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Deep Excavations in Urban Environments: A Review of Recent Developments

A report submitted to The Honors College at The University of Akron

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Abstract

Failure of excavations can be incredibly costly. Lives can be lost, projects delayed for months, and adjacent structures damaged by ground surface settlement related to both basal-heave and serviceability failures. This report summarizes developments in recent years that pertain to deep excavations in urban environments and mathematical methods to best avoid failures. The ultimate limit state (basal-heave and piping failure), and serviceability limit state (ground surface settlement and lateral wall defection) are the basis for geotechnical design in excavations. Structurally, the strength limit state (structural strength of the wall), serviceability limit state (deformation of the retaining wall), and stability (such as buckling) must be considered in design. Geotechnical and structural design must work hand in hand to provide the best retaining system to make sure lives and property are protected.

Keywords: Ultimate limit state; basal-heave; reliability based design; serviceability limit state; ground surface settlement; lateral wall deflection

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1. Introduction

Many construction projects require the use of excavation to move soil for work to be done. Buildings, bridges, tunnels, sewers, and roads are just a few of the types of construction projects that would require the use of excavation. Often times, these excavations must be braced in some way to prevent damage to surrounding buildings, and to avoid failure of the excavation walls.

There are two main types of excavations with retaining walls. The first method is the use of a cantilevered wall. Cantilever walls do not have any support system. They rely on the passive resistance provided by the soil below the excavation to retain the soil behind the wall. Gravity walls are also often described as cantilever walls by practicing engineers. Cantilever walls are great for excavations less than 18ft deep, are much simpler to construct than other retaining wall systems, and leave an obstructed excavation area to work in. Cantilever walls are typically used for basements in houses and for retaining wall systems that do not exceed 18ft in depth.

The second main type of retaining wall system is a braced wall. Braced excavations are typically used at depths greater than 18ft. The excavations are generally performed in stages, and one or several layers of bracing are installed to support the wall at the end of each stage of excavation. The types of bracing systems include struts and tie backs. The struts can run between walls on the interior of the excavation, limiting room for maneuverability while working below the ground surface level. Braced excavations can also include retaining walls that use tiebacks or rock anchors. Tiebacks allow an open work space but are at risk of leakage if the tieback holes are not sealed properly. In order to use tiebacks, the adjacent building owners must give permission to allow drilling beneath their property. Gil-Martín et al. (2012) discussed the developments of the bracing systems of excavations in the past few decades. In terms of construction sequence, the braced excavations can be categorized into bottom-up excavations and top-down excavations. For the bottom-up method, the struts are installed after the retaining wall system has been built, and installed as the soil is being excavated between the retaining walls. For the top-down method, retaining walls are built and will be part of the permanent structure. As soil is excavated, the floors for the building are constructed. These floors act as the bracing system, just as they will in the final structure. This process is repeated until the desired number of floors have been built. These braced excavations are most commonly used in deep excavations, often when buildings are adjacent to the excavation site.

Failures of excavations, specifically deep excavations, can have major consequences. These consequences can range from loss of life, permanent critical injuries, damage to surrounding buildings, and delay or total stoppage of the construction project affected. Design of excavations should not be taken lightly when such high stakes are at risk. A recent example of the consequences of a failed braced excavation is the Hangzhou, China subway collapse from November 2008. The results of the excavation failure included a road sinking roughly 7 meters (which caused a 75 meter by 32 meter collapsed area), a water main breaking beneath the road, the west panels of the excavation breaking, the east panels inclining 3.9 meters towards the inside of the excavation, and all steel pipe struts falling to the base of the excavation. The result of this case study and back analysis of the soil shows that the diaphragm walls were not designed properly, in two sections too much was excavated, a monitoring system was not used to detect signs that the excavation was not in good shape, and lastly, the supporting system was poorly constructed (Chen et al. 2013). The death toll immediately following the collapse stood at 21 people, with 24 critically injured (Yongchi et al., 2010). Yongchi et al. also reported an estimated monetary loss of 4961 million Chinese Yuan based on an issued investigation by the Hangzhou government. Based on the currency exchange in April of 2016 between the Chinese Yuan and the United States Dollar, the economic loss converts to roughly $767 million. This real life example shows how costly the consequences of a failed excavation can be.

