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Modelling and Stress Analysis of Shaft Work Subsidence of Underground Power Transmission Line Tunnel

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Abstract

This research presents an analysis of soil subsidence around shaft work under its construction process and drilling tunnel by finite element method (FEM). The study is focused on the underground power transmission tunnel in the Chao Phraya River construction project (Southern Bangkok Station to Suksawat Road, Thailand) of the Metropolitan Electricity Authority. This research aims to provide information for designing shaft work and preventing drilling tunnel problems. The research analyzed the soil subsidence around shaft work with 12 m of inside diameter and 1 m of thickness that located 33 m underground during constructing a tunnel chimney by sinking method. It is assumed that the analyzed horizontal reaction is the net resistance of the lateral earth pressure around the shaft work. This study found that the subsidence of soil around shaft work during the construction and drilling process had the value between 0.80 - 53.30 mm. In the part of the base slab, the soil subsidence value is between 3.40 - 16.00 mm. It can be concluded that the top of shaft work during the construction and drilling process had a soil subsidence value of 53.30 mm with δ_{max}/H ratio of 0.00162.

Keywords: Shaft work, Subsidence, Sinking the reinforced concrete method, Finite element method, FEM

Introduction

From statistics Bangkok has a rapidly expanding area making it the 5th largest urban area in East Asia and the population has increased at a rate of 2.0 % and is the 9th largest population in East Asia. At present, the development of urban communities in Bangkok and the perimeter to become the metropolis of the Association of Southeast Asian Nations (ASEAN) is causing a large number of people, communities, and buildings. Furthermore, the Metropolitan Electricity Authority has the policy to change the aerial cables to underground cables for improving the scenery, increasing stability, and supporting increased electrical power usage while the previous aerial electrical system could not increase an electrical circuit.

The Metropolitan Electricity Authority has an underground power transmission tunnel in the Chao Phraya River Construction (Southern Bangkok Station to Suksawat Road, Thailand) project which used to distribute electricity from the source station to the other side of the Chao Phraya River. In the construction process, it was necessary to construct a shaft work for connecting underground power transmission tunnels and also for sending and receiving tunnel. During the process of sinking a reinforced concrete tunnel chimney, there was soil subsidence around the shaft work that would damage nearby utilities and cause injury to people. Therefore, soil subsidence analysis around the shaft work is necessary for preventing problems while and after construction

As mentioned above, Srisathitwat [1] simulated the behavior of the soil lateral movement of Bangkok soil during the shaft work construction process by the finite element method. It was found that the optimum of δ_{max}/H ratio of the soil layers were approximately 500 for soft clay, 750 for medium-hard clay, 1000 for hard clay, and 2000 for very hard clay. Kaenpudcha [2] studied the behavior of the deep shaft work for the large drainage tunnels construction by the finite element method. It was found that the relationship of the horizontal soil reaction force and the vertical soil reaction force was about 30 % for soft clay, 25 % for hard clay, and 90 % for sandy soil. The δ_{max}/H ratio of shaft work movement effect was approximately 0.0005. Furthermore, Zhang *et al.* [3] designed a flexible inclinometer probe for model tests of landslide deep displacement measurement. The flexible inclinometer is verified with respect to its principle and arrangement by a laboratory physical model test, and the test results are highly consistent with the actual deformation of the landslide model.

There is also a research study on the behavior of movement and subsidence soil layer. By constructing tunnels and pushing pipes and assessing subsidence by finite element method. Zhou *et al.* [4] analyzed the vertical ground movement during large-scale pipe roof installation and artificial ground freezing of Gongbei tunnel. It shows that the ground settlement during pipe steel pipes is relatively small with a maximum value of 22.00 mm, provided by the fore-jacked pipes reduces the ground loss volume ratio and, consequently, the ground settlement during the follow-up pipe jacking. Wang *et al.* [5] performed numerical simulation to reveal the evolution of structural damage with an increased differential settlement of the damaged working shaft in South China including. The results show a good agreement with field observation in respect to the initiation of concrete tension damage. It is proposed that if a differential settlement higher than 5 mm is observed, preventative measures are needed and the risk is conditional acceptable. Study of Ong *et al.* [6] focuses on the ground responses caused by twin bored tunnelling under mixed-face soil condition and the implementation of building protection measures to the existing shophouses which the tunnel had undercrossed in mixed-face soil condition. Tippawan *et al.* [7] study the influence of the distance between the tunnel boring head and the surface subsidence of the parallel tunnel construction. It can be concluded that the distance between the tunnel boring head is influenced by the pressure in front of the tunnel boring head. In addition, Kunnarong [8] conducted a study the comparison of soil layers without conducting soil quality improvement and with conducting soil quality improvement by the vertical drainage system of Suvarnabhumi Airport runway construction. Khan and Das [9] study the Geological Information System (GIS) to make it easier for engineers to make decisions about storing drilling logs and soil data to the exact location of the borehole. and the selection of future sites to be constructed in that area. Jarosław *et al.* [10] study deep excavation and tunnelling works in city of old town centres, where the technical condition and structural stiffness of historical buildings is rather doubtful. Zhishu *et al.* [11] study used the Hongqinghe air shaft freezing project as an example to perform a numerical simulation and measurement analysis of the temperature field of shaft sinking via the artificial freezing method in Cretaceous strata. In addition, Qixiang *et al.* [12] study the coupled method of the field monitoring, the analytical formula, and the numerical method is used to evaluate the thickness and average temperature of the frozen zone field monitoring was conducted to measure the temperature of the brine and the ground.

