Risk Modelling and Supporting Techniques for Deep Excavations in Metropolitan Locations

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Abstract

Construction is crucial to a country's overall economic growth, particularly in developing countries, in the current era of globalization. If construction operations are not carried out strictly according to a local or national building code, they might result in large-scale failures endangering human lives, personnel property, and the economic balance. It is vital to handle the construction process's risk elements. The self-weight of soil and surcharge loading behind the retaining line is the driving force and the shear strength of soil is the resisting force as a result, deep excavations invariably cause lateral and vertical ground deformations. As a result of the produced ground deformations, nearby structures and services become kinetically loaded. Risks associated with ground movement cannot be calculated solely using mathematical predicting models and engineering simulations as it needs to address the uncertainty of soil properties, Geo-materials, ground constitutive nature, building stage modeling, three-dimensional impacts of deep excavations, time-dependent natures of ground deformations, and the critical necessity to include human variables such as craftsmanship into prediction models are all important considerations. This article presents a review of the most effective methods for evaluating hazards related to deep excavation and current mitigating techniques. Theoretical approaches to enhancing the safety of deep foundation excavation are examined in the context of a hospital building in Khartoum state and a residential district project in southern Jianxi province.

Keywords
Deep Foundations, Risk Assessment, Globalization, Hazards and Geo-Materials.

1. Introduction
The use of below-ground space in the development of congested urban areas for various reasons, such as transportation tunnels, is becoming increasingly popular across the country. Parking garages, basements, and utilities are all underground. Many plans to use the underground were highlighted by El-Nahhas. Deep vertical excavations and subterranean tunnels are required for such ambitious projects, which are frequently near existing structurally susceptible buildings and utilities (Nahhas, 2006). The amount and direction of the generated deformations are dependent on the building's closeness to the excavations, as shown graphically in Figure 1. Ground movement prediction and management around these construction pits are critical during the planning and construction phases of these excavations to protect the surrounding structures from current and future activities as the project progress (Nahhas, 2006).

The advancement of science and technology in the construction sector, as well as the emergence of multiple fast-growing economies throughout the world, has resulted in a decrease in the time necessary to finish a project and an increase in the quality of construction. The foundation of a building project is critical for determining the structure's stability. Extensive foundations, which are frequently used in commercial structures, need extensive excavations

(Mair et al., 1996). The stability of large-scale excavation is critical to the project's progress. The quality of a building's foundation affects its quality, either directly or indirectly. As a result, it is critical to identify and manage the hazards associated with deep foundation construction. The soil conditions and the foundations of the surrounding built environment have a direct effect on the stability of a foundation. Risk management is the act of identifying potential hazards and mitigating or eliminating them to maintain a specified degree of safety throughout the project (Fok, 2012). A variety of elements, including wall stiffness, ground conditions, hydrogeological conditions and control methods, excavation depth, construction sequences, and craftsmanship, can all affect excavation-induced deformations. TR26: 2010: Technical Guide for Deep Excavation is a deep excavation design reference. It necessitates a thorough examination of the potential impacts of deep excavations on the surrounding area, particularly structures near the excavation sites. This evaluation is an essential part of the risk management process when planning temporary excavation activities (Zhang et al., 2021).

2. Literature Review

According to earlier research, the main culprit behind the failure of diaphragm wall in metro projects is the displacement. It has caused various environmental problems, including fractures in neighboring structures and related settlement of ground (Ou et al., 1996; Ng et al. 1998; Hsieh et al., 2003) Recent advances in the management of diaphragm wall deflections have been made by researchers. About 300 well-known instances of deflection of diaphragm wall because of deep excavations has been presented and studied by Long to identify trends and patterns (Long et al., 2001; Zhang et al., 2021). He studied the behavior of walls on the soft soils of shanghai. The study focused on analyzing wall deflections of multi strutted supporting systems. He included a thorough analysis to identify how the wall deflections and depth of excavations are related.

