Schematic figure of the mechanical load cell.

One strut (S5 as shown in Fig 4b) was selected and cut in the proper position and the load cell was welded to both parts of the strut before installation. Fig. 4 shows the location of the S5 strut. The initial length of the load cell was measured using a caliper to determine the changes in load. Later, the compression at four points around the cylinder was measured and calibrated to the load using the stiffness curve. The accuracy of the results from the mechanical load cells was determined using the strain gauges.

## 4. Numerical Analysis

To validate the measurements, a 2D finite element simulation was conducted. The objective of the numerical modeling was the comparison of results observed in the field measurements and the finite element analysis results.

### 4.1. Numerical Modeling

The excavation project, as described in Section 2, was analyzed. The analyses were done for the model exactly the same as the North section of the excavation (A-A Section in Fig. 4b) and East section (B-B Section in Fig. 4b). Two sets of analyses were performed in order to investigate the effect of the struts, (1) excavation with installation of struts and (2) excavation without struts. The analysis was conducted according to the same construction procedure, excavation geometry and support system as the case study.

Numerical analyses were conducted using ABAQUS, a finite element software [19].

Fig.6 shows the prepared meshes. A large zone was selected to avoid any measurable effects from the boundaries. It was assumed that vertical boundary to be free in vertical direction and restricted in horizontal direction; and the bottom horizontal boundary was restricted in both horizontal and vertical directions. To minimize boundary effects, the vertical boundary and the bottom horizontal boundary at the far ends were set almost as 5 times of excavation's width and depth, respectively, from the center of excavation.

The element size is chosen based on the desire to increase the accuracy of the results and reducing the computational effort. A large number of iterations were carried out to achieve convergence criteria and accuracy of deflections. In finite element simulation of excavations it has been demonstrated that the refinement of the mesh had no significant effect on the final displacements [20]. Four nodes element with four integration points are used in modeling the soil.

The nonlinear behavior of soils is simulated by the hyperbolic model [21]. The Duncan-Chang material model is a nonlinear elastic criterion to model the behavior of soil from the beginning of loading to it approaches failure. Duncan-Chang model defines the initial modulus as $E_i$ that control small strain behavior of soil (elastic deformations) and the soil failure behavior (plastic deformation) is governed by the Mohr-Coulomb criterion. The hyperbolic elastic model, which is conceptually understood, is commonly used in analysis of soil problems due to its convenience in implementation into finite element program and in obtaining the model parameters [22]. Hyperbolic model is implemented by user defined model within the subroutine UMAT in the ABAQUS program and then used in the analyses. The hyperbolic model has been extensively used in analyzing excavation problems [9, 12, 22-26]. possibly due to this type of soil model is relatively simple and easy for determining soil parameters [27].

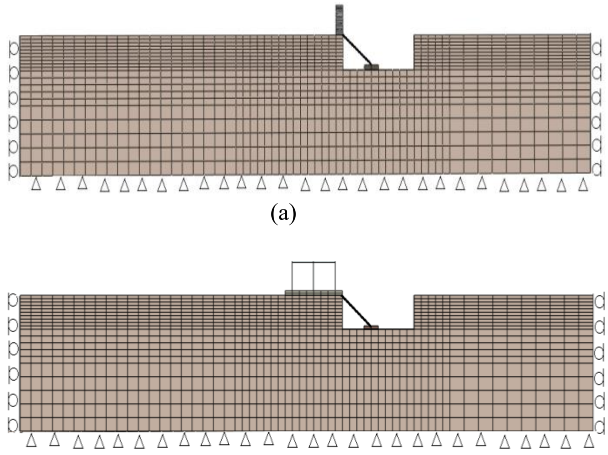



**Fig. 6.** Finite element models (a) North face with an adjacent brick wall (A-A section in Fig.4b), (b) East face with an adjacent concrete frame building (B-B section in Fig.4b).

For the hyperbolic model, seven parameters are required to fully describe the stress–strain behavior of the soil. These are cohesion ($c$), friction angle ($\phi$), stiffness modulus number for primary loading ($k$), stiffness modulus exponent ($m$), stiffness modulus number for unloading– reloading ($k_{ur}$), failure ratio ($R_f$), and Poisson's ratio ($\nu$).

Geotechnical characteristics of the soil are presented in Table 3. The strength parameters c and $\phi$ were obtained directly from triaxial laboratory tests. The value of Young's modulus of the soil at the depth of 2 m was directly obtained from the plate load test results as shown in Fig. 7.