Materials and methods

By studying of theories related to the analysis of soil subsidence around the shaft work in the construction process, the related theories and research are as follows.

Empirical analysis

Zhou *et al.* [4] explained and predicted the surface soil subsidence by Empirical analysis from the equation as follow:

$$S(x) = S_{\max} \exp\left[\frac{-x^2}{2i^2}\right] \tag{1}$$

$$S_{\max} = \frac{V_s}{\sqrt{2\pi i}} \tag{2}$$

where

$S(x)$ is the ground settlement at a distance x from the tunnel axis,

$S_{\max}$ is the maximum ground settlement above the tunnel axis,

x is the horizontal distance from the center of the tunnel (m),

i is the ground settlement trough width coefficient.

Evaluation value of ground loss and the greatest amount of soil surface subsidence

$$V_s = \eta \pi R^2 \tag{3}$$

where
V_s is unit ground loss,
η is the ground loss volume ratio,
R is tunnel radius (m).

Evaluation value of i

$$k = \frac{i}{z} \tag{4}$$

where
k is parameter,
i is the ground settlement trough width coefficient,
z is the burial depth of the roof pipe.

Finite element analysis

In the study of Wang *et al.* [5], finite element method is use to describe the deterioration of elastic stiffness under compression and tension respectively. The stress-strain relationship can be expressed by equations:

$$\begin{cases} \sigma = (1-d)\bar{\sigma} \\ \bar{\sigma} = D_0^{el}(\varepsilon - \varepsilon^{pl}) \\ \dot{\tilde{\varepsilon}}^{pl} = h(\bar{\sigma}, \dot{\tilde{\varepsilon}}^{pl}) \cdot \dot{\varepsilon}^{pl} \\ \dot{\varepsilon}^{pl} = \dot{\lambda} \dfrac{\partial G(\bar{\sigma})}{\partial(\bar{\sigma})} \end{cases} \tag{5}$$

$$\begin{cases} D_c - (1-d_c)D_0^{el} \\ D_t = (1-d_t)D_0^{el} \end{cases} \tag{6}$$

where
$\bar{\sigma}$ is the effective stress,
σ is the effective stress when damage,
d is the damage indicator,
D_0^{el} is the initial elastic stiffness matrix without damage,
ε and ε^{pl} is elastic strain and plastic strain respectively,
$\dot{\tilde{\varepsilon}}^{pl}$, $\dot{\tilde{\varepsilon}}^{pl}$ and $\dot{\varepsilon}^{pl}$ is the equivalent plastic strain rate,
$\dot{\lambda}$ is the coefficient of the non-associated flow rule in this plastic material model.

Analysis of soil subsidence around the shaft work by finite element method with the Midas Gen 2021 program yield criterion and plastic potential function for metals and for concrete in the high pressure range, the effect of hydrostatic pressure on the yield value of material may be neglected. It follows that shearing stress must be the major cause of yielding. The stiffness after yield point can be defined by hardening coefficient. The zero value of coefficient represents perfectly plastic or zero stiffness.

Methodology

This research analyzed the soil subsidence around the shaft work of underground power transmission tunnel in the Chao Phraya River Construction Project (Southern Bangkok Station to Suksawat Road, Thailand) of the Metropolitan Electricity Authority, as shown in **Figure 1**.

Chimney with 12 m of inside diameter and 1 m of thickness which located 33 m underground is shown in **Figure 2**.