The design of braced excavations includes structural design and geotechnical design. The structural design mainly refers to the design of retaining walls and bracing system. In the structural design, the strength limit state (structural strength), serviceability limit state (structural deformation) and stability (in terms of buckling) should be satisfied. The geotechnical design includes the assessment of the ultimate limit state and the serviceability limit state. This Honors project covers a review of developments regarding methods for evaluating geotechnical failures of braced excavations. The focus of this project is the geotechnical engineering design of braced excavations, including both ultimate limit state assessment and serviceability assessment. Herein, the ultimate limit state assessment refers to the basal-heave stability in clays and piping in sands. The serviceability assessment means the excessive lateral wall deflection and ground surface settlement induced by soil movement. Table 1 shows an example design code for geotechnical design of braced excavations considering both the ultimate limit state and the serviceability limit state. Both deterministic design and reliability-based design are reviewed in this student project. To get a better understanding of the papers covered, the author of this report recommends reading the original papers.

Table 1: Criteria for excavation protection levels in Shanghai, China (PSCG 2000).

Excavation protection level	Limiting wall deflection and ground surface settlement	Requirements of the environmental protection
I	1. Maximum wall deflection ≤ $0.14\%H$ 2. Maximum ground surface settlement ≤ $0.1\%H$ 3. FS (basal stability) ≥ 2.2	Metro lines and important facilities such as gas mains and water drains exist within a distance of 0.7H from the excavation; safety has to be ensured.
II	1. Maximum wall deflection ≤ $0.3\%H$ 2. Maximum ground surface settlement ≤ $0.2\%H$ 3. FS (basal stability) ≥ 2.0	Important infrastructures or facilities such as gas mains and water drains exist within a distance of (1-2)H from the excavation.
III	1. Maximum wall deflection ≤ $0.7\%H$ 2. Maximum ground surface settlement ≤ $0.5\%H$ 3. FS (basal stability) ≥ 1.5	No important infrastructures or facilities exist within a distance of 2H from the excavation

Note:

H = Final excavation depth

FS = factor of safety against basal heave, calculated using the slip circle method.

2. Ultimate Limit Assessment

The ultimate limit state design is also referred to as stability analysis. This section summarizes some practical methods for stability analysis for excavation in clays and sands.

2.1 Basal-heave in clays

Basal heave failure occurs in excavations that contain clayey soils. When the weight of the soil overwhelms the shear strength of the soil, basal heave failure occurs. The soil at the bottom of the excavation heaves due to the ground surface soil outside the excavation sinking inward and downward. The braced excavation will fail if the amount of heave is too large. Figure 1 shows a real world example of what happens when basal heave failure occurs.

