ABSTRACT

This study investigated deep excavations, its effects on adjacent structures and excavation support systems. This was in the light of concern that the structural integrity of buildings is compromised when Deep Excavations are executed in close proximity to a structure. In densely built-up areas with high land value, the trend is towards building higher and deeper, often adjacent to existing structures. Such projects involve the adoption of tight ground movement criteria. This study investigated challenges posed by Deep Excavations that included; ground deformations, seepage of water in the excavation site and stability of excavation slopes. A number of documented case studies were analysed. Data for this study were obtained by document analysis of existing literature. The findings of this study will be utilized to establish a suitable procedure of conducting deep excavations.

Keywords: Deep excavations, Kenya, Vision 2030

1. INTRODUCTION

Background

An excavation is a man-made cut, cavity or depression in the earth’s surface formed by the removal of earth (Ou, 2006).

Urban growth due to industrialization, population growth and rural-urban migration has increased the demand for space in towns, cities and other centres of urbanization. The increased demand for space has led to the need to create tall buildings with deep foundations to position car parks, mechanical, electrical and plumbing services in the basements of these buildings (Fantaziu & Chirila, 2014). This has therefore resulted in the need to carry out deep excavations.

In the development of infrastructure such as roads and railways there is great likelihood of encountering deep excavations especially when the earth has to be dug out in order to create a good surface profile of the carriageway through rolling and mountainous terrain.

Research Problem

Deep Excavations pose many challenges that impact on cost and performance. Many buildings will not go as tall as should be because of the problems associated with deep excavations. In Nairobi, the capital city of Kenya, Lonrho House does not have basement parking because of the costs that would have been involved in supporting the deep excavation necessary to create one. Several other buildings within Nairobi encountered the same problem. Ambank House excluded an underground parking facility and opted for storeyed parking so to avert the problem of deep excavations and its effects on the existing adjacent structures.

Objectives

The objectives of this study will therefore be:

- To find out the mechanisms causing damage to existing structures adjacent to deep excavations.
- To review design methods for quantifying the problem.
- To gain insight into mechanisms of soil-structure interaction for buildings adjacent to deep excavations.
- To review procedures for design and mitigation measures employed in supporting deep excavations.

Significance of the study

The study will be of importance and its application to Kenya would reap great benefits for the country. The information from this report will enable engineers design taller buildings as they can lay their foundations deeper and thus create more space for facilities such as underground parking and thus ease traffic congestion in urban areas.

This study will establish a design routine for preparing deep excavations as an endeavour to publish the industry best practice.

Good performance of deep excavations will result in less litigation as there will be negligible effects on adjacent surrounding structures.
2. REVIEW OF LITERATURE

Forces in Deep Excavations
The excavation of soil from a deep excavation has the following main effects:

1. The removal of the weight of the excavated soil results in a decrease in the vertical stress in the soil beneath the excavation.
2. The removal of the soil in the excavation results in a loss of lateral support around the excavation (Bentler, 1998).
3. The excavation sides experience hydrostatic forces as the depth of the excavation goes below the depth of the water table.
4. Pore water pressures result in significantly large forces especially in impermeable soils.

As excavation takes place, forces are encountered on the excavation slopes due to the loss of lateral support. These forces include:

1. Hydrostatic forces: Hydrostatic forces are linear in magnitude and increase as the depth of the excavation increases.
2. Lateral earth pressure: This is the pressure caused to the soil itself. Lateral earth pressures in soil may be influenced by stress history, lateral movement of retaining structures and the shear strength of the soil. The smallest pressure a soil can exert is called active, the largest is called passive and the pressure when static is called at-rest.

Earth Pressure Theories
Problems of deep excavation, whether stability analysis or deformation analysis entail the distribution of earth pressures (Ou, 2006). A proper choice of earth pressure should be chosen to lead to an economical and safe design. Soil pressure is expressed by two main earth pressure theories namely:

1. Rankine’s Earth Pressure Theory
2. Coulomb’s Earth Pressure Theory
3. Caquot-Kerisel Theory
4. Lancellota Theory

<table>
<thead>
<tr>
<th>Earth pressure Theory</th>
<th>Rankine</th>
<th>Coulomb</th>
<th>Caquot-Kerisel</th>
<th>Lancellota</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Surface</td>
<td>Planar</td>
<td>Wedge</td>
<td>Curved elliptical</td>
<td>Log-spiral</td>
</tr>
<tr>
<td>Wall friction</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Correlation</td>
<td>Equation</td>
<td>Equation</td>
<td>Tables</td>
<td>Equation</td>
</tr>
<tr>
<td>$K_a$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1: Comparison of the various earth pressure theories.