Finite element method is also used to analyze the soil subsidence around the shaft work in sinking reinforced concrete shaft work and drilling tunnel process.

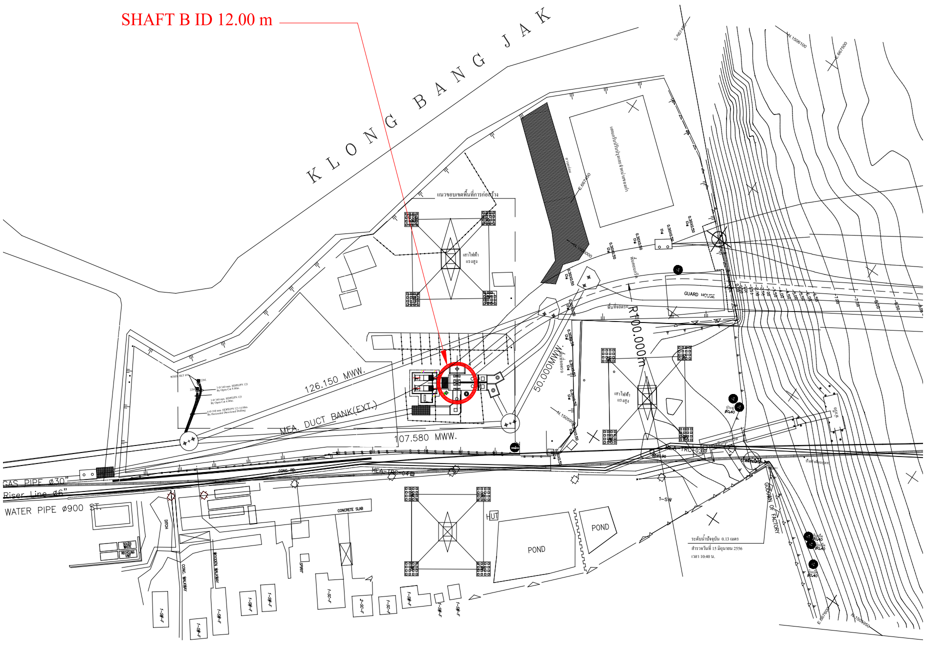


Figure 1 The plan of the construction area of the shaft work within the project.

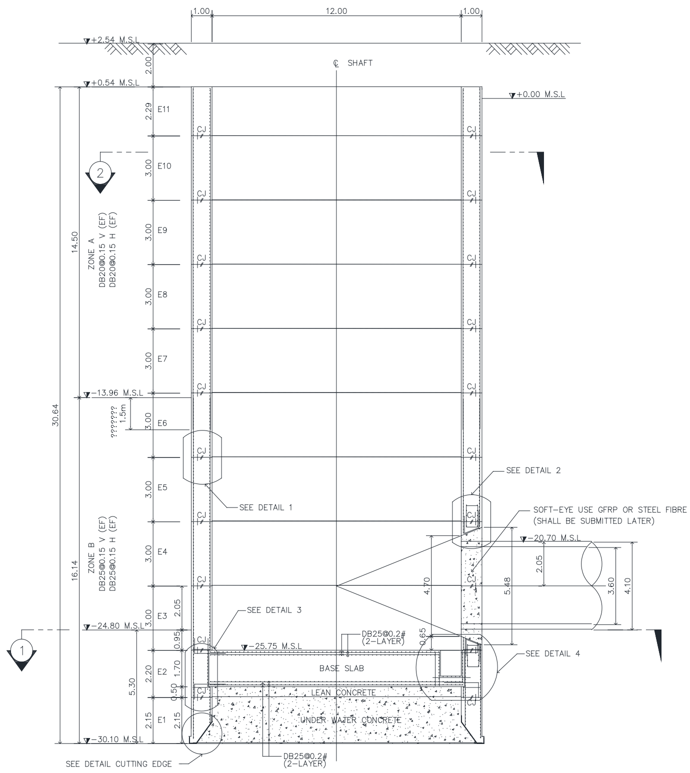


Figure 2 The dimensions of the tunnel.

The process of research

The process of this research is divided into four parts as follows:

1) Study techniques and methods of tunnel construction by sinking reinforced concrete shaft work system.

2) Study the characteristics and the properties of the soil layer in the construction area.

3) Study the parameters used for performing parametric studies for behavior analysis of the shaft work in sinking the shaft work and drilling the tunnel process by the Finite element method (FEM).

4) Analyze and summarize the results, including related recommendations.