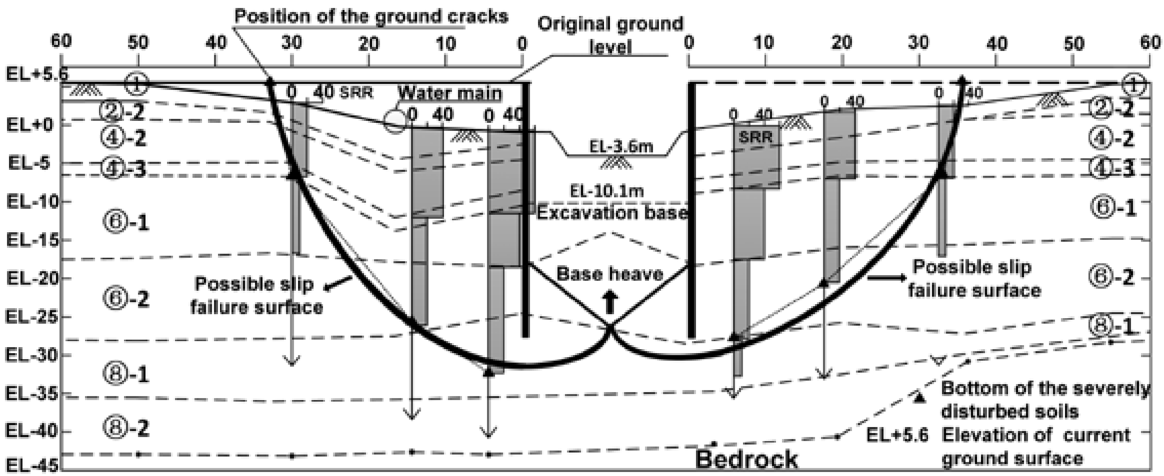

Figure 1: Example of basal-heave failure due to collapse at the N2 excavation of the Hangzhou, China subway collapse (Chen et al. 2013).

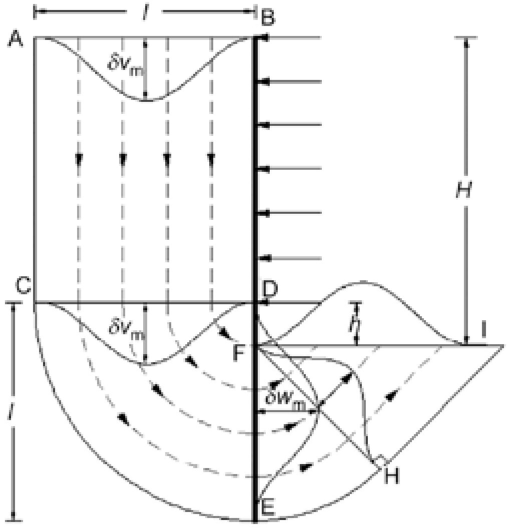

Figure 2: Theoretical figure (against one wall of an excavation) as proposed by Osman and Bolton (2005). Adapted from Wang and Long (2014).

2.1.1 Deterministic Approaches

One way basal heave failure can be dealt with is by the factor of safety, defined as resistance divided by load (Terzaghi 1943; Bjerrum and Eide 1956). A factor of safety is often evaluated to determine the basal-heave stability in braced excavations in clay. For most designs by factor of safety, soil properties are considered constant to simplify the method. Semi-empirical methods to determine the factor of safety have been widely used in deterministic design (Terzaghi 1943; Bjerrum and Eide 1956; Eide et al. 1972; Chang 2000). The factor of safety required will always depend on the method used, such as the example given in Table 1.

Chang (2000) modified Terzaghi's method by reducing the bearing capacity factor N_c to account for a perfectly smooth footing, and moved the side shear term from the denominator to the numerator. By making these changes, the factor of safety calculated is lower than Terzaghi's original method calculates. Chang also presents a limit analysis method, which is a modification of the upper bound limit analysis method presented by Chen (1975). Chang's modified Terzaghi's method and newly proposed limit analysis method were tested in seven case studies presented in Bjerrum and Eide (1956) against Terzaghi's original method and Bjerrum and Eide's original method. The results from Chang's modified Terzaghi's method and the limit analysis method were found to produce lower, and more accurate to field observations, factor of safety values than the traditional methods.

Another method to determine a factor of safety to resist basal heave failure is the slip circle method as employed by the Japanese, Chinese and Taiwanese building codes (JSA 1988; PSCG 2000; TGS 2001). This method is used for its simplicity to consider the undrained shear strength as it increases with depth. In the slip circle method, the factor of safety is defined similarly to how Terzaghi initially defined it, as resistance over load. For the slip circle method, however, the factor of safety is defined as the resistance moment over the driving moment. The resistive moment is calculated by summing the resistances along the slip surface. The driving moment is simply caused by the weight of the soil behind the braced wall of an excavation and any surcharge that might occur. The recommended factor of safety for the slip circle method is 1.2.

