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An investigation into Inclined Struts method as a type of shoring

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ABSTRACT: Underpinning and shoring are two conventional forms of temporary supports given to the buildings next to excavations. "Inclined Struts", as a type of retaining structure which can be used to support buildings next to excavations, can be categorized as underpinning and shoring. In this method, some inclined struts connect the bottom of the excavation to the footing of adjacent buildings. Despite the excessive use of the inclined struts in years, they have been poorly investigated. Herein, the most prevalent construction use of the "Inclined Struts" are simulated using 3 dimensional FDM and the excavation-induced displacements of buildings caused in each method are compared. The presented paper is in the continuation of a previous two dimensional study undertaken by the authors. The current study indicates that excavation-induced displacements of buildings considerably depend on the sequences of excavations. In case an excavation is done in three suggested stages, the least excavation-induced displacement will occur. Indeed, the excavation is firstly done up to the final desired depth but a premital soil margin is remained next to the wall of the excavation. Afterwards, struts are installed and finally the excavation is completed. This paper also discusses the number, position and sequences of installation of struts which results in the least excavation-induced displacements.

1 INTRODUCTION

Excavation-induced displacement caused by underground construction is of great importance in planning the excavations. Particularly, in urban areas it would be impossible to estimate how much of allowable displacement of structures has been done before starting the excavation construction. During excavation and support of open-cuts, changes in the state of stress in the ground mass around the excavation and loss of ground is inevitable. Due to the changes in stress and the ground losses, vertical and horizontal ground movements occurs in the surrounding of excavation, which consequently results in rotation, deformation, and possibly some levels of damages in buildings and facilities next to excavation.

Shoring and underpinning are two frequently-used methods in all over the world. Shoring is a form of temporary support which can be given to existing buildings adjacent to excavation to avoid damage to neighbouring structures. Similarly, underpinning is another temporary support for existing buildings next to excavations. Generally, the main object of underpinning works is to transfer the load carried by a foundation from its existing bearing level to a new level at a lower depth.

"Inclined Struts Method" as a type of retaining system, which can be categorized as a type of shoring or underpinning, is widely used in Iran. Despite the excessive use of "Inclined Strut" method, adequate researches have not been conducted about it. Besides, International references have not adequately point out to this method. Moreover, there are not adequate international resources concerning the mechanism of shoring and underpinning.

Conventionally, there are some differences in using inclines strut in excavation next to buildings. These differences are in the number as well as order of excavation's stages. The aim of this paper is to introduce different construction methods and then compare them to find out the method which leads to the least excavation-induced displacements.

The presented three dimensional study of inclined struts is in the continuation of a previously published research on two dimensional numerical study of inclined struts (Sadeghian & Fakher, 2010).

2 THE USE OF INCLINED STRUT IN EXCAVATION

2.1 *Inclined struts in literature*

Inclined Strut can be considered as shoring or underpinning depending on load transfer mechanism. Shoring is a form of temporary support given to excavations or buildings next to excavations to

prevent excessive deformation of excavation wall or building next to excavation. There are three basic systems of shoring, used to support existing structures next to an excavation named:

I. Dead shoring
II. Raking shoring
III. And Flying shoring

Dead shoring system is used to carry vertical loadings from building next to excavation to the bottom of excavation. In Dead Shoring a vertical support usually installed under the foundation of existing structures. In this type of shoring a measure should be applied to excavate the soil beneath some of the foundations of the buildingBut raking shoring system is used to support a combination of vertical and horizontal loadings. Flying shoring system could be considered as an alternative to raking shoring to give a clear working space at ground level. (Chudley & Greeno, 2006)

Underpinning is another kind of temporary support for buildings next to excavations. Underpinning caries a part of the foundation load to a lower depth where can be the bottom of the excavation. (Chudley & Greeno, 2006)

The use of Inclined Struts method is a traditional method widely used to support buildings next to not very deep excavations. In this method, wooden or steel "struts" are used to connect the foundation of adjacent building to the bottom of excavation (as shown in Fig. 1), so Inclined Struts can be categorized as raking shoring method or underpinning.