Strom and Ebeling showed that secant, tangent and contiguous support systems fall under constrictive type including concrete and slurry walls. On the other hand - Trailing, soldier beams and sheet pile support are considered to be dynamic connections. Condition of being prone to rigid and pilable body deformity arises because most walls are neither completely stiff or pilable. Steel sheet piles are widely recognized for their ability to flex even though diaphragm walls also bend significantly. For instance, when transverse supports are added, bracing wall that was built to prevent the ground below neighboring structures from shifting may initially only make minor horizontal displacement at the level of connection, even though it bends amongst them. Nevertheless, the structure will inevitably bend laterally both during and following the building stages (Maher et al., 2022). A number of variables affecting the displacement of diaphragm walls made of clay was investigated by Wong using the finite element approach. The study concluded that the rigidity of the wall plays a crucial role in it's deflection. The interdependence of motions of wall and ground were investigated by Moormann, key variables were identified that effected the behavior of excavations (Xiao et al., 2018). Although various scholars have contributed to identify the nature and variables affecting wall deflections, a relatively small amount of research has gone into determining the factors that leads to the deflection of walls or failure of supporting techniques in deep excavations via a risk modelling approach.

3. Risk Management Process

Throughout the life cycle of a project, the risk management process is a systematic means of finding, analyzing, and responding to risk events with the least amount of money spent to achieve the best or acceptable level of risk control (Fok, Neo, Veeresh, Wen, Goh 2012). Different phases involved in the model -

•Hazard Identification
•Risk Assessment
•Risk Control
•Risk Monitoring

Because each site has distinct soil conditions and soil characteristics, there is no hard and fast rule for how to implement risk management measures. It is the expertise of the designer and constructional professional to identify the potential hazards as per the given soil conditions (Table 1).

Table.1 Risk assessment matrix (Fok et al., 2012)

		Severity Category			
Risk Category		Cataclysmic	Serious	Minimal	Insignificant
Frequency Category					
	Intermittent	A	A	A	B
	Apparent	A	A	B	C
	Incidental	A	B	C	C
	Unlikely	B	C	C	D
	Rare	C	C	D	D

2.1 Hazard Identification
The very first step in the model is Hazard Identification. A hazard is any source of potential damage, harm, or adverse health effects on something or someone (Mair et al., 1996). Risk is the probability of a hazard manifesting in the work environment (Fok et al., 2012). It's a never-ending process, and risks might arise at any time throughout a project. The various periods when risk can manifest at a construction project are listed below -
•During design and implementation.
•Before important tasks.
•During activity.
•After Near Misses or Minor Events.
Different types of soil have different stress-strain relationships. It has been noticed in past years that many excavation slopes collapse without prior warning resulting in loss of property, serious injury, or even death. Excavations are prone to a variety of hazards. The collapse of sides, proximity to nearby structures, and wall deflection more than predicted are to name a few.

3.2 Risk Assessment
The selected hazards are extensively researched based on their probability of occurrence and consequences in this phase of the risk management model, and a risk matrix is developed by investigating the causes and magnitude of failure in the past. Potential risks are grouped in this matrix based on the frequency with which they occur and the severity of the accident. They are then graded on a scale of A to D. In an ideal circumstance, all identified concerns at a given location would be reduced to a C or D rating.

3.3 Risk Control
Depending on the nature of the potential hazard, this phase entails taking steps to remove, mitigate, or prevent it. During the design process, for example, risk avoidance can mean realigning a public/commercial structure away from an existing structure. By demolishing an older structure in the vicinity, the risk would be eliminated. Applying steel sheet piles to support the earth excavation operation or reinforcing a building's foundation that may be harmed during the excavation process are examples of risk mitigation. All of these strategies include an exhaustive study of numerous alternatives, as well as the criteria for selecting the best one. Cost, duration, and desired project function are some of the elements that must be considered during the selection process (Burland et al., 1997). As previously stated, it is a continuous process that begins with design and continues well beyond the start of construction. Regularly, the contractor may be needed to do additional operations (Fok et al., 2012), (Burland et al., 1997). Certain precautions, such as a supervising plan or the use of correct equipment, can help reduce the risk of certain dangers to an acceptable level.