Chen et al. (2013) reviewed the subway collapse in Hangzhou, China. The excavation involved organic soft clays. Basal heave was found to be the resulting soil failure mechanism. The factor of safety against basal heave calculated by Terzaghi's method, Bjerrum and Eide's method, and the slip circle method were all much smaller than recommended values. Due to failures involving the empirical method in the deterministic approach, numerical methods and modeling have become another way to find the factor of safety.

The numerical methods in geotechnical engineering include but are not limited to the finite element method and the finite difference method. Finite element analysis and modeling (FEM) have started to become widely used for more accurate predictions of how soils will react given certain excavation conditions. These finite element analyses and models must be tested against case histories to assure their predictability, accuracy, and practicality for engineers. FEM for basal-heave analysis typically adopts the shear strength reduction method to yield a factor of safety. The factor of safety is determined as the ratio of the original soil strength to the reduced soil strength when numerical solutions diverge. A few scholars, such as Goh (1990), Faheem et al. (2003), Do et al. (2013), Zhang and Goh (2015) used FEM to analyze the stability of excavations in soft clays.

Wang and Long (2014) formulated a new method using the upper bound theory to evaluate failures in excavations. Three case studies were used to confirm this method's possible application. In case study 1, the failure depths calculated by this new method are very close to those calculated by the FEM. For cases 2 and 3, this method is more precise for calculating failure depth than the capacity and failure surface methods. By optimizing the failure depth, the factor of safety for this new method can be obtained.

Using the finite element method, Do et al. (2015) analyzed four case studies with reduced shear strength taken into account. Elastic and elastoplastic support systems were analyzed. When the elastoplastic support system was used in the excavation, it was found that the failure of the support system is what caused the failure in the excavation. When the elastic support system was used and analyzed, the FEM found the stability of the excavations to have greater strength than what they actually had in the field. Both failures occurred as a result of soil upheaval at the bottom of the excavations. When these support systems were analyzed in thick clay, the struts bent until failure due to upheaval of the supporting posts and sinking of the walls.

2.1.2 Reliability-based Approaches

The aforementioned empirical and numerical models for basal-heave analysis have involved considerable model error or model bias for the designs in the practice. Even with a conservative factor of safety basal-heave stability cannot be always be achieved due to variability of soil properties like undrained shear strength and unit weight (Luo et al. 2012). Soil properties are considered as homogeneous fields in traditional reliability analysis. Uncertainty comes from inherent variability in soil, as not all soil is 100% the same in a sample, and from spatial variability. For spatial variability, the variation in soil properties can be modeled using the random field theory (Vanmarcke 1977). Spatial variability can be defined by the scale of fluctuation. The scale of fluctuation is the maximum distance between spatially random parameters over which they become uncorrelated (Akbas and Kulhawy 2009). Soil parameters in a random field vary more as the scale of fluctuation decreases.

Goh et al. (2008) demonstrated the potential for reliability index-based approach to evaluate braced excavations against basal-heave failure. Goh et al. uses basic structural reliability principles for the foundation of this process to allow practicing engineers to get a better understanding of uncertainties and their effects on a probabilistic chance of failure. That study shows that assuming a linear limit state surface will give rational estimates of the reliability index and of the probability of failure. It also shows that the same factor of safety can have different levels of risk, depending upon the degree of uncertainty of the design parameter of a given project. This is all presented in a table analyzing case studies, showing that even with a high factor of safety, the probability of failure can be high.

Wu et al. (2010) investigated the effect of spatial variability in the basal-heave assessment. Luo et al. (2011) presented a simplified approach for reliability analysis of basal-heave in a braced excavation in clay for estimating the effect of spatial variability in a 2-D random field. Luo's approach utilizes the equivalent variance technique to consider the effect of spatial variability in soil so that probability of basal-heave failure analysis can be executed using the first-order reliability method, which is different from using random field modeling, which requires the use of Monte Carlo simulation. Luo et al. checks this new method against a case study to show these results are very close to results given by the Monte Carlo simulation based random field modeling technique. This new method is thus easier to use because it is simplified from the computational heavy random field modeling technique. Luo et al. (2012) again present a simplified approach for reliability analysis of basal heave failures in braced excavations taking into account spatial variability. The first order reliability method is used with a variance reduction technique to model spatial variability instead of traditional random field modeling. The new approach is simpler, easier to use and requires less computational effort. This gives it potential to be used as a practical tool when solving reliability-based design that deals with spatial variability in soils.