Previous studies regarding inclined struts, tried to find the best place for inclined strut to be connected to the building next to excavation. In fact, they used two dimensional analysis and simulated excavation configurations shown in Figure 1. As can be seen in Figure 1, struts were assumed to connect the bottom of the excavation to the first floor, the wall or the foundation of the adjacent building, or they were assumed to connect two adjacent footing of neighboring buildings (Sadeghian & Fakher, 2010). These studies concluded that Configuration shown as Figure 1-b results in the least excavation-induced displacement and in this respect it is advisable to connect the bottom of the excavation to the foundation of neighboring building in case inclined struts applied as retaining system to support building next to excavation.

2.2 Combination of vertical and horizontal displacement to assess damages

To assess damages occurred in buildings next to excavations both vertical and horizontal displacements should be considered. Firstly, settlement damage to masonry buildings was addressed by Burland and Wroth (1974) and Burland *et al.*
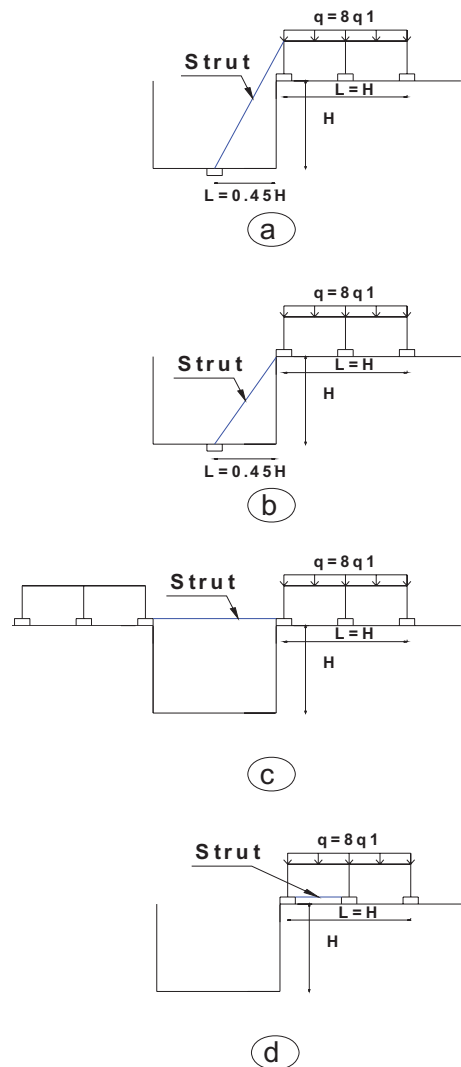

Figure 1. Common configurations of excavation procedure used in traditional shoring method which are investigated in previous studies. (a) Inclined struts connected to the first floor. (b) Inclined struts connected to the footing. (c) flying shoring. (d) Two adjacent footing of neighbouring building are fully connected. (Sadeghian & Fakher, 2010).

(1977), who introduced a damage classification system. Later, Boscardin and Cording (1989) illustrated the importance of horizontal displacement in initiating damage. Figure 2 illustrates the combination of angular distortion; define in this case as the maximum change in slope angle of the "beam" or "wall", and horizontal strain. Damage categories were based on the criteria suggested by Skempton and Macdonald (1956) and work of the
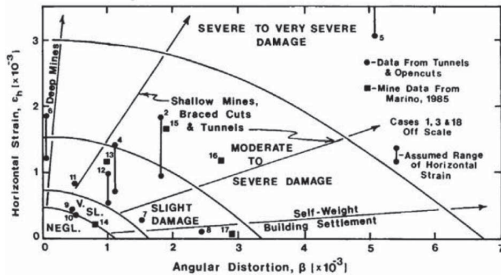
Figure 2. Relationship between angular distortion, horizontal strain, and damage category Boscardin and Cording (1989).
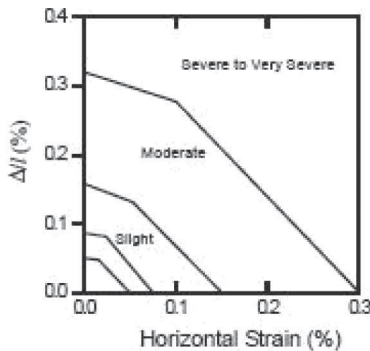