3.4 Risk Monitoring
Risk monitoring is an important phase of the risk management model. This stage ensures that the identified and assessed risks are maintained at an acceptable level throughout the construction process and that the assessment is consistent as the activities progress. The mitigation measures that must be adopted during construction to decrease risk to acceptable levels are taken and followed through until the activities are completed or the related hazards are no longer present (Fok et al., 2012). During construction, instrumentation work is a crucial component in assessing the danger of construction to buildings. The findings of the instrumentation should be interpreted concerning the construction activities on-site, and the data of different instruments should be compared and connected to gain a better understanding of the ground's behavior.

Ground deformations are the notorious consequences of deep excavations. Due to a sudden decrease in the minor stress or the confinement pressure around the excavation trenches, the soil mass tends to deviate laterally (Hui, 2014). They may also occur due to a sudden decrease in water table I.e an increase in effective stress. Vertical deformations are usually downward (settlement); but, occasionally upward deformations (heave) can be seen next to the retaining wall or at a great distance from it. Despite recent advancements in analyzing the stability of excavations and the consequences of excavations on surrounding properties, structures, or highways close to excavations continue to fail. Figure 1 depicts a current example of a failure case history of a collapsed 13-story skyscraper in Shanghai, China, caused by toppling (Hui, 2014).

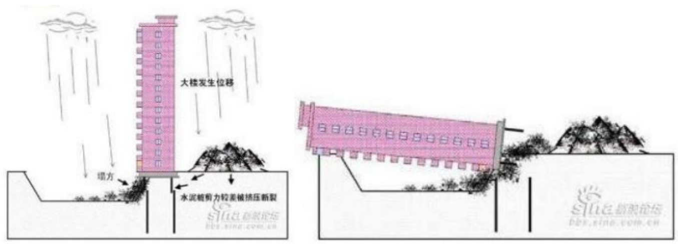

Figure 1. Failure of a building in china instigated by a nearby excavation work (Hight et al., 2004)

Another well-known failure in history due to a lack of geotechnical knowledge is the Nicoll Highway in Singapore (Figure 3), which was caused by insufficient site studies, misunderstanding of findings, flaws in the bracing system design, and the use of an inappropriate technology for wall strutting by jet grouting (Whittle et al., 2006). Much more common than breakdowns are serviceability issues caused by considerable foundation settling and lateral deformations caused by extensive excavations (Horodecki, 2007). Due to the generated deformations, the structure may face distresses such as structural or architectural element fracturing, uneven flooring, or unusable windows and doors (Clough, 1990). The number of acceptable deformations and the degree of earthwork-related damages are determined by the type, configuration, and stiffness of the building, as well as the parameters of the excavation support, soil conditions on the ground, and the sequence of construction. To avoid structural damage, geotechnical and structural engineers must collaborate to determine the amount of building settlements, assess the risk of structural damage, and design countermeasures and risk mitigation techniques. It has been observed through the research done in the past that the settlements or deformation of soil around excavation pits hugely depend upon the type of soil i.e in-situ soil conditions. Peck explained the correlation between these elements in Figure 2. Based on soil characteristics, he proposed three zones of settlement profiles (Puller, 2003).