Deep Excavation Failure Cases
Deep excavations pose a challenge to engineers all over the world. Geotechnical failures of deep excavations have occurred and it is from these failures that more can be learned once the back analysis has been carried out. A failure is a good source of information for engineers to learn and to get more insight on the geotechnical problems to enhance knowledge.

The main causes of failure of deep excavations are:

**Inadequate stability analysis** of an open cut excavation in North Jakarta, Indonesia, resulted in slope failure. The driven piles that had been put in place were subjected to large lateral forces that resulted in the failure of the excavation supports.

**Insufficient toe penetration** of steel sheet piles, would lead to excessive movement of the sheet piles toe, which might lead to kick in failure. A kick in failure results in large and sudden sagging of the ground behind the wall.

**Seepage**: In China, failure to support a 4.6 metre excavation resulted in the collapse of a 13 storey structure. Seepage of water into the surrounding soil and the mobilization of pore water pressures resulted in the tilting of the building and its eventual collapse.

Piping in cohesionless soils, if not prevented, causes boiling near base inside and loss of passive resistance,
water and soil transferred inside through large openings leads to failure of wall (Ergun, 2008).

Undetected artesian pressures under relatively impervious soils may cause blow out of base resulting in submergence of excavation pit.

On April 2004, a serious incident of excavation failure took place in Singapore. This was a cut and cover excavation project for a tunnel for an underground rail. Poor analysis of the earth pressure induced by the soft clay was attributed to the failure. The earth retaining system used was diaphragm walls with steel beam installed as the shoring system. The original design misinterpreted the local geology and overestimated the soil shear strength in its analysis. The structure was therefore under designed to resist lateral earth pressures. (Whittle & Davies, 2006)

Modes of failure for excavation support systems
- Overturning failure
- Sliding failure
- Bearing capacity failure
- Tension failure
- Rotational slip failure

Classification of Excavations
Excavations were considered shallow or deep depending on the ratio of their width to their depth. Terzaghi (Simpson, et al., 2008) (1943) defines excavations with depths smaller than their widths as shallow excavations while excavations with depths larger than their widths as deep excavations. Years later, Terzaghi and Peck (1967), and others, including Peck et al. (1977), revised that excavations whose depths were less than 6m could be defined as shallow excavations and those deeper than that as deep excavations.

Deep excavations are required when the bearing stratum lies at great depth. As large quantities of earth are removed from the site to reach the bed rock, a deep excavation is formed. The University of Nairobi towers is one such example whereby the bedrock was overlaid by 30 metres of soft volcanic ash. It was therefore necessary to perform a deep excavation in order to set up a suitable platform for subsequent piling and raft foundation of the structure. The University of Nairobi Towers is one of the Vision 2030 flagship projects.

Although a lot of effort is put into design and construction of these facilities, this does not mean that their construction is without problems. On the contrary, during many underground construction activities, problems such as damage, delays and cost overruns will often be encountered.

Problems encountered in Deep Excavations
Deep excavations face a number of problems. Key among them are:
1. Ground deformations.
2. Seepage of water into the excavation.

Types of deep excavations
Depending on the challenges anticipated on the site it may be necessary to support the excavation or employ measures so as to provide solutions to these challenges. Deep excavations are of two main types:
- Open excavation: This is where there is no retaining system and the slope of the excavation slope has to be maintained at the ratio of 1:2. Open excavations are subject to ground and site conditions.
- Retained Excavations: These are excavations whose sides are supported. The excavations slopes are usually vertical or near vertical. Retained excavations maximize the size of excavation and therefore suitable for urban construction. All excavations that are deeper than 3.5m may require structural support.