Figure 3. Relationships between damage category, horizontal strain and deflection ratio (Δ/L) which is defined as maximum deflection between the beam deflection line and the straight line between the two end points (chord) divided by the chord length, Burland (1995).

U.K. National Coal Board (1975). Figure 2 was derived for building with length (L) to height (H) ratio of 1 in terms of horizontal strain and angular distortion (β). In fact, angular distortion is the maximum change in slope along the beam or the slope at the supports.

A later modification of the critical strain approach by Burland (1995) induced lateral strain based on the work of Boscardin and Cording (1989) and adapted different values of critical strain to reflect different damage categories, as illustrated in Figure 3. However this approach was limited to the case of $L/H = 1$.

2.3 Governing mechanism

As proposed by the authors (Sadeghian & Fakher, 2010) predominant mechanisms of Inclined Struts to support buildings next to excavation are as follows:

a. Due to the excavation, the bearing capacity of the foundations next to it reduces. Using inclined struts, a portion of building loads conveys to the bottom of the excavation. So inclined struts conveniently compensate the bearing capacity reduction.

b. Inclined and horizontal Struts restrain the excavation-induced horizontal displacement and also tensile strain in buildings next to excavation. Therefore, it reduces the damage of the building as Boscardin and Cording (1989) presented a graph, shown in Fig. 6, which shows the importance of horizontal displacement.

3 NUMERICAL ANALYSIS

Conventionally, if inclined struts is used to support the building next to excavation, excavation will be done in several stages. To find the best construction method in terms of the number of stages in which full excavation should be divided as well as the order of chosen stages, numerical analysis are used in the present study. A number of most common configurations of construction methods regarding applying inclined struts to support buildings next to excavation, are modelled using three dimensional Fast Lagrangian Analysis of Continua, FLAC (Itasca, 2002).The results are compared and ones which leads to the least excavation-induced deformation introduces.

3.1 Numerical simulation and input data

The inclined struts and adjoining building are modelled using beams (a type of structural element in FLAC). Mohr-Coulomb constitutive model has been chosen for soil elements. The parameters of soil and structural elements have been shown in Table 1.

Table.1. The parameters of soil and structural elements used in numerical modelling.

Parameters	Units	Amount
Moment Interia	m^4	4.80E-05
Beam cross section	m^2	4.80E-03
v	–	0.35
γ_{soil}	kN/m³	20
H	m	8
E_{steel}	kN/m^2	2.0E+08
E_{soil}	kN/m^2	8.0E+04
C	kN/m^2	20
φ	–	35
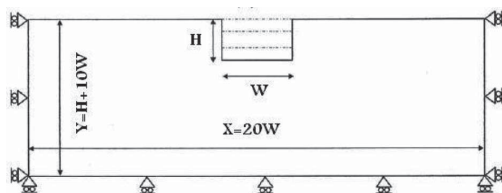
Figure 4. Boundary condition of the numerical model.