The failure ratio, $R_f$, is normally in the range 0.5 and 1.0. In this study, $R_f$ is assumed to be 0.85. The stiffness modulus exponent, m, can reasonably assume to be 0.6 [28]. Poisson's ratio is assumed to be 0.35 at the prefailure condition and 0.49 at or near the failure condition. The lateral earth pressure at rest, $K_0$, is obtained from Jaky's equation.

North brick wall was modeled as a continuous wall by plane strain elements and linear elastic material model. Since the wall was recognized, from field observations, as very weak, the value of stiffness in analysis was $E_{wall} = 3.4\times10^4$ kPa [29]. Building on east side of excavation was modeled as a concrete frame using two dimensional beam elements and linear elastic model with no failure criterion. Young's modulus of concrete was set $E_{concrete} = 2.0\times10^4$ MPa. The struts were two dimensional steel beam elements and linear elastic with no failure criterion. Young's modulus of steel struts was set $E_{steel} = 2.0\times10^5$ MPa.

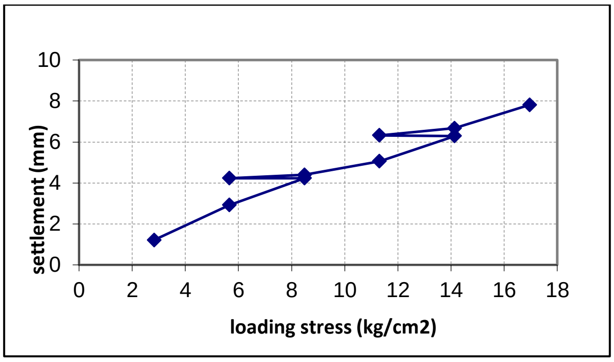



**Fig. 7.** Plate load test result

**Table 3.** The input parameters used in numerical modeling

| **Parameter** | *k* | $k_{ur}$ | *m* | *c (kPa)* | $\phi$(°) | $R_f$ | $\nu$ | $K_0$ | $\gamma$ (Kg /m$^3$) | *H* (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Amount** | 4500 | 10000 | 0.6 | 30 | 35 | 0.85 | 0.35 | 0.43 | 1900 | 3.5 |

Note: $k$, $k_{ur}$, $c$, $\phi$, $m$, $R_f$, $\nu$ : the hyperbolic model parameters, $\gamma$= soil density, $K_0$= "at-rest" coefficient of lateral earth pressure, H= excavation height.

The foundation of building and the foundation of strut were modeled as concrete solid elements and linear elastic with no failure criterion. Dimensions of structural elements in building and struts were the same as the studied case. The interface between the structure and the soil elements was modeled by contact elements. Connections between strut and structure and its foundation modeled as pin.

## 5. Results and Discussion

In this section, the results of the measurements and finite element analyses are presented and discussed and followed by the proposed performance mechanism of struts.

### 5.1. Comparison of Observations and Numerical Results

The loads in S5 strut as measured by the mechanical load cell and electrical strain gauges are shown in Table 4. The load generally increased in the strut as the excavation progressed. Table 4 compares the load obtained from the finite element results to the measurements. It is clear from the measurements that the mechanical load cell was capable of representing the load change in the struts and can determine the load with acceptable accuracy.

The strut was pre-loaded to about 0.9 Tons soon after installation. Pre-loading was carried out because of the installation method. To ensure a tight support system, struts were connected to the building and were subjected to loading in the direction of the building using jacks at the opposite ends of the struts and welded to the base plate of the foundation. This procedure created a good connection between the strut and the structure. The pre-loading of the strut was back-calculated from the stiffness curve of the cell and was used in the finite element model. The load predicted for the strut using finite element analysis corresponded to the measurements. The results of the measurements generally showed that the strut was capable of bearing a portion of the weight of the building.

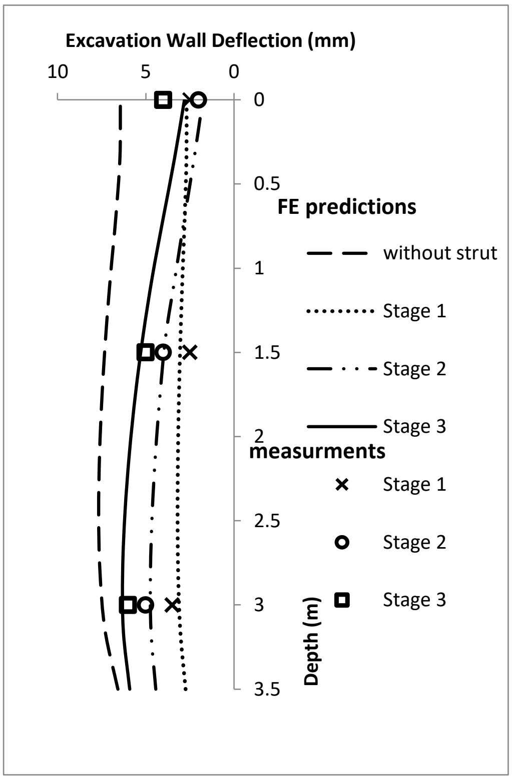
**Table. 4.** Strut load during excavation procedure in S5 strut.