Factors affecting deep excavations
Stability and performance of deep excavations are affected by the following factors:
- Soil type
- Level of the water table
- Adjacent Structures

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Consideration while excavating</th>
</tr>
</thead>
</table>
| Sand      | - Permeability for dewatering and stability of excavation bottom  
            - Shear strength for loads on retaining structures and stability of excavation bottom |
Geotechnical Investigation
In order to execute a deep excavation, proper analysis should therefore be conducted. An assessment should be carried out to determine all sources of problems that may be encountered. The nature of the soil should be investigated, the level of the water table should be determined and neighbouring adjacent structure should be put into consideration before excavation starts on the construction site.

3. EXCAVATION SUPPORT SYSTEMS

Overview
Excavation support systems are temporary earth retaining structures that allow the sides of excavation to be cut vertical or near vertical. They are used to minimize the excavation area, to keep the sides of deep excavations stable, and to ensure that movements will not cause damage to neighbouring structures or to utilities in the surrounding ground (Nemati, 2005).

Purpose of Deep Excavations Support Systems
Excavations result in ground movements and thus the purpose of a deep excavation support system is to provide lateral support for the soil around an excavation and to limit movement of the surrounding soil system (Bentler, 1998). A structural system includes wall, props, floor slabs or ground anchors. Soil-structure interaction (SSI) analysis is important for ground supported by structures as the soil generates the loading as well as provide resistance to the load. SSI considers interaction of stiffness and deformation between structure and soil for an adequate assessment of stresses, forces and bending moments in the supporting structure.

Performance of Deep Excavations
Performance of a deep excavation is related to both stability and deformation. Deep excavations should be designed to be stable and to limit deformations to acceptable levels. A stable deep excavation is an excavation whose walls do not collapse, and whose base does not heave uncontrollably (Bentler, 1998).

Stability and deformation are used to predict the performance of a deep excavation. Stability refers to resistance against failure such as basal or upheaval failure. Stability is easily evaluated with sufficient accuracy using simple limit equilibrium calculations. Deformations are the strains that occur in the surrounding soil and the movement that accompanies the strains. Finite Element Analyses is often used to evaluate deformations especially when ground movements are particularly important (Cane, 2013).

Design Process
There are major analysis methods that are used in the design of the retaining walls. The difference between the two in application of the earth pressure. The two methods are described in the below:

a. Conventional method: This requires the designer to manually calculate the earth pressure and to apply the earth pressure to a wall. It utilizes Terzaghi and Peck (1967) and Peck (1969) formula. This method involves a lot of calculations and is mostly suitable for shallow excavations. It is highly conservative and implementation of this design is expensive.

b. Numerical analysis: The design is applicable through software application and involves creation of a finite element mesh and assignment of a constitutive model to soil. The software calculates the stresses, strains and forces in the structural element and the soil. This method is suitable to shallow and deep excavations. Numerical analysis ends up with an optimum design that is much more economical to implement.

Assessment of Deep Excavations
To identify the buildings and infrastructure that will be influenced and to what extent, an assessment of the building damage is usually performed. This assessment generally consists of the following steps:

1. Determine green field displacements.
2. Impose displacements onto building.
3. Assess potential damage.
4. Design measures if necessary.

Trends in construction of deep excavations include deeper excavations, and situated closer to buildings, this study aims to improve the methods to assess building damage related to deep excavations.

Selection of types of retaining walls and support systems.
Support systems for deep excavations consist of two main components. The first is a retaining wall. The second component is the support provided for the retaining wall (Bentler, 1998). The combination of these two components affect the efficiency of using a particular excavation support system. Various types of retaining walls and support systems can be adopted for deep basement construction. The selection usually made on the basis of:

- Foundation of adjacent properties and services
- Design limits on walls
- Subsoil conditions and groundwater level
- Working space and site constraints
- Cost and time of construction
- Flexibility of the layout of the permanent works

<table>
<thead>
<tr>
<th>Clay</th>
<th>Shear strength for loads on retaining structure and stability of excavation bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity testing to assess the strength and stability and the possibility of reusing material as a backfill</td>
</tr>
</tbody>
</table>

Table 2: Summary of typical site investigation requirements for idealized soil types (Cobb, 2009).
Foundations of adjacent properties and services is an important criterion in determination of the selection system.

