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The Stability of Diaphragm Wall for Deep Excavation

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ABSTRACT

Rapid urbanisation and the increase in population has led to massive use of underground spaces, especially in the city. Before an underground structure is built, the use of retaining structure is crucial in order to prevent the excavation from failure. Diaphragm wall is a widely used retaining structure, particularly for deep excavation. A holistic understanding of the performance and its behaviour is essential to provide stability of the soil retained. A parametric study by using Plaxis2D has been conducted to determine the factors affecting the stability of diaphragm wall and the excavation sites in underground Mass Rapid Transit station of Hospital Kuala Lumpur (HKLX). The objectives of this study are to determine the effect of diaphragm wall stiffness, groundwater drawdown and the depth of wall for deep excavation. The stability is captured based on the lateral deflection of wall, bending moment, safety factor and ground movement near the diaphragm wall. From the study, it is found that the diaphragm wall with high stiffness can reduce wall deflection up to 20% with the addition of 49% bending moment and achieve a high factor of safety. Furthermore, groundwater drawdown is seen reducing lateral deflection of the wall up to 1.08% as well as increasing the factor of safety. Finally, decreasing wall depth reduces the wall deflection by 0.38% and also the basal heaving.

Keywords : Finite element analysis, diaphragm wall stiffness, groundwater drawdown, depth of wall

1. INTRODUCTION

One of the major concerns in constructing an underground facility within a built-up environment is the impact of associated ground movements on adjacent buildings. In underground development, braced excavations are commonly used to reduce the ground movements and minimise damage to the adjacent structures. To ensure that the serviceability limit state is satisfied, a common design criterion is to limit the maximum wall deflection to a fraction of the excavation depth typically in the range of 0.5% to 2% more than the excavation depth. Reliable estimates of wall deflections under working conditions are essential [1]. Before an underground structure is built, excavation works must be carried out first. Excavation is a risky operation in construction especially when it involves greater depths. According to Terzaghi [2], an excavation is classified as deep excavation if the depth is greater than its width. Later, Peck et al. [3] came out with a new definition that classifies shallow excavation within the depth less than 6 m, whereas deep excavation goes deeper. To conduct excavation works on site, retaining structure such as diaphragm wall is used to prevent the failure of soil structure. Diaphragm wall is commonly used due to its capability in covering great depth as well as the reduced ground movements from installation [4].

The relationship between lateral earth pressure and the depth of excavation have been discussed by Ou et al. [5]. The study was carried out on the construction project of Taipei National Enterprise Center (TNEC) with the ground conditions comprising of six alternating clay and silt layers. The amount of lateral loads acting on the diaphragm wall is measured using pressure cells. Comparisons of at-rest pressure, K_0, before and after excavation show that increasing depth of excavation leads to increased magnitude of lateral earth pressure. This in turns contributes to further deflections of the wall. Kaiser et al. [6] conducted a study on the impact of groundwater flow on the stability of diaphragm wall at excavation site. The study was executed on an excavation with a dimension of 15 m deep, 13 m wide and a water level at 6.7 m from ground. The finite element method analysis was carried out by using triangular velocity coefficient and the steady-state flow principle at free flow surface. The findings show that the drop in groundwater level can cause arching effect of soil. The arching is due to the difference in hydraulic gradient from the flow of seepage. As the difference exceeds the critical gradient, failure on the toe of wall can occur.

Diaphragm walls are generally constructed by using stiff concrete of same stiffness thoroughly. Research has shown that as wall flexibility increases, the stress imposed by the soil redistribute and reduces structural forces on the wall. Yajnheswaran et al. [7] investigated the effect of stiffness on the performance of diaphragm wall. In the investigation, two diaphragm wall sections of non-uniform stiffness were analysed by using finite element software Plaxis3D. It is found that reduction of stiffness reduces the bending moment. However, it is followed by considerable increase in wall movement. Many research also has been undertaken to optimise the use of diaphragm wall inclusive in soft soil by Zhang et al. [8] and granular soils by Mozó et al. [9], investigating the effects and design criteria of excavations by L'Amante et al. [10] and [11] Ilieş et al. [11] work and analysing the effect of ground settlements and lateral deflections as studied by Demeijer et al. [12], Comodromos et al. [13] and Wang et al. [14]. Numerical modelling in geotechnical problems have been widely used over the decades. However, many other methods and challenges are faced with validating reliable outcomes of the models.