The Building Next to Excavation
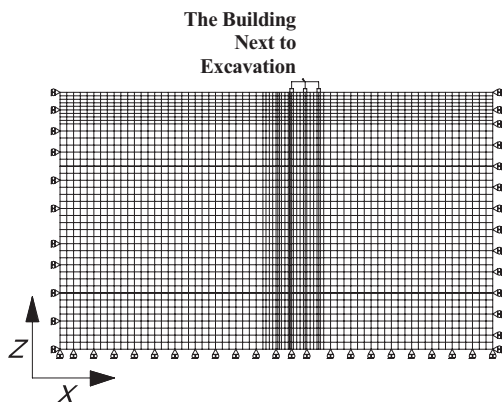
Figure 5. Discretisation of the medium for modelling.
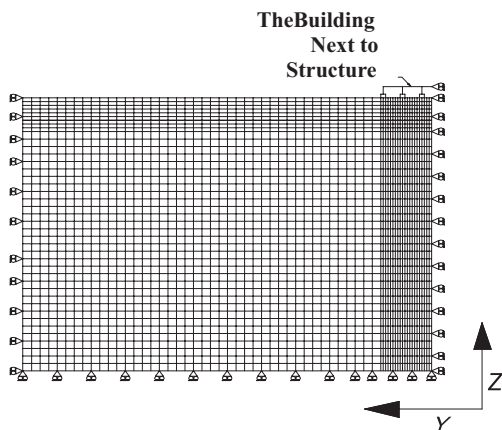
TheBuilding Next to Structure

Figure 6. Discretisation of the medium for modelling.

To minimize boundary effects, the vertical boundary at the far ends is set 80 m away (almost 10 times of excavation's width) from the centre of excavation, (Fig.4). It, therefore, is assumed to be free in vertical direction and restricted in horizontal direction. The bottom horizontal boundary is restricted in the both horizontal and vertical directions. The boundary condition and the discretization of the medium for modelling have been shown in Figures 4 to 6.

3.2 Modeling Stages

Firstly, the *in-situ* horizontal and vertical stresses are generated. Initial *in-situ* horizontal and vertical stresses are as follows:

$$\sigma_y = \gamma h$$

$$\sigma_x = K_0 \sigma_y$$

where γ is the soil density, K_0 is the coefficient of earth pressure at-rest, and σ_v and σ_h are the vertical and horizontal initial stresses at depth of h respectively.

Secondly, it is assumed that an eight-floor building with 5 and 2 spams in y and x direction respectively has been located next to the excavation. The depth of modelled excavation (H) is considered to be 8 m since it is a typical depth when the traditional Inclined Struts method is used.

The width of excavation (W) and also the width of neighbouring building (L) are assumed equal to 8 m in the models as a number of researchers consider H/L and H/W equal to one in their studies. (e.g., Burland & Wroth, (1974)).

Thirdly, excavation stages are modelled according to common excavation procedures. Boundaries between the stages are modelled by geometry lines and on the basis of considered order for excavating as described later in this paper. Restrained areas in geometry lines are omitted, according to the desired excavation stages. It is assumed that the underground water level is low enough that total stress analysis can be conveniently applied.

3.3 Modeling different configuration

As it has been mentioned here before, the inclined struts are supposed to connect the foundation of adjacent building to the bottom of the excavation. Conventionally, full excavation is done in several stages. Various construction procedures associated with inclined struts method are commonly as follows:

Procedure (1)
According to this procedure, the excavation is done in merely one stage. Afterwards, inclined struts are installed. In fact it is the easiest way of installation method of inclined struts.