2.2 Piping (Seepage failure) in sands

Seepage failure can occur when diaphragm walls are used to hold back soil where the groundwater table is high. Water flows through the soil and slowly erodes soil around the base of the excavation when the water pressure in the soil is too high. This can especially be a problem in excavations that require dewatering, as they have higher groundwater tables surrounding the excavation. The safety factor against piping is usually predicted using the method of Terzaghi and Peck (1967). Due to time restraints and course load, piping failure will not be reviewed in this Honors project, but should not be considered any less important than other failure modes.

3. Serviceability Limit Assessment of Geotechnical Design

Ground settlement around excavations can be very costly when actual settlement exceeds allowable settlement. It is imperative to be able to accurately predict both factors in order to avoid costly failures. The ground settlement profile is often estimated with the use of finite element method to model the soil-structure problems that can be encountered during braced excavations. While the wall deflection is often easy to calculate, the estimation of surface settlement is much more difficult and less accurate (Whittle and Hashash 1994; Hsieh and Ou 1998). Studies have shown that accurate predictions by FEM are possible if small strain levels can be properly represented (Simpson 1993; Whittle et al. 1993; Hight and Higgins 1995; Stallebrass and Taylor 1997; Kung 2003). Ground surface settlement has also been estimated through the use of empirical and semi-empirical models (Peck 1969; Bowles 1988; Clough and O’Rourke 1990; Ou et al. 1993; Hsieh and Ou 1998). However, these studies do not completely link ground surface settlement and wall deflection and are unable to calculate uncertainty in the predictions of excavations.

The owners or local regulatory agencies will establish the limiting criteria for serviceability assessment, such as the example in Table 1. In a deterministic design, the predicted maximum lateral wall deflection and ground surface settlement must be less than the limiting criteria for a certain protection level. In a reliability-based design, the probability of exceeding the limiting criteria should be smaller than an acceptable probability of failure. Several approaches for the serviceability assessment are discussed in this section.

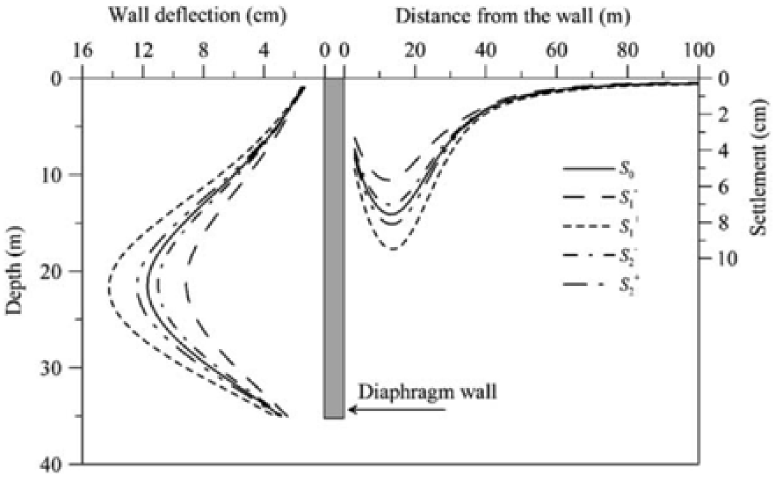

Figure 3: Examples of ground surface settlement and lateral wall deflection profiles (Dang et al. 2014).

3.1 Observational Method

Peck (1969) summarized ground surface settlement based on field observations from excavations into a graphical format as shown by Fig. 4. This method is suitable for spandrel type settlement profiles, an example of which is shown by Fig 5. The figure clearly shows three zones which are classified by the quality of workmanship and type of soil around the excavation. Peck used excavation case studies that used sheet piles or soldier piles with lagging to develop Fig. 4. Peck's method was the first practical way to estimate ground surface settlement due to excavations and has been widely used since.