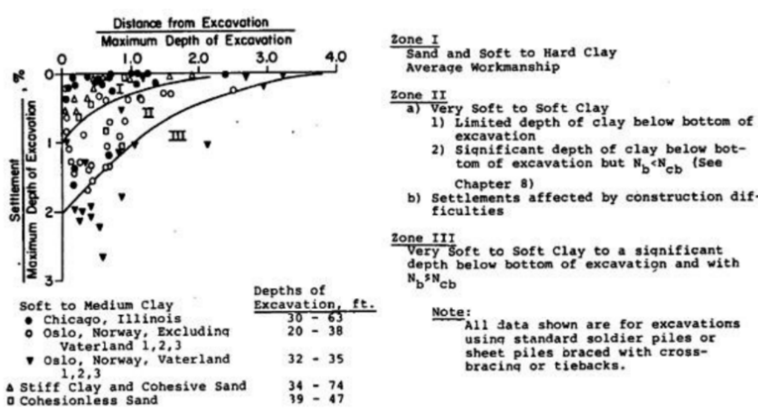

Figure 2. Variation of ground deformation with soil type (Peck, 1969).

Excavations in soils with lesser strength and stiffness cause higher wall deflection and ground deformations in general. Many following study attempts confirmed the influence of soil type on the defamations caused by deep excavations](e.g, Clough & O'Rourke; Goldberg et al; Bentler; and others). The average maximum horizontal wall deflection for excavations in sand or hard clays is 0.19 percent H, whereas the average maximum horizontal wall deflection for soft to stiff clays is 0.45 percent H, where H is the depth of excavation. In sands/hard clays, the maximum settlement averages 0.22 percent H, whereas in soft-stiff clays, it averages 0.55 percent H. The ratio of maximum vertical settlement to maximum wall deformation is usually between 0.5 and 1 as demonstrated by Bentler 1998.

4. Supporting Techniques for Deep Excavations

In metropolitan locations, it is common practice to support deep excavations with continuous walls to prevent induced disturbances and, as a result, associated dangers. Deep excavation support systems are made up of two basic components: a wall in combination with various bracing options that supports it. Wall supports for Deep excavation may be classified as -

•Sheet Pile Wall
•Soldier pile and lagging wall (Berliner wall)
•Contiguous bored piles wall
•Secant piles wall
•Diaphragm wall
•Soil-mixing walls

4.1 Steel Sheet Pile

The behavior of deep excavation support systems is defined and evaluated using a variety of variables, including displacement of wall components and earth pressure distribution, movement of neighboring soil masses, and forces acting on lateral supports (Wendong, 2019). It is a common supporting technology for supporting deep excavations. Sheet piles are interlocking lengths of sheet materials driven into the ground to withhold the soil layers exposed due to excavation. Steel sheet piles are most prevalent but they can also be made of wood or reinforced concrete. These sheet piles are reusable i.e they can be pulled out from the ground and can be used in another site with slight modification. The high cost of installation and limited soil flexibility are major drawbacks of this supporting system (Zhang, 2021). Additionally, the following methods are frequently used to support deep excavations: diaphragm walls, pile walls (secant or tangent), and soil mix pile walls. The above-mentioned retention mechanisms are combined with a variety of bracing options, such as horizontal struts, corner struts, and anchor retaining systems. Some of the common uses of sheet piles are - used as retaining walls, landfilling process, underground construction, and maritime environments (Wendong, 2019). The interlocking mechanism of these piles requires skilled professionals for installation.

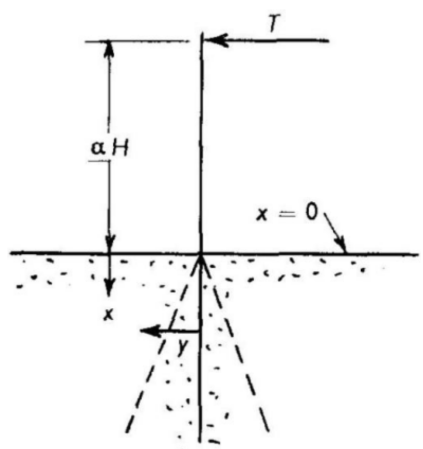

Figure 3. Cantilever pile subjected to line load(Rowe 1955).