| Excavation Stage | Strut Load (Ton) | | |
|---|---|---|---|
| | Mechanical Load cell | Strain Gauge | FE prediction |
| Stage 2 | 0.92 | 0.915 | 0.9 |
| Stage 3 | 1.02 | 1.015 | 1.05 |

Figs. 8 and 9 show the horizontal deflection of the excavation face and the ground surface settlement at the north and east sides of excavation with and without struts at different stages (As described in Table 2). The field measurements for the same positions are also shown. A comparison of the results at the north and east sides indicate that the deflections obtained from the numerical study closely matched the field measurements. The figures show that the horizontal deflection and vertical settlement of the soil without installation of struts could be much larger than the measured value.

Fig. 8 compares the results of numerical analysis with and without inclined struts and indicates that the strut effectively decreased the horizontal displacement of the excavation face. The horizontal deflections near the contact point of the struts were decreased 40% on the north face and 45% on the east face by installation of struts. The figure also shows that the excavation without struts could experience large horizontal deformation near the surface; it means maximum deformation could occur near the excavation surface. The use of struts connected to the building decreased horizontal deformation to a slight value near the excavation surface around the contact point and lowered the location of maximum horizontal deformation. Hence the deformation pattern of the excavation face was strongly affected by the use of inclined struts connected to the building.

Fig. 9 shows ground surface settlement. Analysis of the excavation with and without inclined struts shows that the inclined struts decreased ground surface settlement at the point of installation of the struts about 30% on the north side and 45% on the east side of the excavation. It can be seen from the shape of the ground surface settlement that the soil beneath the foundation subsides considerably near the excavation face when struts were not used. But ground surface settlement near the excavation face is slight with the use of struts. Hence excavation without struts produced spandrel-type settlement in which maximum surface settlement occurred near the excavation face. Excavations using strut decreased ground surface settlement near the excavation face and produced concave-type settlement in which maximum surface settlement occurs at a distance from the excavation face. Hsieh and Ou investigated similar types of settlement for earth retaining walls [30].

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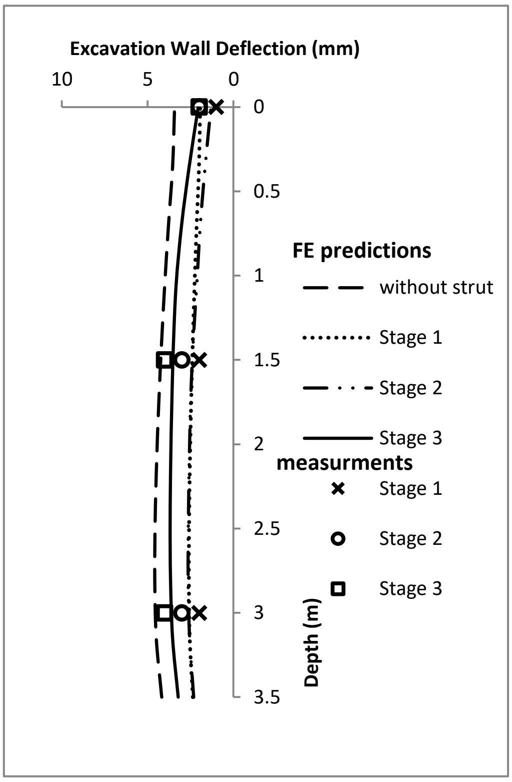
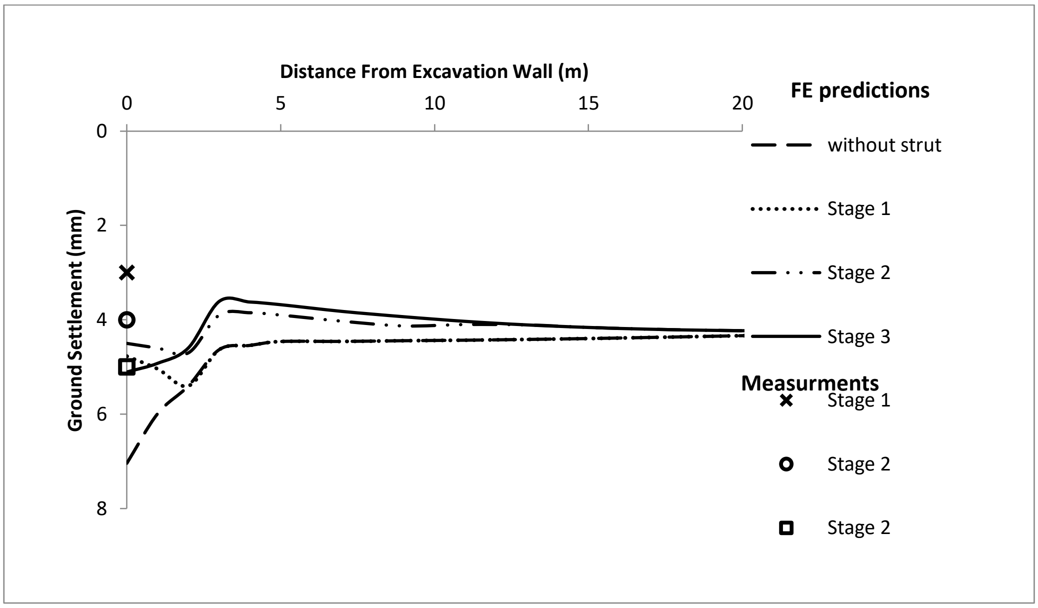