Deep excavations in urban areas have the increased complexity of interacting with existing infrastructure. The removal of portions of a building during demolition or excavation usually results in making other parts unsafe, and it is therefore necessary to make a careful survey before commencing work to decide which portions will need securing before demolition commences. If the building adjoins other buildings it will have to be ascertained and agreed with the adjoining owners whether the walls are party or external walls. In either case, the adjoining buildings need to be given such lateral support as is given by the building to be demolished, and it is often advisable to erect the requisite shoring before demolition proceeds too far. Care should be taken that such shoring is placed in positions that will not interfere with the erection of a new building (BS 8004, 1986).

Factors affecting the efficiency of the support

More than several types of in-situ walls are used to support excavations. Ergun (2008), outlines the criteria for the selection of type of wall as size of excavation, ground conditions, groundwater level, vertical and horizontal displacements of adjacent ground and limitations of various structures, availability of construction, cost, speed of work and others. One of the main decisions is the water-tightness of wall.

However, a more widely used consideration are as published in the CIRIA that emphasize on the need for support systems to provide a free space to allow movement in the excavation site (Twine & Roscoe, 1999). These factors are:

- Width of excavation
- The number of times props will be moved
- The ease with which materials can be excavated
- Limits placed on walls and ground movements
- The distance that the props will span across the excavation
- The ease of fabrication of props
- Availability of props
- Buildability

Classification of Excavation Support Systems

Excavation support systems may be classified according to how they produce stability. These excavation supports therefore fall into three main groups:

1. Gravity Walls
2. Embedded Walls
3. Reinforced and anchored earth.

Gravity Walls

Masonry Walls

They are typically used for the retention of fill and embankments. The compaction of the fill normally results in higher earth pressures and structural stresses

Reinforced Concrete Walls

These are used for small excavations.

Ground movements due to compressible soil beneath the wall leads to rotation of the wall.

Driven Sheet-Pile Walls

Sheet pile is a thin steel section which are manufactured in different lengths and shapes like U, Z and straight line sections. Commonly used for water bearing soils.

Contiguous bored-pile walls

In contiguous bored pile construction, spacing between the piles is greater than the diameter of piles. Spacing is decided based on type of soil and level of design moments but it should not be too large, otherwise pieces of lumps etc. drop and extra precautions are needed. Cohesive soils or soils having some cohesion are suitable. No water table should be present. Acceptable amount of water is collected at the base and pumped out. Waling beams are mostly reinforced concrete but sheet pile sections or steel beams are also used.

Secant bored-pile walls

Secant bored pile walls are formed by keeping spacing of piles less than diameter (S<D). It is a watertight wall and may be more economical compared to diaphragm wall in small to medium scale excavations due to cost of site operations and bentonite plant. There is also need for place for the plant. It may be constructed “hard-hard” as well as “soft-hard”. “Soft” concrete pile contains low cement content and some bentonite. Primary unreinforced piles are constructed first and then reinforced secondary piles are formed by cutting the primary piles. Pile construction methods may vary in different countries for all type of pile walls like full casing support, bentonite support, continuous flight auger (CFA) etc.

Diaphragm walls

Diaphragm wall provides structural support and water tightness. It is a classical technique for many deep excavation projects, large civil engineering works, underground car parks, metro pits etc. especially under water table. These reinforced concrete diaphragm (continuous) walls are also called slurry trench walls due to the reference given to the construction technique where excavation of wall is made possible by filling and keeping the wall cavity full with bentonite water
mixture during excavation to prevent collapse of the excavated vertical surfaces.

**Reinforced and anchored earth**

**Reinforced earth wall**

This is soil whose structural properties have been strengthened by use of chemical additives such as lime or by other structural supports.

**Soil nailing**

Hole is drilled, ordinary steel bars are lowered, and grout is placed without any pressure. Soil should be somewhat cohesive and no water table or significant water flow should be present.

**Ground anchors**

Ground anchor is a common type of supporting element used in the design and construction of in-situ retaining walls. It is an installation that is capable of transmitting an applied tensile load to a load bearing stratum which may be a soil or rock.