In another context, the methods used in computer science also complement the applications in engineering. These methods include Narkedamilly et al. [15] who reviewed the several techniques of improvement and restoration of underwater image capturing where it is important to investigate the structural organisation of soils underwater. Furthermore, Sven Erikson L. et al. [16] discussed the monitoring and communications automation system that could effectively aid in studying agricultural growth whereby, in this case, it can be applied to assess the progressive stability of deep excavation. Moreover, Nijhawan et al. [17] explored the theoretical implications of utilising sustainable and innovative solar-wind systems that could reduce the consumption of energy. In soil models, a similar approach can be an added value to the systems that may lessen the impact on the environment as the soil monitoring system is being operated. Also, research with various extended features such as expert systems studied by Guanzon et al. [18] and risk analytical applications founded by Sayoc et al. [19] can be used to enhance the investigation of soil behaviour. Additionally, several approaches in geotechnical engineering itself are being studied and implemented such as Schäfer et al. [20], Wang et al. [14], Ou et al. [21], Mozó et al. [9] and Boltton et al. [22] projects that scrutiny the advancement of geotechnical modelling mostly in excavation techniques and Pedroso et al. [23] for cases in partially saturated soils. Research in soil stabilization, as well as rainfall induced slope behaviour and monitoring, all relates to better understanding of the various soil properties and soil-structure behaviour such as studies conducted by Mohd Taib et al. [24], Mukhlisin et al. [25], Altalhea et al. [26], Mukhlisin et al. [27] and Mukhlisin et al. [28].

The aim of this paper is to investigate the stability of diaphragm wall for deep excavation with the following objectives: (i) to determine the effect of diaphragm wall stiffness, (ii) to capture the effect of groundwater drawdown and (iii) to assess the influence of the depth of wall for deep excavation. The stability of the diaphragm wall is presented based on the changes of lateral deflection of wall, bending moment, safety factor and ground movement. Comparisons are then made between the current findings and previous studies to ensure the reliability of the findings.

2. METHODS AND MATERIAL PROPERTIES

This research is conducted based on a case study of deep excavation work at the underground MRT station in Kuala Lumpur Hospital (HKLX). The dimension of diaphragm wall used at the location of study is 1.2 m thick, 6 m wide and 40 m deep. The depth of excavation from the ground level is 18 m while the width of the area is 30 m. The ground condition is made of alluvium soil comprises of clay and silty sand in several layers. Table 1 shows the properties of soil used in the modelling.

Table 1: Soil properties

Parameter	Clay	Sand
γ_{unsat}(kN/m^3)	19.0	19.5
γ_{sat}(kN/m^3)	20.0	20.0
k (m/day)	1.04x10^{-3}	0.038
c (kN/m^2)	5.4	5.0
φ (°)	25.0	34.0
Ψ (°)	0.0	0.0

2.1 Stiffness of Diaphragm Wall

A total of three diaphragm models of increasing stiffness have been used for this study as presented in Table 3. The walls are modelled by using an elastic plate. The elasticity of wall is defined through EA and EI parameters indicating the normal stiffness and bending stiffness respectively. The study is conducted by using an initial stiffness of the wall, mounted at the underground MRT station of HKLX. In addition, groundwater levels are assigned to a depth of 5 m from the ground. To ensure the stability of the excavation site, struts are installed at depths of 3 m, 7 m, 12 m and 16 m which measured from the ground level. In the finite element analysis, all four levels of struts with EA value of 3.08x10^7 kN/m are used to simulate the strength of the struts. Furthermore, other inputs such as the dimensions of wall, groundwater level and soil parameters are assigned with fixed values. A new parameter, α, was introduced representing the stiffness factor of the wall. The parameter can be calculated by using Equation 1 as follows:

$$\alpha = \frac{EI}{\gamma_w h^4{}_{avg}} \quad (1)$$

where EI = stiffness of wall, h_{avg} = average vertical struts spacing.