Characteristics of soil layers and soil drilling data

The varied depth and the properties of soil layers in the underground power transmission tunnel construction area under the Chao Phraya River are listed in **Table 1**.

Table 1 Properties of the soil layer in the tunnel construction area.

Depth (m)	Soil layer	Traits found
−3.0	Ground water	It is ground water level.
0 - 1.0	Concrete coring	It is a road and concrete road floor.
1.0 - 16.0	Very soft to medium stiff clay	It is dark gray clay. The natural moisture content in the soil layer is between 49.3 ~ 79.1 % and the unconfined compressive strength is between 1.39 ~ 8.5 tons per square meter. Classified as the soil in group CH.
16.0 - 17.5	Stiff clay	It is gray clay The natural moisture content in the soil layer was 42.1 % and the unconfined compressive strength was 17.16 tons per square meter. Classified as the soil in group CH.
17.5 - 26.0	Very stiff to hard clay	It is a light gray and brownish-gray clay. The natural moisture value in the soil layer is between 25.2 ~ 34.5 %, the SPT-N value is between 20 - 34 times per foot, classified as the soil in the CH group.
26.0 - 36.5	Dense to very dense clayey sand, silty sand, trace grand	It is a gray and brownish-gray clay. The natural moisture value in the soil layer is between 22.6 ~ 28.1 %, the SPT-N value is between 32 ~ 56 times per foot, classified as SC, SM soil.

Analysis of soil subsidence around the shaft work by finite element method

This research studied the behavior of the shaft work in sinking reinforced concrete shaft work and drilling tunnel process by finite element method (FEM) with the Midas Gen 2021 program. The program uses the Mohr-Coulomb theory yield criterion is a generalization of the Coulomb's friction rule and is suitable for materials such as concrete, rock and soils, which exhibit volumetric plastic deformations. The results are presented as follows.

Model of the shaft work structure

A model of the shaft work structure was created to analyze the behavior of the reinforced concrete shaft work with the Midas Gen 2021 program. This model is formed by plate structure that is composed of 3 - 4 points. The direction of the axes is set between the minor axes (horizontal sub axis). The elements are combined to become the shaft work structure that consists of the shaft work wall and slab, as shown in **Figures 3** and **4**.

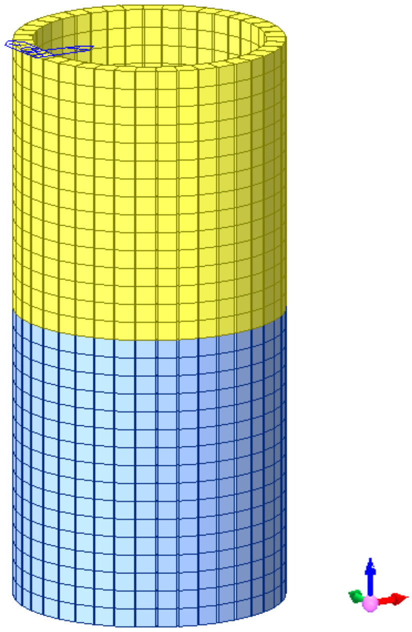


Figure 3 The model of the working shaft structure.

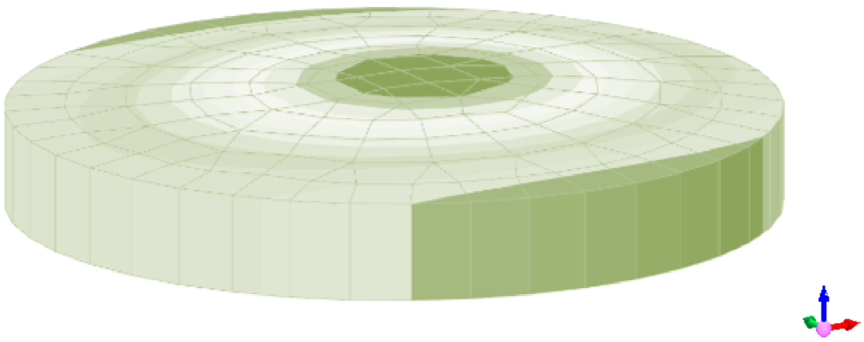


Figure 4 The model of the working shaft floor structure.

Characteristics of the analyzed shaft work support

Support at the shaft work slab

The bottom of the shaft work (Cutting shoe supports), shaft work vertical load and resists subsidence due to soil pressure around the shaft work are as shown in **Figure 5**.