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diaphragm/slurry wall</td>
<td>• Constructed before excavation and below ground water level.</td>
<td>• Large volume of spoils and disposal of slurry.</td>
</tr>
<tr>
<td></td>
<td>• Suitable for most soils.</td>
<td>• Very expensive.</td>
</tr>
<tr>
<td></td>
<td>• Relatively high stiffness</td>
<td>• Not suitable when adjacent to shallow spread footing.</td>
</tr>
<tr>
<td></td>
<td>• Can become part of the permanent wall</td>
<td></td>
</tr>
<tr>
<td>Sheet pile wall</td>
<td>• It can be constructed before excavation and below Ground Water level.</td>
<td>• No driving through fills, boulders.</td>
</tr>
<tr>
<td></td>
<td>• Soft to medium stiff soils</td>
<td>• Vibrations and noise.</td>
</tr>
<tr>
<td></td>
<td>• Quick placement and removal.</td>
<td>• Joint sealing.</td>
</tr>
<tr>
<td></td>
<td>• Low initial cost.</td>
<td>• Possible large lateral movements.</td>
</tr>
<tr>
<td>Soldier pile and lagging wall</td>
<td>• Low initial cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Easy construction</td>
<td>• Lagging cannot be installed below Ground Water Level.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Not usable in soils with base instability.</td>
</tr>
<tr>
<td>Secant Wall/Tangent Pile wall</td>
<td>• It can be constructed before excavation and below ground water level.</td>
<td>• Equipment cannot penetrate boulders; predrilling may therefore be required.</td>
</tr>
<tr>
<td></td>
<td>• Low vibration and noise</td>
<td>• There must be continuity between piles.</td>
</tr>
<tr>
<td></td>
<td>• Wide flange beams for reinforcement</td>
<td></td>
</tr>
<tr>
<td>Micropile wall</td>
<td>• It can be constructed before excavation and below the ground water level.</td>
<td>• Large number of piles are required</td>
</tr>
<tr>
<td></td>
<td>• Useful especially in built up areas with constricted space.</td>
<td>• Continuity must be there for the wall to be effective.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low bending resistance.</td>
</tr>
</tbody>
</table>

Table 3: Properties of commonly used excavation support systems.

### 4. CASES FROM LITERATURE

The cases in this chapter were selected for the insight they provide in the soil-structure interaction caused by deep excavations. To determine the behaviour of buildings due to excavation induced deformations the main aspects are related to the soil structure interaction. How the building reacts to the soil displacements and the presence of the building itself influences the surrounding soil? To analyse this problem, documented cases in which both ground deformations and building deformations have been measured were collected. These cases show aspects of the relationship between deformation of the building and damage occurring.

**Francis Xavier Warde School, USA**

The Francis Xavier Warde school is in Chicago, United States of America. Adjacent excavation for the renovation of Chicago Avenue and State Subway station affected the structural integrity of the school buildings. Finno et al. (2002) described the observations made during the excavation process. The reaction of the building to soil displacements and the influence of the presence of the building itself influence the surrounding
Description of the project

Figure 3: Plan view of the Chicago and State excavation.

The construction at the site was separated into three stages; wall installation, support system installation and excavation and station renovation and backfill.

Charter Station, Hong Kong

Description of the project

The construction of Charter Station, part of the Hong Kong Mass Transit Railway in the years 1976-1980 was performed in a congested urban area of reclaimed land. Old colonial building and new high rise blocks were nearby. Ground conditions are known as poor, with loose reclamation fill and marine deposits overlying a layer of silty sand. At about half way the excavation depth the top of a layer of decomposed granite is found. High water tables are present in the area. The excavation involved was 27 m deep, 400 m long and about 20 m wide. Diaphragm wall of 1.2 m thick were constructed, after which the roof was made.

Buildings were situated at small distance (few meters) of the older buildings and even closer to the high-rise blocks. The Courts of Justice building is founded on timber piles under individual footings. Depth of the pile foundation is about 16 m. The Prince’s Building and the Mandarin hotel are founded a concrete slab with driven piles to 19 m. Swire House, 22 storeys high, is founded on small individual pile caps with 6 driven piles each reaching into the decomposed granite at 15-18 m below ground surface.

Final deformations

Final deformations for the Courts of Justice building are presented in the figure below. The final settlement of the building is 4.5 times the wall deflection and 0.7% of the excavation depth. These high values relate to the drawdown and diaphragm wall installation rather than the excavation itself.

Nicoll Highway Collapse, Singapore

The Nicoll Highway collapse was a severe construction that occurred on 20th April, 2004 in Singapore when a deep excavation under construction collapsed. The project was a cut and cover excavation. The tunnel was part of construction of an underground Mass Rapid Transit Line near the Nicoll Highway MRT Station. The supporting structure for the deep excavation work failed. The collapse killed four people and injured three.