(b)

**Fig. 8.** Deformation of excavation face (a) north face, (b) east face.

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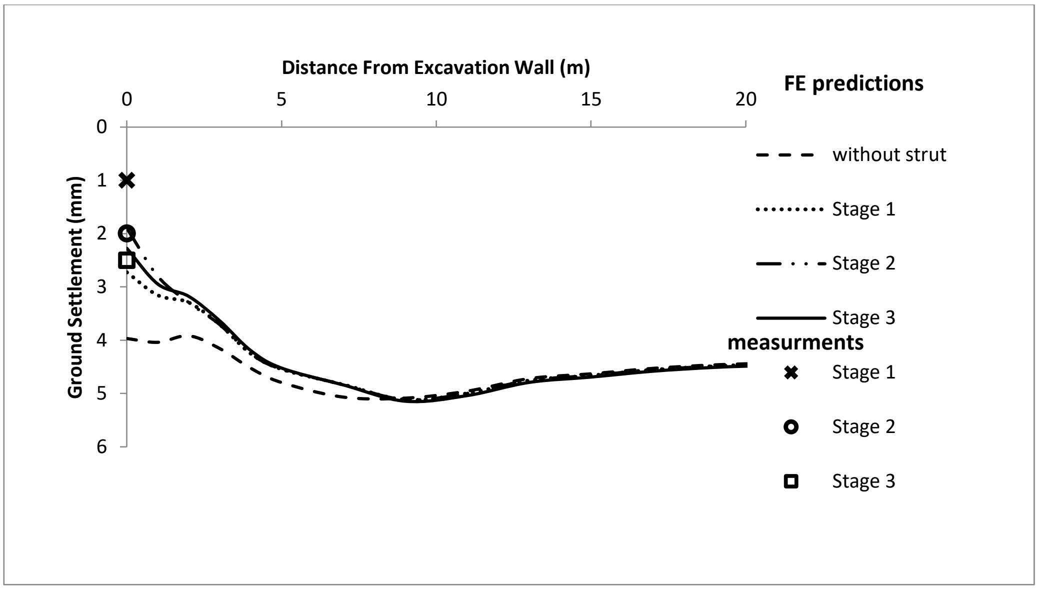


(b)

**Fig. 9.** Ground surface settlement (a) north side, (b) east side.

## 5.2. Performance Mechanism of the Struts

Fig. 10 shows field measurement of settlement of soil beneath the foundation at P7, P8 and P9 on the eastern face of the excavation. These points surround the S9 strut. As excavation progressed, vertical settlement increased. As seen, the amount of settlement in the final days of excavation at point P8 corresponding to the S9 strut is about 40% less than in surrounding areas. This indicates that the strut successfully decreased vertical settlement at the installation point. Measurement of the displacement shows that the struts effectively decreased vertical settlement of the building. Fig. 11 shows horizontal displacement of the soil beneath the foundation at P7, P8 and P9. As shown, as the excavation progressed, horizontal deflection toward the excavation increased. Comparison of displacement in the final days of excavation shows that horizontal displacement at the strut installation point is 30% less than in the surrounding area. In other words, the struts controlled horizontal displacement of the building.