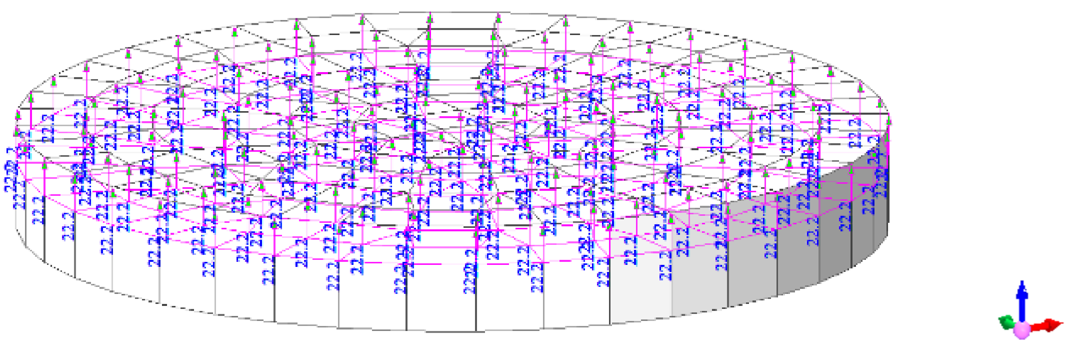


Figure 5 The support point at the shaft work slab.

Multilinear spring support is used to simulate soil resistance behavior in case of compression and tension by determining the load per the subsidence ratio (δ_{max} / H).

Considering reaction at the supports with ring shape of foundation structure which the vertical subgrade reaction, Ks. At any point of the structure (Node) can be estimated from Eq. (7):

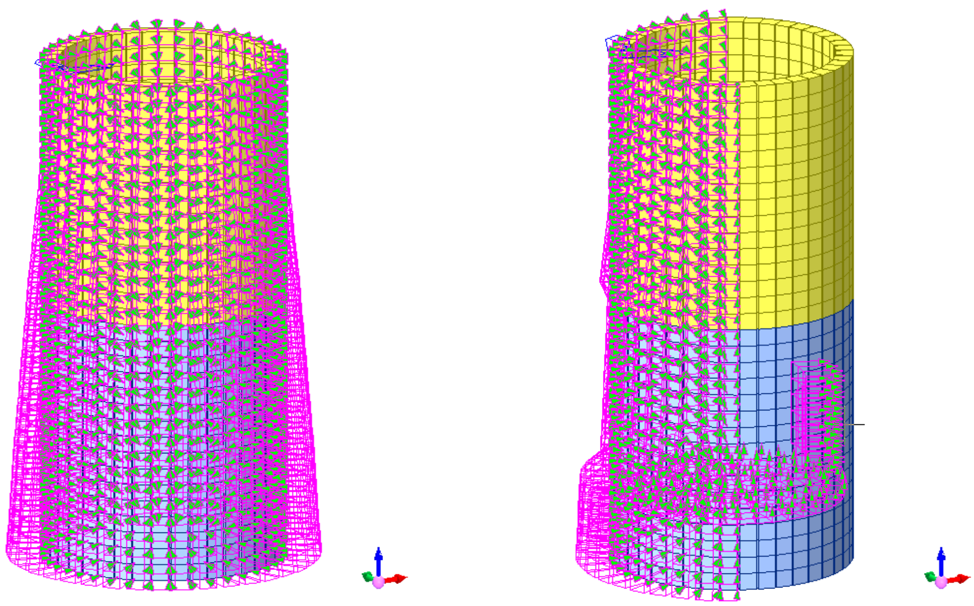
$$Ks = \frac{\pi(OD^2 - ID^2)k_s}{4N} \qquad \text{(Bowles, 1796)} \qquad (7)$$

where

Ks is vertical subgrade reaction,
OD is outer diameter (m),
ID is inner diameter (m),
k_s is modulus of subgrade reaction,
N is number of node.

Side support point at shaft work wall

Support point is located in the shaft work wall around the direction of the ground, as shown in **Figure 6**. It is defined as spring support in the major axes XZ (reaction force of spring support at shaft work wall. (KF_x and KF_z)). The Midas Gen 2021 program select the displacement based method as specified in clause 21.9.6.2 of ACI318-08/11. Select the stress based method as specified in clause 21.9.6.3 of ACI318-08/11.



(A) (B)

Figure 6 The side support point at the shaft work wall: (A) Sinking reinforced concrete shaft work process, and (B) Drilling tunnel process.

Properties of analyzed material

Properties of the shaft work structure is required in analysis model of the shaft work. It consists of the shaft work wall and slab structure, as shown in **Table 2**.