Table 2: Diaphragm wall stiffness

Parameter	Model		
	A (Initial)	B	C
α	0.1	1.0	10
EA (kN/m)	2.40x10^5	2.40x10^6	2.40x10^7
EI (kNm^2/m)	2.88x10^4	2.88x10^5	2.88x10^6
Poisson Ratio, *v*	0	0	0

2.2 Groundwater Drawdown

A total of 10 models are developed to study the effect of groundwater drawdown on the stability of diaphragm wall. By referring to the data obtained, the groundwater level on-site is ranging from 33.7 m and 26.89 m at the adjusted level, mRL. However, this study is continued until the groundwater level reaching to the toe of diaphragm wall to further collecting information. The first simulation is conducted by fixing the groundwater level at 4 m from the ground before the water level is reduced at a rate of 4 m from one model to another. At the same time, other inputs such as the stiffness of wall, struts force as well as soil parameters are assigned at fixed values and constant. Table 3 summarises the groundwater level inputs for all the models.

Table 3: Height of groundwater level

Model	Height of groundwater level (m)	Model	Height of groundwater level (m)
A	4	F	24
B	8	G	28
C	12	H	32
D	16	I	36
E	20	J	40

2.3 Depth of Diaphragm Wall

A total of five models are developed to study the effect of wall depth on the stability of diaphragm wall. Model A adopts the initial properties of diaphragm wall as used in the research location which has a depth of 40 m. In order to investigate the influence of this factor, other inputs such as well stiffness, groundwater level, struts force, and soil parameters are assigned fixed and constant. This simulation is undertaken by reducing the depth of the wall from 40 m to 32 m. The reduction on the depth of the wall shows the changes at the toe from the clay to sand layer as presented in Figure 1 and 2. Table 4 summarises the input of depth of wall used for all the models.