Section 5.1 demonstrated that struts carried part of the building load and decreased the load exerted on the soil beneath the foundation. The results of numerical analysis show that the strut has an important role in decreasing horizontal displacement of the building and excavation face. By bearing part of the weight of the buildings, the struts decreased settlement, thus decreased damages imposed to the structure. According to the above mentioned remarks, the following mechanisms are proven for struts:

***Mechanism (a), Underpinning***: Part of the load of the adjacent building is passed to the bottom of the excavation through the strut and less pressure is exerted on the soil beneath the foundation. Therefore the amount of settlement beneath the foundation decreases. This mechanism suggests that inclined struts act as “underpinning” because underpinning is conducted mainly to reduce the settlement of structures and to transfer the loads to a lower hard stratum.

***Mechanism(b),Performance Improvement***: The inclined strut reduces the horizontal displacements of the buildings due to the lateral constraints it creates. Consequently it can reduce the horizontal deflections of excavation face. As found by Boscardin and Cording and Burland [1,2], a reduction in horizontal deflection could improve the performance of building which are adjacent to excavation.

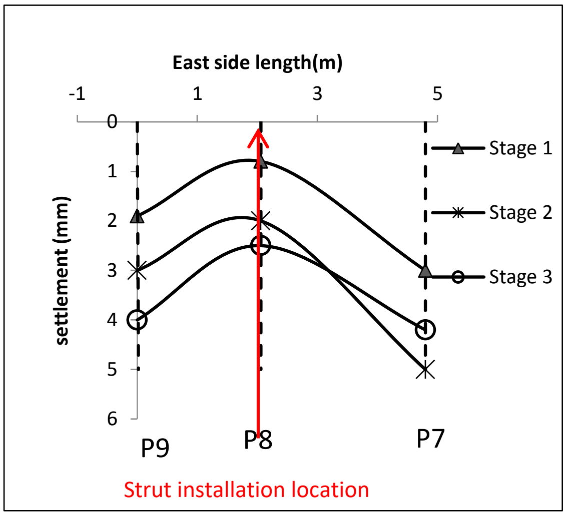


**Fig. 10.** Settlements of part of the eastern side during the excavation phases.

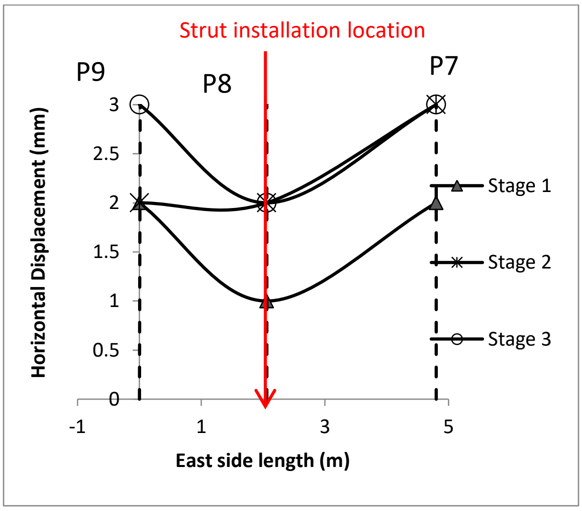


**Fig. 11.** Horizontal deflection of part of the eastern side during the excavation phases.

## 6. Conclusion

Inclined struts connected to buildings adjacent excavations have been used in many small excavations in urban areas. *But* it is not fully investigated and its behavior in restraining movements is still not entirely understood. In this paper the efficiency of the struts in decreasing excavation-induced deflections was evaluated by field monitoring and numerical analysis. The following conclusions were drawn from the present research:

1. Horizontal deflections of the excavation face and ground surface settlement decreased substantially using struts. Horizontal deflections and ground surface settlement at the strut installation point decreased about 40% to 45% and 30% to 40% respectively.

2. The proposed mechanism for struts based on the results of field measurements is in line with numerical studies. The results confirm that:

- The inclined struts bear some part of the load exerted on the foundation and decrease the settlements of the building and the soil. The inclined struts, thus, act as underpinning.

- The struts also decrease horizontal displacement of the buildings and the excavation face. A decrease in horizontal displacement can considerably decrease damage to structure.

3. The inclined struts connected to the buildings influences the deformation patterns:

- Using struts connected to building, the shape of the horizontal deflection at the excavation face changes from cantilever type (Which occurs in unsupported excavations) to lateral-bulging type.

- Using struts connected to building, the shape of the ground surface settlement changes from spandrel-type (Which occurs in unsupported excavations) to concave-type beneath the foundation.

A mechanical load cell was designed and fabricated and implemented. Moreover a set of practical instruments and a simple monitoring program that is appropriate for small-to medium-depth excavation projects were proposed and used in this study and suggest to use in similar projects.

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