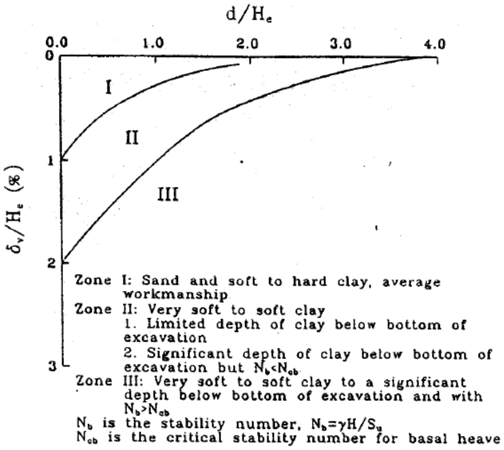

Figure 4: Peck's (1969) method for predicting ground surface settlement (Adapted from Hsieh and Ou 1998).

Ou et al. (1993) studied ten spandrel type (as shown in Fig. 5) excavation failures to better understand the characteristics of ground surface settlement and lateral wall deflection during the excavation phase of a given project. The ten case studies chosen were based on one basic criterion, that wall deflection and ground surface settlement occur only due to soil removal inside the excavation. Through these case studies, a range of maximum wall deflection was determined based on final excavation depth, and a range of values for ground surface settlement was determined based on the magnitude of maximum lateral wall deflection. The distance from the retaining wall that the ground surface settlement occurs was determined not to vary with excavation depth and can simply be estimated as half the final excavation depth. Finally, Ou et al (1993) give an empirical formula that finds the relationship between ground surface settlement and the distance from the wall with good accuracy under ideal and plain strain conditions. Ou et al. recommended more field data to be tested against this formula and further refinement of the equation.

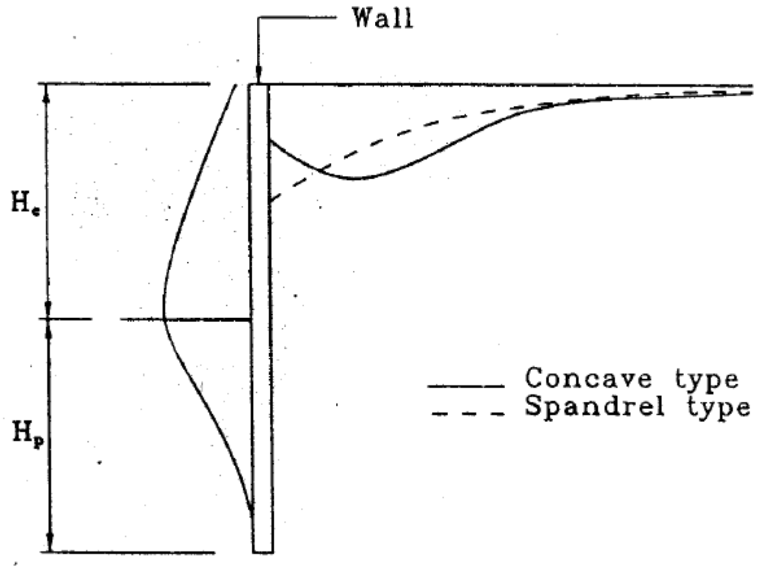

Figure 5: Concave vs Spandrel ground settlement profile (Hsieh and Ou 1998).

3.2 Empirical Method

In 1988, Bowles created a method to estimate spandrel type ground surface settlement due to excavation. This method involved estimating the lateral wall deflection and then calculating the volume of soil moved due to the estimation of deflection. The influence zone is calculated by the method recommended by Caspe (1966) followed by a calculation of maximum ground surface settlement, assuming that it occurs at the excavation wall. Lastly, the settlement can be calculated.