Table 4: Depth of diaphragm wall

Model	Depth of wall (m)
A	40
B	38
C	36
D	34
E	32

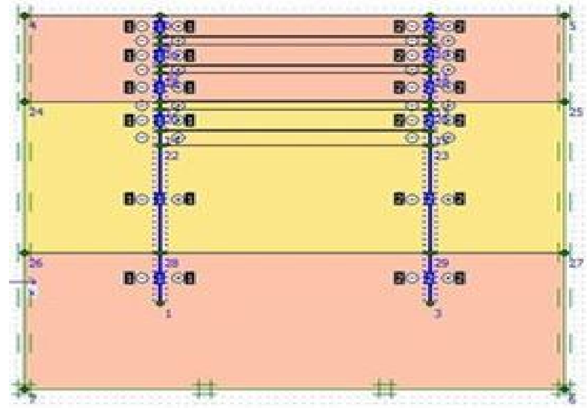

Figure 1: Toe of wall in clay layer

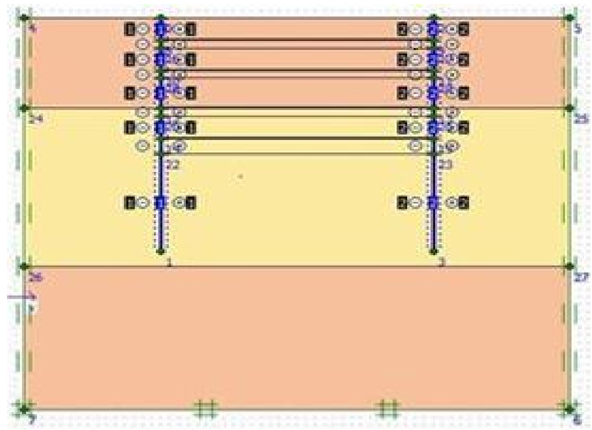

Figure 2: Toe of wall in sand layer

3. RESULT AND DISCUSSION

3.1 Stiffness of Diaphragm Wall

The stiffness factor of the diaphragm wall was analysed by looking at the magnitude of lateral wall deflection, bending moment and safety factor. A detailed discussion is made based on the findings to evaluate their impact on the stability of diaphragm wall. Figure 3 shows the lateral deflection of diaphragm wall with different stiffness. From the graph, it can be seen that stiffer wall results in smaller magnitude of wall deflection. Model A with the lowest stiffness factor shows the highest maximum deflection with value of 56.05 mm. Model B have the maximum deflection value of 32.32 mm while model C with the highest stiffness factor shows the lowest value of deflection at 12.96 mm. Comparisons have been made with research by Goh et al. [1]. From the study, they concluded that for every 10 times increase of wall stiffness factor, the reduction of wall deflection reaches up to 15%. In this study, the increase of wall stiffness factor from $\alpha = 1.0$ for model B to $\alpha = 10.0$ for model C shows a reduction of 20% lateral wall deflection.

Figure 4 shows the bending moment of diaphragm wall for different wall stiffness. From the graph, it can be observed that wall with greater stiffness will have a greater bending moment value. Model A with lowest stiffness factor shows the lowest bending moment of 96.54 kNm/m. Model B shows the maximum bending moment at 181.84 kNm/m while model C with the greatest wall stiffness factor, shows the greatest value of bending moment at 271.66 kNm/m.