Photograph 3: Overview of the collapse of Nicoll Highway (Asianews, 2004)

The conclusions of Simpson et al. (2008) and Whittle and Davies (2006) were studied to give an overview of the different causes and opinions about the accident.

Description of the Project

The excavation was being carried out within a diaphragm wall supported by steel struts and jet grout slabs. The width of excavation is about 19.85m and the depth about 33.5m. The excavation was situated in an area of reclaimed land with over 40 m of soft marine clay present and a ground water table only 0.2 m below the surface.

Cause of collapse

The official report (COI, 2005) concluded that the collapse occurred as a result of two primary errors:

- The under-estimation of the soil loads applied to the diaphragm wall which was calculated using method A.
- The under-design by a factor of 2 of the strut-waler connection at level 9, and the inability of the overall system to redistribute loads after its failure. The under-design was independent of the under-estimation of soil loads as it arose from the omission of assumed splayed ends to the struts and a misinterpretation of BS5950, but had the effect of eliminating any spare capacity (Korff, 2009).

There were also a number of significant contributory factors, most extensively explained by Simpson et al. (2008):
• Failures in data collection
• There was a lack of design reviews to modify or verify the design as was necessary.
• The back analysis process was inadequate
• Triggers levels were not set.

University of Nairobi Towers
This was a 22 storey tower located in the heart of Nairobi Central Business District. The site of the building was a relatively built up area with relatively soft soils. Nairobi is underlain by volcanic materials that resulted from the formation of the rift valley (Mwea, et al., 2011). The combination of these two factors made the supporting of the deep excavation of the two towers made supporting of the deep excavation problematic.

Conclusions from cases studies
1. Settlements are significantly influenced by the stability of the trench.
2. Installation of several panels close to each other or in a short time or in high ground water pressures during construction will increase the ground displacements behind the wall.
3. Most damages to buildings can be explained by the curvature of the building. Relative rotation and deflection ratio give similar results as indicators of damage if they are calculated in a similar way.
4. From the failure of the Nicoll Highway collapse, the lesson learnt is the importance of interpretation and monitoring data, need for design review teams and proper construction management methods.

5. DISCUSSION OF RESULTS
Based on the cases investigated in this study the author has summarized the possible technical issues that often forgotten or ignored or wrongly calculated. In the design stage and in the execution phases, starting from the simple equation of earth pressure theory to the implementation of sophisticated finite element software.

Factors leading to failure
Cohesion factor in the earth pressure formulas.
\[ \sigma_h' = K_a \sigma_o - 2c \sqrt{K_a} \]
\[ \sigma_h' = K_p \sigma_o + 2c \sqrt{K_p} \]

Where symbols have their usual notations.

The c value in the above formula reduces the active earth pressure and increases the passive earth pressure hence overestimating c results in unsafe conditions. In soft soils, as in the case of the Nicoll Highway collapse, c = 0.

For deep excavations, the passive earth pressure calculated by the Coulomb theory shall be overestimated and it is therefore prudent to use the earth pressure coefficient derived by Caquot and Kerisel (Gouw, 2009).

Water Pressures
Fluctuation of ground water tables must be investigated. In an area where the rain intensity is high, the difference within the rainy and dry season can be as high as 10m. Proper measurement should be done by installing observation wells and piezometers, best installed in every significant layer of soils. The measurement should span over the rainy and dry season. By employing this method, the correct water table during the dry and rainy season can be identified (Gouw, 1994).

Seepage Force
Seepage of ground water toward the excavated area is of great importance and is often overlooked. The mode of seepage depends on whether water can pass through the retaining wall or not. For open cut excavations and retaining walls systems where water can flow through the wall, the stability of the excavation shall be seriously impaired if the ground water is allowed to flow through the slopes or the walls. It is very important to prevent the ground water from flowing out through the slope of the open cut excavation or through the retaining wall system. Dewatering wells should therefore be installed at the perimeter of the excavation areas (Gouw, 1994).