Procedure (2)
In this procedure, excavation is divided into two main stages. The boundary of these two stages has been shown by a boundary line in Figure. 7. The soil in the further part of the excavation area from the neighboring structure (named V0 in Figure. 7) is firstly removed. Then the soil margin, remaining
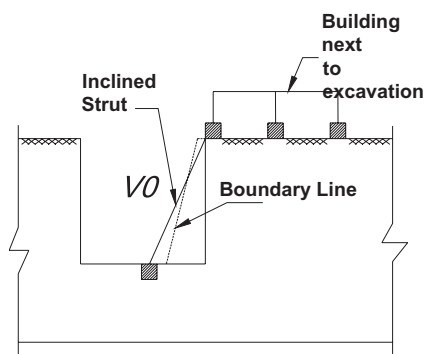
Figure 7. Cross section of excavation stages and strut installation in various procedures studied.
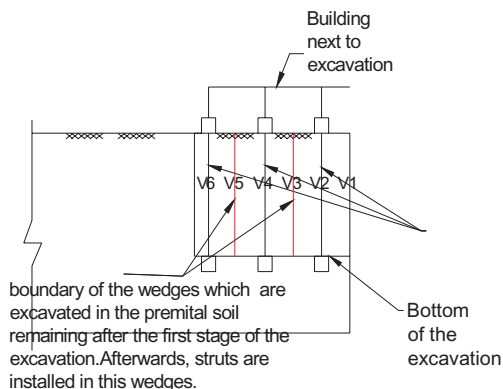

Figure 8. The longitudinal cross section of studied excavation and consequence of strut installation in procedures (1) to (4).
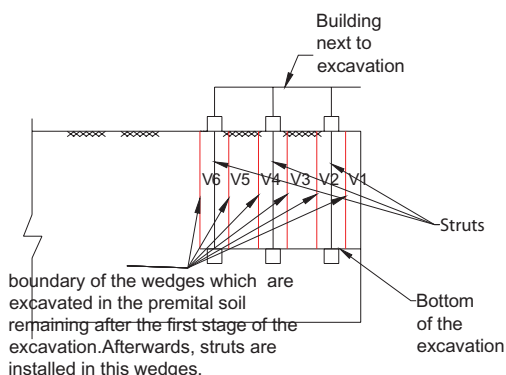

Figure 9. The longitudinal cross section of studied excavation and consequence of strut installation in procedures (5) and (6).

in front of the foundation of neighboring structure and placed in areas called V2, V4, and V6 are excavated and simultaneously inclined struts are installed and connect the foundations to the bottom of excavation. Finally, excavation is completed and the soil in areas named V1, V3, and V5 are removed.

Procedure (3)
Similar to first procedure, soil in area V0 (Fig. 7) is removed. Then, the soil margin which is remained in front of the foundation and situated in areas named V2 and V6 are replaced by inclined struts, connecting foundation of neighboring structure to the bottom of excavation. Next, the soil which is remained in V4 is removed and an inclined strut is installed, instead. Finally, the soil situated between inclined struts is removed. (Fig. 8)

Procedure (4)
Similar to No. 2 and 3 procedures, soil in V0 is removed. As shown in Figure. 7. Then, the soil placed in front of foundation (between boundary lines as shown in Figure. 8) and placed in V4 is removed and replaced with an inclined strut. Afterwards, the soil margin in area V2 and V6 are replaced by inclined struts. Finally, the remained soil is removed. (Fig. 8)

Procedure (5)
Similar to the rest procedures (except procedure No 1), the soil in V0 is removed as shown in Figure. 7. Then, the soil in V1 and V3 in Figure. 9 are replaced with inclined struts. Next, the soil margin in V2 is removed and inclined struts are installed.

Procedure (6)
It is exactly the same as No. 5 but after excavating V0 (Fig.7), the premital soil in V2 (Fig. 8) is removed and an inclined strut which connect the foundation of adjacent building to the bottom of the excavation is installed. Next, the soil in V3 and V1 is replaced with inclined struts as can be noticed in Figure. 9

3.4 *Analysis result*

Excavation-induced displacements in ground next to excavation as well as the wall of the excavation caused by different excavation procedures are compared in Figures 10 and 11.