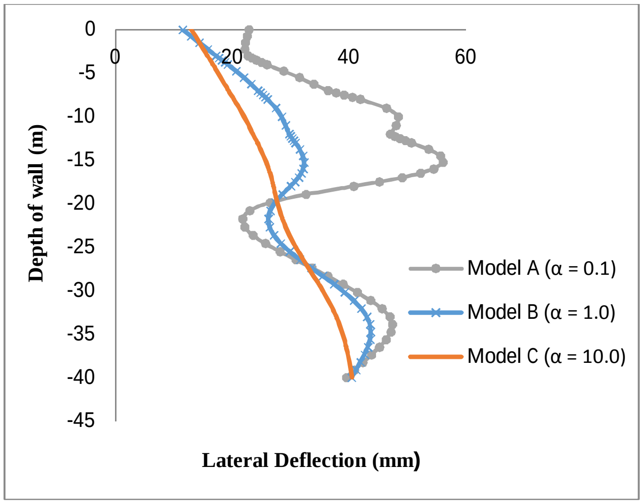

Figure 3: Lateral deflection of diaphragm wall

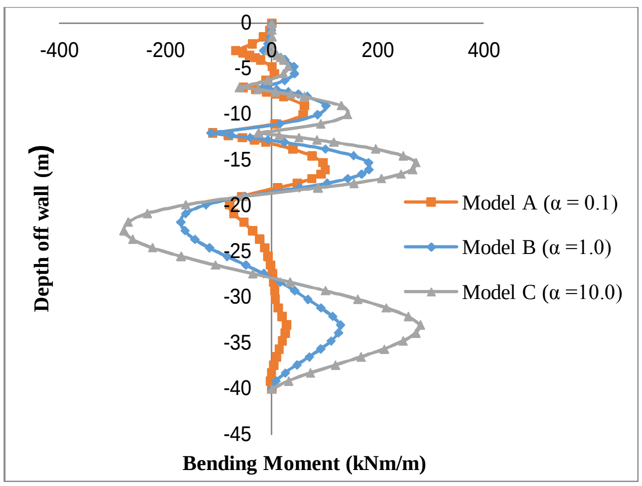

Figure 4: Bending moment of diaphragm wall

The results were compared with research made by Yajnheswaran et al. [7]. In their study, they concluded that wall with high stiffness factor will have greater bending moment which results in bigger wall deflection. This is in line with this study where the increment of stiffness factor from model B to model C shows an increment of 49% bending moment. Moreover, Figure 5 shows the factor of safety against different wall stiffness. From the results, model A with smallest wall stiffness factor shows the least safety factor of 3.54. While model C with the greatest wall stiffness factor shows the greatest safety factor value of 5.23. Typically, the safety factor for retaining wall system is estimated between 2.5 to 4.0. From these findings, model A which adopts the initial wall stiffness is already sufficient to be used in ensuring the stability and safety of excavated area.

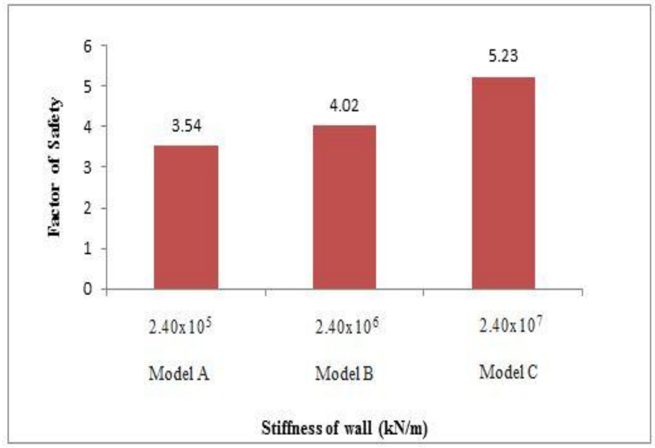

Figure 5: Factor of safety against the stiffness of wall

3.2 Groundwater Drawdown

Several aspects have been observed in studying the effect of lower groundwater levels on the stability of the diaphragm wall. The assessment was made by looking at the lateral wall movements and safety factors. Figure 6 shows the lateral wall deflection at different groundwater level. From the graph, lowering the groundwater level from 33 m to 21 m results in greater wall deflections. Model A shows maximum wall deflection of 51.33 mm while model D shows maximum wall deflection of 86.29 mm. However, smaller wall movement up to 1.08% is found then the groundwater level is lowered until the toe of the wall. Comparisons were also made with research conducted by Mohamed et al. [29]. They studied the effect of lowering the groundwater table towards the deflection and bending moment of diaphragm wall. From the findings, they found that the groundwater drawdown from 1 m to 5 m under the ground did reduce the lateral deflection of wall. This is consistent with the findings of current research that also suggests groundwater drawdown imposes less deflection to the diaphragm wall.

The groundwater level affects the number of lateral loads imposed on the wall structure. The lateral loads that occur at the back of the wall depending on the cohesion and friction angle of the soil. In addition, groundwater will also cause hydrostatic pressure on the diaphragm wall. The reduction of groundwater level will reduce the hydrostatic pressure generated. Therefore, lateral deflection of the wall too decreases. Figure 7 shows the factor of safety for different level of groundwater. The safety factor obtained also shows a fairly consistent value as they are all within the range of 2.5-4. This shows that the groundwater drawdown does not have a serious impact on the wall movement.