Based on case studies, Clough and O'Rourke (1990) were able to suggest that ground surface settlement is triangular for excavations in sandy soils and stiff clays. Clough and O'Rourke determine that the maximum ground surface settlement occurs at the excavation wall as shown by a spandrel type settlement profile. However, for excavations occurring in soft to medium clays, Clough and O'Rourke determined that the settlement occurs at some distance away from the wall, as given by a trapezoidal shape for a settlement profile. Clough and Rourke's method is meant to deliver a conservative envelope for ground surface settlements that can occur around an excavation wall.

Hsieh and Ou (1998) build an empirical method from Peck (1969), Bowles (1988) and Clough and O'Rourke's (1990) methods to more accurately estimate ground surface settlement if the lateral wall deflection in known for spandrel and concave settlement profiles. Through the back analysis of case studies, Hsieh and Ou determine their method is accurate for both soft and stiff clay. Hsieh and Ou also found that the maximum ground surface settlement ranged from 50% to 75% of the maximum wall deflection, except in very soft clays, where the maximum ground surface settlement could be larger than the maximum wall deflection. Ultimately, Hsieh and Ou's method for concave and spandrel type settlements is more accurate than Clough and O'Rourke and Bowles empirical methods.

Osman and Bolton (2006) developed a new semi empirical method called the mobilisable strength design (MSD) for predicting ground movements around soft clay excavations using actual stress-strain data and the undrained shear strength profile of the in-situ soil. A practical application of the MSD method is shown through analyzing a case history that involved a braced excavation of soft clay in Singapore. The MSD method is practical for practicing engineers because it allows the use of a stress-strain curve and simple calculations to solve for both stability and wall displacements without requiring FEM.

Kung et al. (2007) presented a simplified semi-empirical model based on the results of a large number of FEM analyses and database of excavation case histories. It is used to accurately estimate maximum wall deflection, maximum surface settlement, and surface settlement profile for soft to medium clays. Kung et al. (2007) used many case studies to prove their model's reliability when solving for the factors mentioned previously.

Juang et al. (2014) used robust geotechnical design of braced excavations to optimize cost and robustness. All designs that are optimized also meet any safety requirements, including all stability and serviceability requirements. Lowest cost does not often give the most robust design. Therefore, a single design is not the best, but rather a set of non-dominated designs known as the Pareto Front. These non-dominated designs give a relationship between robustness and cost of the braced excavation which can be used to select the most ideal design for an individual case.

Dang et al. (2014) developed a simplified approach in conjunction with PLAXIS, a finite element code, to calculate the effect of parameter uncertainty with consideration of spatial variability in analysis of braced excavations using user-defined soil models such as the hyperbolic and the modified pseudo plasticity (MPP) methods to accurately predict wall deflection and ground movement. To show the success of this simplified method, an example implementation was given.

Zhang et al. (2014) recently developed a simple polynomial regression model based on the excavation geometry, soil strength and stiffness, and wall stiffness to find maximum wall deflection when the wall penetrates the stiff stratum beneath the excavation. Zhang et al. tested this semi-empirical model against 21 well-documented case studies to verify its accuracy. These tests revealed their model could predict the wall deflections fairly well.

3.3 Numerical Method

Several numerical methods are available to predict the excavation-induced wall and ground movement. This Honors project only focuses on the widely-used finite element method (FEM). Hashash and Whittle (1996) studied the effects of ground surface settlement caused by deep excavations where the bottom of the retaining wall is embedded in soft clay. ABAQUS paired with the MIT-E3 effective stress soil model were used in numerical experiments based on non-linear finite element analyses to gather data. Hashash and Whittle drew several conclusions from these tests and ultimately provided a design chart for predicting ground surface settlement as they relate to excavation depth and support conditions, all while including the effects of base stability from wall length.