Table 2 Properties of the shaft work wall and slab structure.

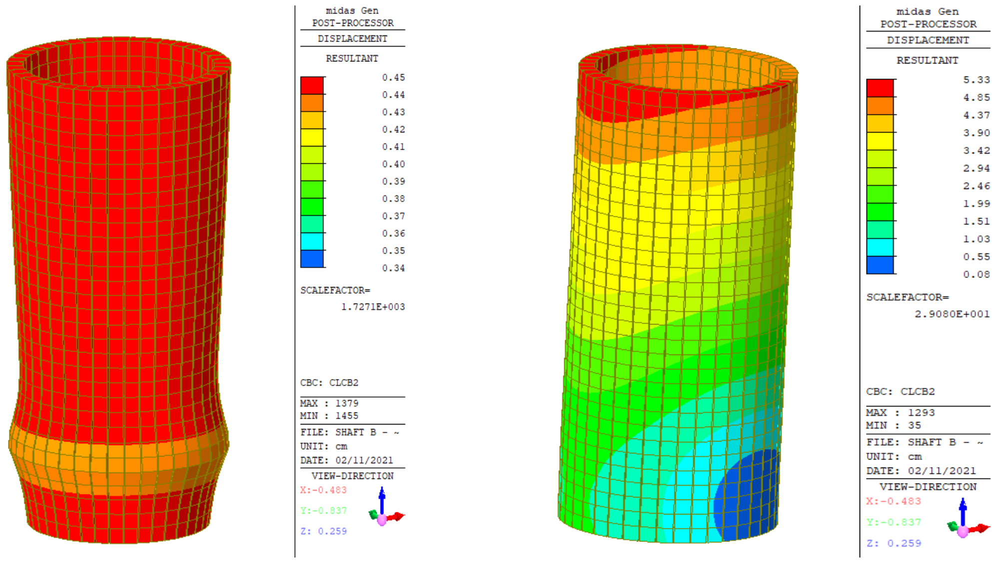
Item	Description
Material	Reinforced Concrete
w	23.536 (kN/m^3)
fc'	49.033 (MPa)
E	2.770×10^4 (MPa)
Thickness (Wall)	1.00 (m)
Covering (Wall)	0.05 (m)
Thickness (Slab)	1.70 (m)
Covering (Slab)	0.10 (m)

Results and discussion

This research found that the types of soil were very soft to medium stiff clay, dense to very dense clayey sand, silty sand and trace grand that located between 1 - 36.5 m underground. The simulation of this research is divided into 2 parts as follows.

The simulation results of the shaft work wall

The simulation results of soil subsidence around shaft work wall during sinking reinforced concrete shaft work construction and drilling tunnel process by finite element method are presented as **Figure 7**.



(A) (B)

Figure 7 This is the soil by The soil subsidence around shaft work wall: (A) Sinking reinforced concrete shaft work process, and (B) Drilling tunnel process.

Figure 7(A) shows that the minimum soil subsidence around the shaft work wall is in the shaft work slab construction area. The soil subsidence value is between 3.40 - 4.20 mm and the soil subsidence value increased when the distance from the shaft work slab construction area increased. The maximum soil subsidence value appeared in the top and the bottom of shaft work because its farthest distance from the shaft work slab construction area. The soil subsidence value is around 4.50 mm with $\delta_{\max}/H$ ratio of 0.0000136 ($\delta_{\max}$ is 4.50 mm and H is 33 m).

Figure 7(B) shows that the minimum soil subsidence around the shaft work wall is in the bottom of shaft work construction area (In front of the tunnel drilling head), the soil subsidence value is between

0.80 - 48.50 mm. Therefore, the soil subsidence value is increased when the distance from the bottom of shaft work (In front of the tunnel drilling head) increases. The maximum soil subsidence value is in the top of shaft work (behind the tunnel drilling head) because its farthest distance from the bottom of shaft work construction area. The soil subsidence value is around 53.30 mm with 0.00162 δ_{max} / H ratio (δ_{max} is 53.30 mm and H is 33 m).

Accordingly, it can be summarized in the graph (**Figure 8**) that shows the relation of the soil subsidence around the shaft work wall and the depth of shaft work. **Figure 8** shows that the soil subsidence around the shaft work wall during the drilling tunnel process is more than the value in the sinking reinforced concrete shaft work construction process.