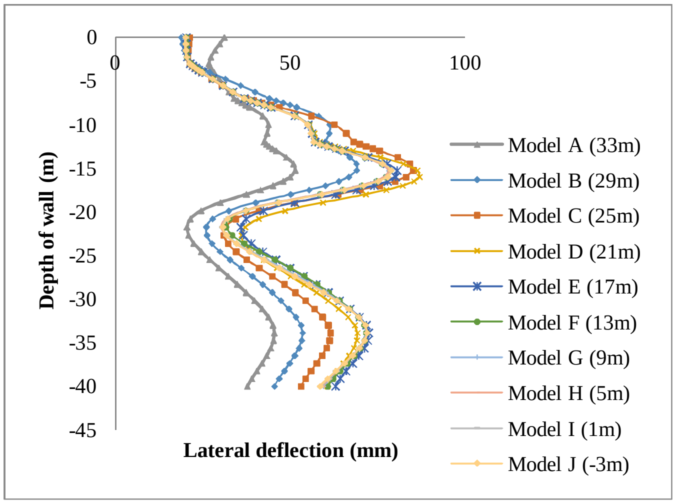

Figure 6: Lateral deflection of wall

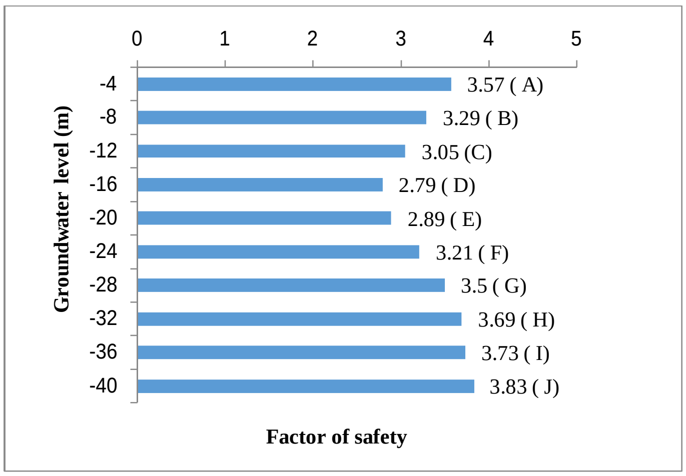

Figure 7: Factor of safety against groundwater level

3.3 Depth of Diaphragm Wall

Several aspects have been observed to study the effect of lowering the depth of wall towards the stability of the diaphragm wall and excavation site. The assessment was made by looking at the lateral wall movements, basal heaving and factor of safety. Figure 8 shows the lateral wall deflection at different depth of the wall. From the results, it is clear that there is no significant difference when the depth of the wall is reduced from 40 m to 32 m. If the maximum lateral deflection were analysed closely, there is a decreasing trend from one model to another. However, the difference is really small at approximately 1 mm. The maximum lateral deflection for model A = 56.05 mm, B = 55.99 mm, C = 55.47 mm, D = 55.23 mm and E = 55.15 mm. In average, the reduction is 0.38% with every 2 m reduction of the depth of wall. From this observation, depth of wall does not significantly impact the stability of diaphragm wall as well as the excavation site.

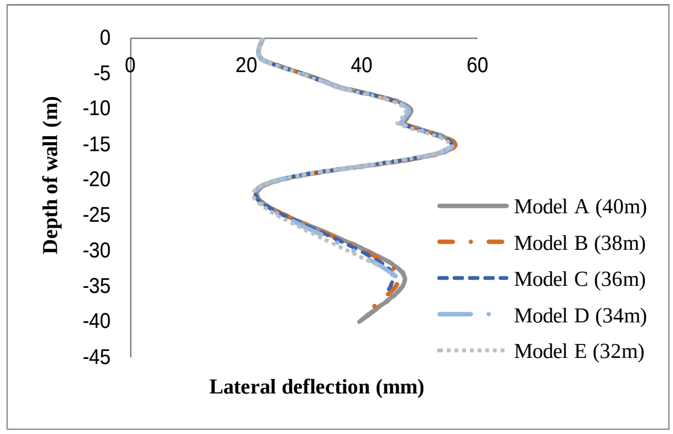

Figure 8: Lateral deflection of wall

Figure 9 shows the basal heaving that occurs when the depth of wall is reduced from 40 m to 32 m. The heaving obtained from Plaxis2D refers to the vertical soil movement that happens on the surface of final excavation level. From the results obtained, it can be observed that basal heaving decreases as the depth of wall reduce. The reduction of basal heave is 0.38% for every 2 m reduction of depth of wall. From the research undertaken by Luo et al. [30], the occurrence of basal can be observed inside the excavated area. During excavation works, soil from the back of wall moved downward and inward due to the weight of the soil. Given that the soil within excavation area is unable to expand horizontally and upward, the result indicates that the exposed surface of the ground at the final excavation level receives the heaving effect. The heaving, however, usually occurs less than 150 mm. Figure 10 shows the factor of safety for different depth of diaphragm wall. The factor of safety presents a consistent value whereby they range between 2.5-4. In average, there is a difference of 1.4% safety factors between the model. This shows that reducing the depth of wall only lightly impact the stability of diaphragm wall as well as towards the excavation site.