4.2 Diaphragm Wall

Diaphragm walls are the most accepted supporting construction technique due to their ability to address multiple issues regarding the safety of excavation pits at the same time. They can also serve as permanent foundation walls and effectively obstruct the passage of groundwater. These are concrete walls with better water tightness than a secant wall due to the continuous nature of the structure. The typical lengths of these walls range from 3m to 7m but lengths change according to the site conditions and the width is 600-1800mm again varying with site conditions. Wall deflections and ground settlements must be carefully addressed during the design and construction of deep excavations, since their shape and size affect the safety of adjacent structures, particularly in metropolitan settings. Ground and wall motions are also connected in some excavations.

Numerous empirical relationships between wall deflections and ground settlements have been hypothesized in the works of literature by Ou et al. (1993), Bowles (1996), Hsieh, Ou (2006), Kung et al. (2007), and others. Thus, after determining the wall deflections, it is possible to calculate the ground settlements and evaluate the safety of buildings next to the excavation. Likitlersuang et al. (2013), Juang et al. (2013), Hsieh et al. (2013), Khoiri and Ou (2013), Finno et al. (2015), Orazalin et al. (2015), and Hsieh et al. (2015) all performed simulations to investigate the behavior of soil around excavation pits. Excavation reference envelopes have been created for a variety of excavation circumstances. During the early phases of excavation, it is discovered that wall deflection is approximately inversely proportional to the stiffness of the soil around the pit. In conclusion, altering wall thickness results in a small change in the reference envelope during shallow excavation, but this may not be true as the excavation progresses deeper.

4.3 Anchor Retaining Wall

This supporting technique uses an anchor rod and a retaining pile, which is usually built of concrete, to block the soil surrounding deep excavation trenches (Zhang, 2021). This type of support mechanism is adopted where the space is limited and the quality of the soil is poor. This technique is especially well suited to loose dirt on top of boulders. The retaining pile is driven sideways into the earth, the concrete ends provide the anchoring to the wall. The anchors act against the lateral pressure and overturning effect. The length of prestressed concrete anchors should be carefully chosen. If the length of the anchor rod is increased without a relative increase in bond strength, the load will be less and the system may become unstable (Zhang, 2021), (Xiaoyan, 2018). Because the setting of the anchor rod is not easily impacted by nearby subsurface buildings during the construction process, the anchoring power of the surrounding land may be significantly increased, and the supporting effect will be dramatically boosted as a result. The prestressed anchor may be utilized in the anchor-pull retaining structure on occasion.

4.4 Row Pile Support

There are 2 types of pile support. Soldier piles with lagging and Auger drilled cast-in-place piles. In the soldier piles with lagging steel beams are driven into the ground using vibratory drivers. Between the piles, different materials are used as fillers. The fillers carry the load from the soil and transfer it to the piles (Zhang, 2021). Various types of bracing mechanisms are available to provide additional lateral support. Anchors are mainly used for this purpose. Between the piles, reinforced concrete and shotcrete are primarily utilized as fillers. Auger drilled cast-in-piles are constructed by boring cast-in-place concrete adjacent to one another along the retaining line. Tailored to the needs of the location, several variants of this retaining system are used.

5. Case Study

The most common supporting technique for deep excavation are Diaphragm Walls. Diaphragm wall can be defined as reinforced concrete walls that is built underground. The primary material used for the construction of such walls are slurries mainly based on polymer or cement bentonite. The method entails digging of small entrenches that is continuously filled with slurry. This method allows the construction pf walls with thickness ranging from 300 to 2000mm thick to a depth of 80m. Other cross-sections besides rectangular such as T-shaped beams are also possible. In some circumstances, a thicker wall is required unless multiple supports employed to the thin wall. It might applied in to supplement the top-down approach. There are 8 processes in which the construction is carried out -

1. Initial Alignment Fix
2. Construction of Guide Wall
3. Trench
4. Trench Cleansing
5. Secure Stop-Ends
6. Deploying Reinforcement Formwork, Cage
7. Concrete Pouring
8. Removal of Stop-Ends