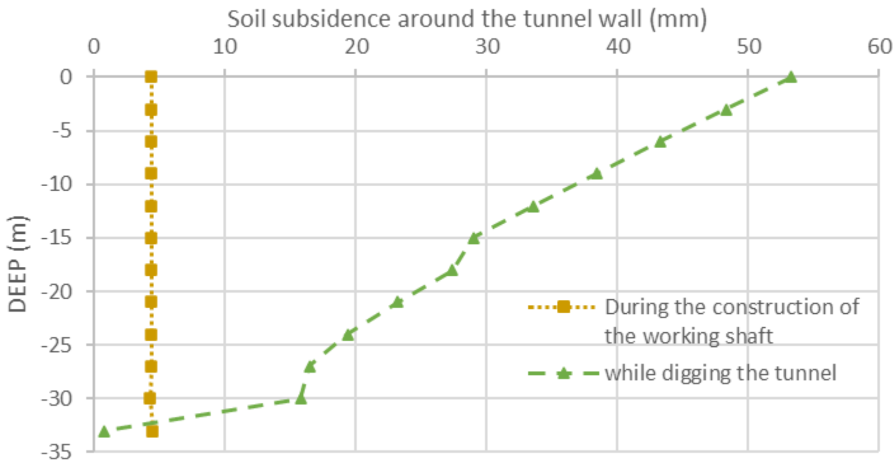
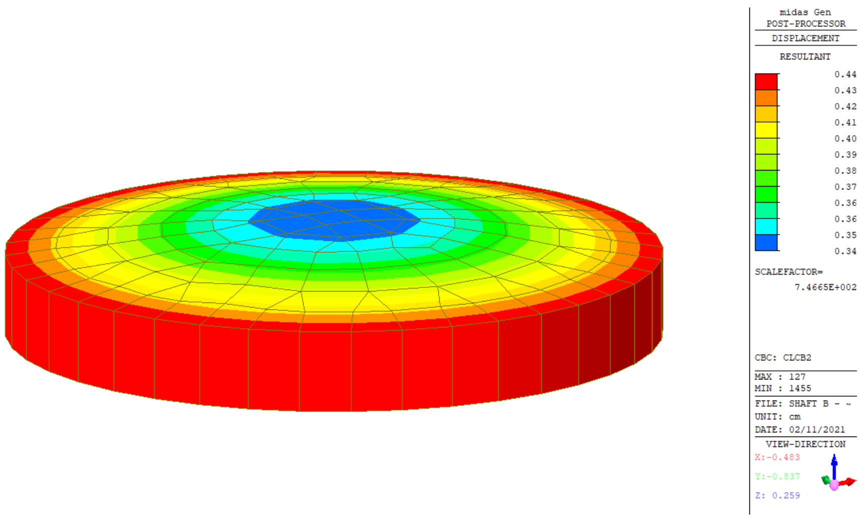


Figure 8 This is the relation by the relation of the soil subsidence around the shaft work wall and the depth of shaft work.

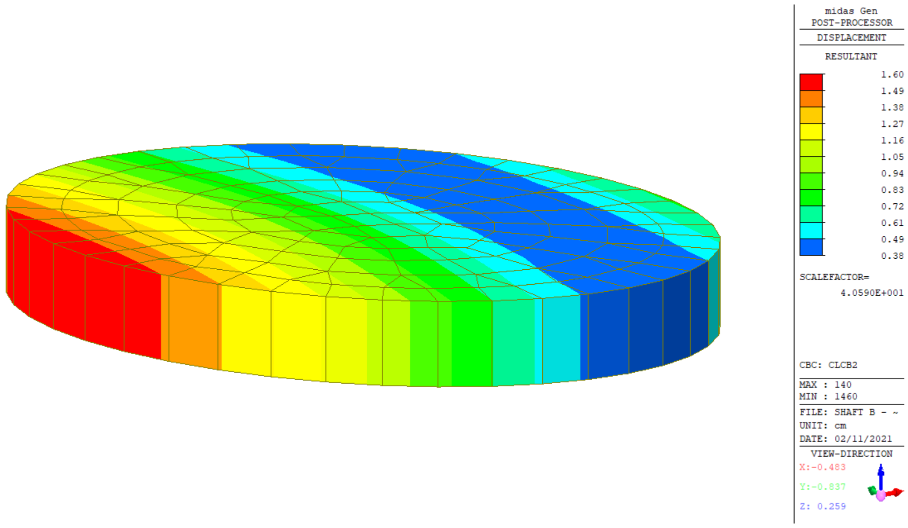
The maximum soil subsidence value is around 53.30 mm with δ_{max} / H ratio of 0.00162. (δ_{max} is 53.30 mm and H is 33 m).