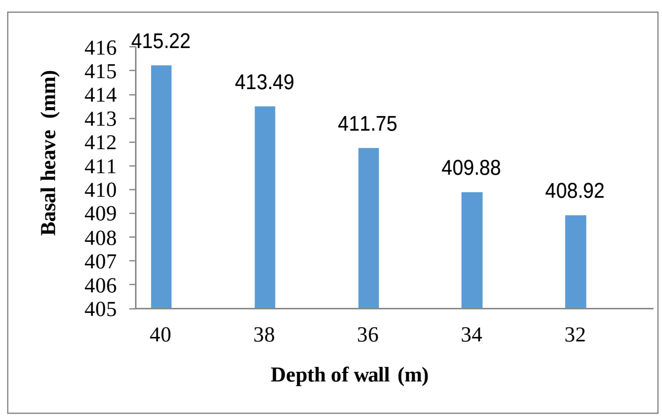

Figure 9: Basal heaving

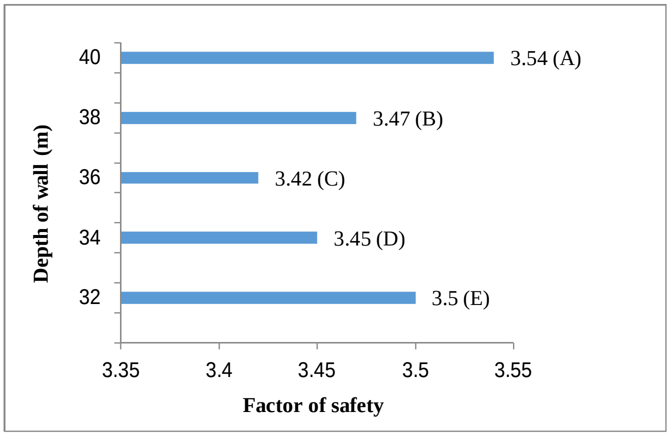

Figure 10: Factor of safety against the depth of wall

4. CONCLUSION

Diaphragm wall is one of the most used retaining structure, especially in deep excavation. In this research, the influence of stiffness of wall, groundwater drawdown effect as well as the depth of wall were thoroughly studied to determine the effect of these factors on the stability of diaphragm wall and the excavation area. From the study on the stiffness of diaphragm wall, it can be concluded that the wall with great stiffness will result in smaller deflection of the structure. There is 20% reduction of lateral wall deflection with the increase of stiffness factor. However, the increase of wall stiffness is accompanied by greater bending moment up to 49%. Furthermore, the factor of safety also shows an increase in value as the wall becomes stiffer. The groundwater level also plays an important role in ensuring the stability of the wall structure. During the excavation, it is observed that the deflection of wall reduces as the groundwater level drops. However, only 1.08% reduction was recorded. Next, the safety factor of the wall system also shows an increment up to 5.6% when the groundwater level drops to the toe of wall. In addition, the depth of the wall also has an impact on the behaviour of wall structure. By reducing the depth of wall, 0.38% reduction of lateral deflection value is recorded. In addition, the depth of wall also affects the basal heave on the final excavation level. This occurrence can be reduced by reducing the depth of the structure. Also, the factor of safety shows an increase of 1.4% when the depth of the structure is reduced. Based on these findings, the factors affecting the stability of diagphram wall is thoroughly investigated.

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