Bentonite in digging of trench is transported from silo to blender and mixed with water to create a slurry before being pushed by a centrifugal pump to slurry reservoir. Slurry is then pushed into the trench, where it is chopped up and combined with extracted dirt to form cut mud. This chopped mud is then transported via pumping to a solid control equipment to isolate the excavated dirt from the bentonite. The used bentonite is transported to a slurry tank where it is utilised to dig trenches once again and remove the excavation dirt. If there is rock present, a chisel weighing 1.5 to 3.5 tonnes is utilised to shatter it. Grabs are used to reach deep trenches for the diaphragm walls. Cable suspended grabs, pneumatic or hydraulic (Kelly) grabs, and hybrid grabs placed on a crane integrated together known as Clamshell may all be classified according to how they work. To facilitate penetrating the soil, the grab is constructed in such way that it's interlocks.

The heavy assembly of grabs often limit their usage to dense soil and are not preferred in relatively loose soils and hydraulic pressure affect the effectiveness of excavation. It is challenging to regulate lateral digging activity. When alternate excavation techniques are unavailable, a grasping crane is used. The grab is suitable for lengthy distances like deep excavations for diaphragm walls or if attached to extended boom, used across water. One can calculate the production of clamshells by multiplying the volume extracted in one cycle knowing the number of cycles per hour and grab fill factor and efficiency. The heaping capacity is used to quantify capacity per cycle. In Table 2, which notably highlights mass disparities vs. volumes of grabs, bare weight and capability ratings of medium weight cable grabs and hydraulic grabs are roughly compared.

Table.2 Differentiating medium rope grabs and hydraulic grabs

Capacity	m^3	2.0-2.5	1.75-2.25	1.6-2	1.5-1.75	1.1-1.4	1.0-1.25
Empty Weight	ton	2.4	2.35	1.8	1.75	1.37	1.35
Length	m	4.2	4.0	3.8	3.8	3.5	3.4
Capacity (HG)	m^3	3.04-3.48	1.77-2.25	1.6-2.0	1.5-1.75	1-1.5	0.63-0.98
Empty Weight (HG)	ton	20.5-21.2	17.3-19.3	16-17.5	16-17.5	15-16.4	13.6-14.8
Length (HG)	m	2.5-3.2	2.5-3.2	2.5-3.2	2.5-3.2	2.5-3.2	2.5-3.2

4.1 Hospital Building in Khartoum State

Excavation during construction has influenced the projects. The study included a field inspection of the site's condition as well as data collection on the design and any other relevant information. To aid in the identification of failures, a visual assessment of the location and pictures of the failed sections were obtained. The building consisted of six floors plus two basement levels in a 50 by 50 sq meter plot. Except for the north and west directions, which are enclosed by main roads, the project site is dominated on the other sides by branch roads.

Figure 4. Basement perimeter surrounded by shoring piles (Zumrawi et al., 2016).

A geotechnical survey was performed before the design which showed that the subsoil mainly consists of dense to very dense silty to clayey sand. The groundwater table was measured at 12 meters. Perched water was discovered at a depth of 6 meters during borehole digging. Rafts and piles were recommended for foundations (Gue et al., 2004). Excavation should be carried out to a depth of 8 meters, as planned. Before beginning any excavation, the contractor chose to install a shoring system consisting of 50 cm bored, cast in situ piles with an 8-meter length beginning at a depth of 5 meters. The reinforced piles 8m in length were cast in bored holes 13m in length. The consultant and contractor confidently installed shoring piles all around the perimeter with varying gaps ranging from less than 1 meter in some places, as shown in Figure 3. This was due to an undefined well-shoring item and a lack of attention to the groundwater table and dense soil layers (Gue et al., 2004).

The excavation for the basement was started and as the construction gradually progressed and the depth of the excavation reached 6m the perched water started flowing into the pit from all directions. The water collected started corroding the top dense layer of soil and cavities were formed behind the piles. To collect the running water, the contractor chose to dig trenches in front of the piles all around the perimeter and begin dewatering (20 hours/day pumps). The sand layer at 6 m deep was crushed by piling concrete, resulting in necks at that level. 11 piles on the east side of the plot had been sheared due to the allocation of necks inside the permissible line for retaining walls. The collapse had led to the fall of 1m long supporting soil. Lack of attention to the report from the geotechnical survey, the casting of shoring piles without appropriate control, and irregular gaps between them are the causes outlined for this failure (Gue et al., 2004).