For excavations with impervious retaining walls such diaphragm wall or secant piles, where the toe of the walls is located in permeable soil layer means that water can seep from outside into the excavation area through the permeable soil layer. The ground water seepage creates seepage force which increases the effective overburden pressure in the active sides of the walls and reduces the effective stress in the passive side of the walls. The implication of this is that the lateral pressure in the walls in increased and the passive pressure is decreased which subsequently induces piping and boiling (Gouw, 2011).

If the retaining wall is embedded into an impermeable layer, there will be unbalance water pressure within the active and passive sides. The base of the excavation will then be subjected to an uplift force. It is important to consider the uplift force if the base and walls of the excavation are impermeable (Gouw, 2011).

Artesian Water Pressure
Existence of artesian water pressure can greatly affect the stability of an excavation. The weight of the soil from the excavation level to the top of the aquifer layer and the friction of the soil-wall system should be able to withstand the artesian pressure, otherwise the base of the excavation shall fail. This type of failure is known as bursting or boiling.

Soil Flow
When soldier piles system is used as the retaining structure for soft soils, soil flow through the gaps within the soldier piles may take place. This phenomenon may affect the stability of the adjacent structures. The gaps...
within the soldier piles must be close enough to ensure the formation of arching where the soft soils cannot penetrate or squeeze of the gaps.

Heaving

This phenomenon occurs due to the of the soil columns, of 0.7 excavation width, at the sides of the excavation pushing inward from the bottom of the excavated area. If the bearing capacity of the soil beneath the excavation area is unable to withstand the soil column weight, then heaving failure can take place.

Geotechnical Software

In recent developments, with the advance of computer technology, computer applications have gained popularity and are being used in geotechnical analysis and design. However, wrong use of the software results in wrong results obtained from the computer. This principle is known as Garbage in, Garbage out. Some of the reasons that results in incorrect design and analysis are:

- Wrong application of the soil model
- Wrong adoption of soil parameters
- Wrong modelling of undrained parameters

Design Process

To conclude, it may be useful to go through the design steps the subject of which are the sections of the chapter:

1. An office and site study on buildings and underground facilities around the excavation pit is required especially for possibility of interference of anchors and nails with adjacent basements and facilities.
2. Photographs or videos of adjacent buildings, streets and other details are taken before excavations start. Any cracks, depressions etc. should be recorded, and they may be needed in future conflicts with the owners or municipality.
3. Instruments planned to be used are ordered and installed before excavation starts.
4. Soil profile, soil properties, groundwater level, depth of excavation, availability of certain wall types and construction details of structure are altogether considered to select type of wall and support system.
5. Dewatering and drainage works are planned if any.
6. Depending on the method of analysis to be used either required soil properties and water level are input or earth and water pressure diagrams are specified. If soils are represented by springs subgrade coefficients are selected.
7. Support levels and horizontal spacing are selected for the first trial and so the support and wall properties.
8. Initial solution for shears, moments, support reactions, displacements are obtained, and necessary changes are made before the second trial.
9. From few to several trials are made in stages (staged solutions) before finalize the wall, supports and spacing.
10. External stability calculations are performed.
11. Anchor or strut connections to waling or breasting beams are designed.
12. During construction if any excessive horizontal and vertical displacements or support reactions are recorded at a stage, diagnosis is made, and required changes or revisions are made in design and/or construction.

6. CONCLUSION

At the end of this study, the researcher concluded that the mechanisms causing damage to existing structures adjacent to deep excavations are the loss of lateral system.

The design methods for quantifying the forces in deep excavations include empirical methods, limit equilibrium and finite element analyses. Finite Element analyses and Empirical methods are the common methods used. Nonetheless, due to the demand for the taller structures with deep excavations and the growth of technology, deep excavations are more commonly used. Empirical methods are used in shallow excavations whereas Finite Element Analyses are more suitable for deep excavations.

The researcher gained insight into mechanisms of soil-structure interaction for buildings adjacent to deep excavations. The simulation of the University of Nairobi towers with the application of this study shows the knowledge gained from this study.

The procedures for design and mitigation measures employed in supporting deep excavations are use of retaining walls and anchored walls.

7. REFERENCES

5. COI, 2005. Report of the Committee of Inquiry that led into the incident at the MRT Circle Line Worksite that led to the collapse of the Nicoll Highway on 20 April 2004, Singapore: Ministry of Manpower.
6. Coulomb, C. A., 1776. An attempt to apply the rules of maxima and minima to several problems of...