Diao and Zheng (2008) investigated the relationship between the effects of friction on a diaphragm wall with the ground surface settlement around the excavation. A finite element model was used in combination with ABAQUS to establish this relationship. Diao and Zheng concluded that friction between the soil and the wall can lower the deflection of the wall and the maximum ground surface settlement. However, the further away from the wall you get, the lower effect the friction has on reducing ground surface settlement. The friction angle was found to have different effects at different depths along the diaphragm wall. At the depth of maximum deflection, the reduction effect is the highest, but the reduction can be neglected at the base of the wall. Lastly, different friction angles affect the shape and profile of wall deflection and ground settlement, respectively.

Luo et al. (2011) created a streamlined framework to estimate the probability of serviceability failure in braced excavations in a spatially random field. Five elements are used in this simplified framework: FEM, fuzzy set modeling of parameter uncertainty, spatial averaging technique to handle spatial variability, vertex method to process the fuzzy model through FEM, and interpretation of the output from the fuzzy output. Through back analysis of well-documented case studies, Luo et al. were able to verify the accuracy of this new framework in predicting the probability of serviceability failure in braced excavations in a spatially random field.

Chowdhury et al. (2015) studied the effect of fine content retained in sandy soil on braced excavations using numerical and experimental models in terms of design factors: strut force, bending moment in the wall, lateral deflection of the wall, and vertical displacement of the ground surface. Chowdhury et al. set up a model structure to further investigate how greater fine particle content in soil affects these four factors. They found that for particular values of embedment depth over excavation depth, wall thickness over excavation depth, and strut stiffness, for an increase of fines up to 40%, max strut force, wall moment, and wall deflection increase. However, beyond the 40% increase, the rate that at which these parameters increase begins to slow. For those same values mentioned previously, ground displacement increases as the amount of fines increases up to 30%, after which it begins to decrease. Ground surface displacement shifts from basal heave failure to issues regarding settlement as the amount of fine content increases from 0-50%. The variability of the struts in relation to wall moments, wall deflection, and ground displacement is also covered in the research of Chowdhury et al.

Luo and Das (2015) use PLAXIS, a finite element program, along with user-defined soil models to accurately predict wall deformation and ground movement as a result of excavation. The response surface method is used for the performance functions for both wall deflection and ground surface movement. This method is then used in a back analysis of the Formosa excavation failure case in Taiwan. This modeling method is able to predict very closely the wall deflection and ground movement as compared to what was observable in the field of the Formosa case.

4. Structural Design in Braced Excavations

The structural design in braced excavations mainly refers to the design of the retaining wall system used, along with any cross bracing or tieback anchors used in conjunction with the retaining wall system. The bracing helps in reinforcing the retaining wall system through using the axial strength in steel beams in the case of cross bracing. Cross bracing, however, complicates construction in an excavation, as the beams can obstruct machinery and can slow progress. One thing that must be considered is the possibility of the steel beams buckling in the event of extreme lateral loads on the retaining wall system. Tiebacks rely on anchoring into the soil behind the wall to provide support to the retaining walls. Sometimes tiebacks cannot be used in the event there are many utility lines on the other side of the retaining wall. Due to time restraints and course load, structural design of braced excavations will not be reviewed in this Honors project, but should not be considered any less important than other geotechnical failure modes.

5. Summary

This Honors project is meant to give a brief review and serve as an introductory source of information for those who are entering the sub-discipline of geotechnical engineering with a focus on deep excavations. This review work mainly focuses on the geotechnical design of excavations. Geotechnical design must satisfy both the ultimate limit state requirement and the serviceability state requirement. The ultimate limit state assessment was discussed, with a focus on basal-heave failure in clays. Piping failure in excavations in sands was briefly described. The factor of safety method and the reliability-based design approach were reviewed with recent design methods discussed. Serviceability limit states, assessment with the consideration of geotechnical failures due to excessive ground surface settlement and excessive lateral wall deflection, were also discussed in this Honors project. Observational, empirical, and numerical methods were covered spanning from Terzaghi up to the latest techniques that are being developed by researchers. Another major concern of braced excavations, namely the structural design, was only briefly reviewed due to time restraints and course load during this Honors project.

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