The simulation results of the shaft work slab

The simulation results of soil subsidence of the shaft work slab during sinking reinforced concrete shaft work construction process by finite element method as shown in **Figure 9**.



(A)



(B)

Figure 9 This is the soil by The soil subsidence of the shaft work slab: (A) Sinking reinforced concrete shaft work process, and (B) Drilling tunnel process.

Figure 9(A) shows the minimum soil subsidence of the shaft work slab occurred in the center of the shaft work slab with the value between 3.40 - 4.30 mm. The soil subsidence value increased when the distance from the center of the shaft work slab increased. Therefore, the maximum soil subsidence value appeared in the edge of the shaft work slab. The soil subsidence value is around 4.40 mm with δ_{max} / H ratio of 0.0000133 (δ_{max} is 4.40 mm and H is 33 m).

Figure 9(B) shows the minimum soil subsidence of the shaft work slab occurred in the middle area of the shaft work slab with the value between 3.80 - 14.90 mm. The soil subsidence value increased when the distance from the middle area of the shaft work slab increased. Therefore, the maximum soil subsidence value appeared in the rim area of the shaft work slab (behind the tunnel drilling head) because its farthest distance from the middle area of shaft work slab. The maximum soil subsidence value is around 16.00 mm with δ_{max} / H ratio of 0.000485. (δ_{max} is 16.00 mm and H is 33 m).

Accordingly, it can be summarized in the graph (**Figure 10**) that shows the relation of the soil subsidence around the shaft work slab and the radius of the shaft work slab. **Figure 10** shows that the soil subsidence around the shaft work slab during the drilling tunnel process is more than that in sinking reinforced concrete shaft work construction process.

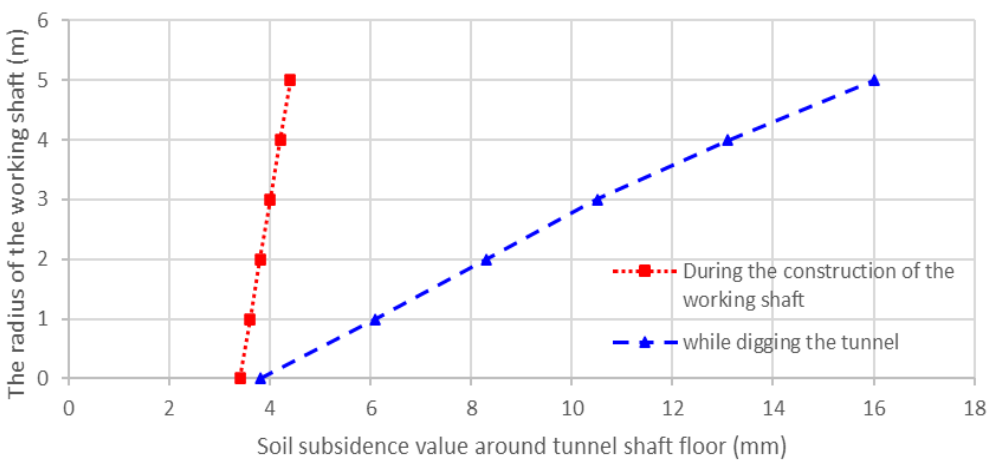


Figure 10 This is the relation by the relation of the soil subsidence around the shaft work slab and the radius of the shaft work slab.

Conclusions

From the research results, it can be concluded that the maximum soil subsidence around the shaft work wall occurred in the top area with the depth between 3 - 12 m underground (very soft to medium stiff clay layer). The maximum soil subsidence value is around 53.30 mm with δ_{max} / H ratio of 0.00162 (δ_{max} is 53.30 mm and H is 33 m).

Therefore, it is seen that during the construction there should be a work control that requires a lot of attention and focus on this point and the lubricants such as bentonite or polymers is necessary for reducing the friction around the outer wall of the shaft work during the shaft work construction and tunnel drilling process, which affects the soil subsidence around the shaft work wall. A special monitor while the construction process is also necessary too. However, the installation of instrument (inclinometer and extensometer) to compare the soil subsidence around shaft work in the field with the analysis by finite element method (FEM).

It can be seen from the analysis results of the shaft work slab that, the soil subsidence of the shaft work slab is not affected to the soil subsidence around the shaft work because the forced reaction behavior of the shaft work slab is under the uplift pressure whose responsibility is to preventing and stabilizing of the soil to prevent the bulged soil into the inside shaft work (heave stability).

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