4.2 Residential Project in Jianxi

The project building has 32 floors and 2 basement levels. The building is located in a residential district of southern Jianxi province in a suburban area. On the south side of the excavation, there are many resettlement houses and sewer pipelines. The perimeter of the pit is 180m and the bottom of the pit is 12m below the water table. The existence of relocation houses and pipelines is to hold accountable for the complex nature of the project and the increased rate of occurrence of accidents. Soil retaining systems discussed above are to ensure the safety of buildings around the foundation pit and for slope stability. It is been observed that safety accidents often occur during the construction of these retaining wall systems affecting the construction pace and loss of personnel property. The materials available in the suburban region are not enough and the initial design of the support mechanism is heavily dependent on the experience of the professional. Any minor flaw in the support design safety accidents of a relatively larger magnitude. An administrative penalty was imposed due to the disturbance caused by the accumulation of mud on public road surfaces during the construction of the diaphragm wall (Gaoxiang, 2018). A survey conducted on the people involved in the construction process revealed that the majority of the workers believe luck to be a major factor in determining the safety of the pit. The failure of construction schemes and safety measures as well as the personnel's lack of safety awareness are the main sources of accidents. To scale back or even eliminate the occurrence of safety accidents, it is necessary for every construction technician to strictly follow the building code, and development plan and take safety measures in each step to achieve a safe environment (Gaoxiang, 2018).

Because of the uniqueness and complexity of the surrounding environment and the project, as well as the high cost of steel sheet pile support and the soil's poor adaptation, the diaphragm wall support and row pile support with anchors were chosen for the project as they are least susceptible to the hydrological aspects and underground structures around the site. The Supporting techniques of deep foundation pits are varied in different sites and it produces different consequences. If we would like to offer full play to all or any of the functions of deep foundation pit support technology, we should always take the initiative to offer full play to the benefits of support technology, and judge the characteristics of the project intimately consistent with the development requirements and therefore the characteristics of the building itself, then choose the supporting method which is suitable for it. The analysis of the encompassing environment and therefore the hydro-geological condition should be taken because the key points within the analysis of the characteristics of the project, and therefore the support mode of the deep foundation pit should be adapted to the surrounding environment and hydrogeological condition (Xiaoyan, 2018), (Ou et al., 1993).

3. Conclusion

Even for shallow excavations, appropriate temporary earth-retaining structures should be constructed to protect the sidewalls of the excavation. The design should take into account the impacts of severe weather as well as the presence of existing foundations of structures Extra precautions should be taken when working close to an existing building and resettlement houses. Risk Management is a crucial stage in a project, having cost efficiency and safety of the environment as its primary objectives. To limit the damage of deep excavation works to nearby buildings, a building evaluation is an important aspect of the risk management process. The technique is given in Technical Reference 26: 2010 – Technical Reference for Deep Excavation (Singapore Standard 2010) provides designers with a good reference on how to conduct building assessments.

The supporting technology adapted in the construction of a deep foundation pit should be such that it avoids long-term effects on the environment or destabilizing existing structures around the excavation. It is vital to study and build the monitoring and management mechanism from all perspectives, paying special attention to the management of dust pollution and noise pollution in the surrounding environment, to protect people from the negative effects of production and life. To study the structural behavior of retaining walls due to soil-structure interaction and also monitor the structural health of structures near the excavation, a comprehensive study was presented. From the results obtained it can be stated that bracing or reinforcement mechanisms are necessary to provide constraint or limit the wall movement and deflections. An anchor retaining bracing mechanism is recommended to keep the effect of excavation on nearby structures to a minimum.

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