As it can be seen in Figures 10 and 11, No. 1 procedure leads to the greatest excavation-induced displacements. Therefore, doing excavation in one stage, results in the highest level of damage in neighboring building although it is the easiest procedure in using inclined struts. Other procedures contribute to almost the same excavation-induced
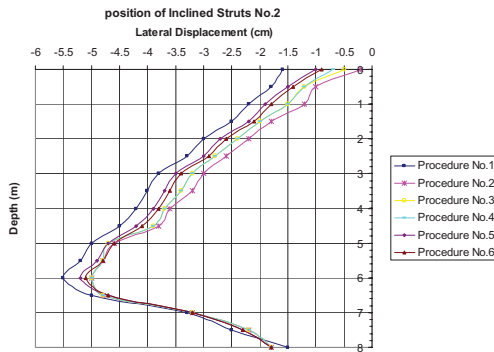
position of Inclined Struts No.2
Lateral Displacement (cm)

Figure 10. Lateral displacement caused by mentioned procedures.

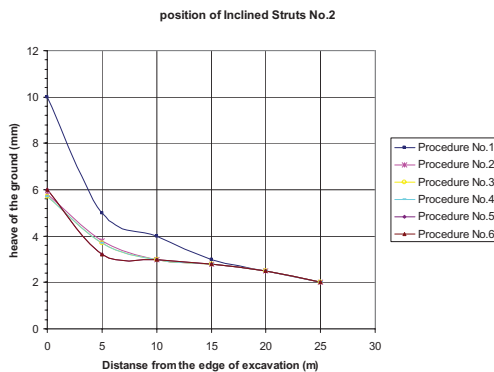**position of Inclined Struts No.2**

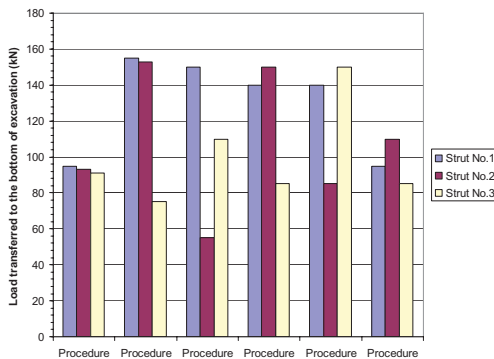Figure 11. Displacement of the adjacent ground caused by mentioned procedures.

Figure 12. Load transferred to the bottom of the excavation in different procedures.

displacements. However, more detailed studies, reveals that Procedure No. 2, 3 and 4 leads to the least displacements in comparison with Procedures No. 5 and 6. However, there are not to much

difference between the displacement rendered by Procedure 2, 3 and 4. this may reveals the fact that the order of stages do not affect the excavation-induced displacement considerably. The little difference between displacement associated with procedures No. 5 and 6 confirm this fact, as well. On the other hand it can be concluded that the width of the wedge play an important role in the excavation-induced displacement. The later conclusion inferred from the different displacement caused by procedure No. 2, 3 and 4 compared with procedure No. 5 and 6. (Fig. 10 and 11)

Moreover, Figure 12 compares the amount of the load which is transferred to the bottom of the excavation via inclined struts. Considering the mechanism of inclined strut which is discussed previously, one of the main objects of inclined is to transfer a portion of load of the adjacent building's foundation from its bearing level to the bottom of the excavation. Therefore, it can be noticed from Figure 12 that procedure No. 1 is not work efficiently in comparison with other methods. Although, No. 2 and 3 seems slightly more efficient in this regard, there are not considerable differences between the rest procedures.

4 CONCLUSION

The presented 3D study confirms the results of previously published 2D studies (Sadeghian & Fakher, 2010). In addition, the following conclusions are suggested base on the presented research.

a. To minimize excavation induced displacement, it is essential that a premital soil margin of excavation to be left before the installation of inclined struts. It means, the excavation of the premital margin should be done after the installation of inclined struts.
b. The sequence struts installation has not any considerable effects on excavation induced displacement. However, the simultaneous installation of struts could minimize displacement.
c. To install each inclined struts, the above mentioned perimital soil margin should be excavated in a very narrow trench perpendicular to the excavation wall. The width of this trench plays an important role on the amount of displacements and should be minimized.

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