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Parametric Analysis of Cantilever and Anchored Sheet Pile Walls

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Abstract
Due to the rapid increase in congestion in major cities of Nepal like Kathmandu, it becomes necessary to plan any excavation-related works properly so that there is less impact on the existing facilities or constructions. For this purpose, earth retaining structures, which may be either rigid or flexible, becomes a priority. The purpose of this study is to analyze the behavior of excavation support systems: Cantilever and Anchored Sheet Pile Walls by numerical method. In this study, the effect of embedment depth of the cantilever sheet pile wall is studied. Single anchored sheet pile wall is considered and the analysis of the effects of anchor inclination, location of the anchor with respect to the ground surface, depth up to which excavation is done before anchor installation, embedment depth of sheet pile, anchor load, free anchor length, grout length and variation of water table are studied. All the parametric analysis is done by using Plaxis 2D. The results from the study are analyzed and the effect of various parameters on the stability and serviceability of the support systems are studied.

Keywords
Sheet Pile Walls, Excavation, PlAXIS2D, Finite Element Analysis

1. Introduction

When excavation is being done on any landmass, if the excavated region is left unsupported, after a certain height of excavation, the excavated section of soil begins to move from its position. For this purpose, earth retaining structures, which may be either rigid or flexible, becomes a priority. If a wall don't undergo significant bending deformations and moves as a single unit, it is considered to be rigid. On the other hand, flexible walls, in addition to rigid body motion, experience bending deformation as well. The most common example of a flexible wall is a sheet pile wall which can be used in riverbank protection, waterfront structures, cofferdams, bridge abutments, etc.

Sheet pile wall is classified as steel sheet pile, concrete sheet pile, and timber sheet pile based on the material used. Among these, the steel sheet pile is the most common one because of its slender shape, ability to tolerate relatively higher deformation, easy handling, and easy manufacturing. A sheet pile wall can also be classified as a cantilever or anchored sheet pile. The selection of a particular wall type is governed by its purpose, its proximity to existing structures, and the foundation soil characteristics. When the depth of excavation is small, cantilever sheet piles are used to support the excavation. Whereas, in general, if the excavation depth exceeds about 6m or the allowable wall deflection is limited , anchored sheet pile walls are used [1]. For greater backfill height, the number of anchors needs to be increased to avoid the failure of the wall. The use of anchors results in lesser penetration depth and a decrease in the value of bending moment, shear force, and deflection of the wall. The stability of cantilever sheet pile walls depends on the passive soil resistance whereas that of anchored sheet pile walls depends on passive soil resistance as well as the combination of anchors. The benefit of putting an anchor in a sheet pile wall is that it reduces the wall's weight, cross-sectional area, and embedded depth, all of which are requirements for construction [2]. The length of the anchor, its location relative to the ground, its inclination, and the number of anchors utilized along the height of the sheet pile wall are some of the crucial factors that affect a structure's stability [3], [4]. The maximum displacement of sheet pile walls and soil is decreased when these parameters are best chosen. Additionally, it influences the anchored sheet pile wall system's economical design. The sheet pile wall experiences the maximum displacement, and soil analysis is done to allow the displacement up to an acceptable value. The value of horizontal displacement is often taken into account in retaining structures up to 2% of the maximum depth of excavation. According to [5], [6], and [7], underground projects typically choose this value of horizontal displacement.

1.1 Sheet Pile Failure Mechanism

While designing a sheet pile wall, several possible failure modes needs to be considered. The failure can be deep seated failure, failure of sheet pile due to overstressing, rotational failure due to insufficient embedment of sheet pile, failure of steel tendon, failure of ground and grout bond and failure of grout and tendon bond. Deep seated failure is a failure of soil mass where whole soil mass rotates along a single failure surface. The potential failure conditions in anchored sheet pile wall are summarized in Figure 1.

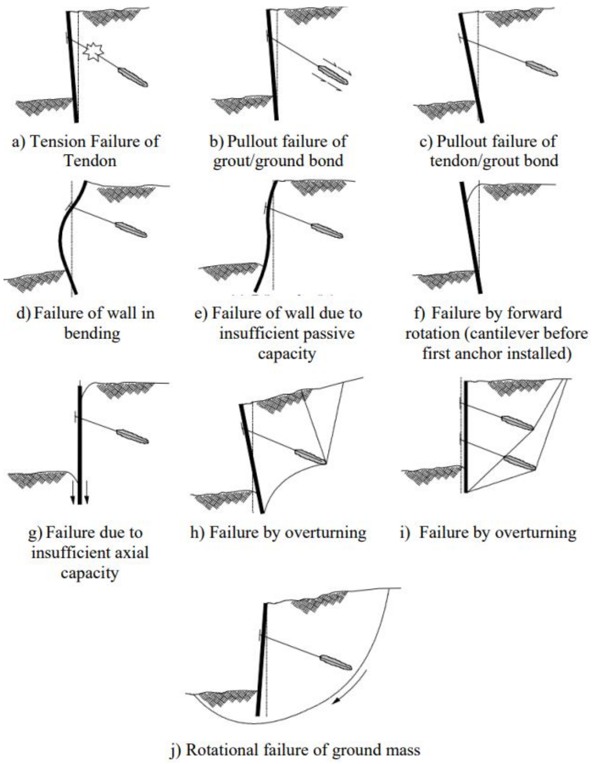

Figure 1: Potential failure conditions to be considered in design of anchored walls [8].

2. Materials and Methods

All the analyses are carried out using a finite element analysis programme PLAXIS 2D, Version 20. The type of soil considered for the analysis is a $c-\phi$ soil with a fill layer $\{\phi$ soil$\}$ on top. The soil data is from the proposed construction site of the Thapathali Campus at Balkhu, Kathmandu. The soil investigation was conducted by G.S. Soil & Materials Engineers Pvt. Ltd. in 2018 A.D. and it comprises percussion drilling, Standard Penetration Test (SPT), and some laboratory tests. 7 boreholes were drilled in total, out of which only the result from Borehole-2, drilled up to 20m, is considered in the analysis as the result from this borehole is almost the average of data obtained from other boreholes. From the borehole log sheet, it is found that the strata consist of 3m brownish-coloured silty soil layer on top, underlain by grey-coloured clayey soil up to 20m. Since the borehole was drilled up to 20m, it is assumed that this clayey layer extends up to an infinite depth. The summary of soil parameters used in the model are given in Table 1 . In this analysis, Mohr Coulomb Model is used as material model. Sheet pile wall is modeled as a plate element, anchor as a node to node anchor, and grout as an embedded beam.

Table 1: Properties of Soil

Parameter	Silty Layer	Clayey Layer	Unit
Unsaturated Γ	16.6	16.73	KN/m3
Saturated Γ	18.9	17.2	KN/m3
Modulus of Elasticity, E	3600	28266.23	KN/m2
Cohesion, c’	0	12.1	KN/m2
Frictional Angle	28.61	24.2	Degree
Dilatancy Angle	0	0	Degree

3. Numerical Modeling

The modeling is done using two dimensional Finite Element Software PLAXIS 2D.

3.1 Project Properties

Here, the plain strain model is used to model the situation under consideration. The dimension of the model is fixed as per Figure 2. The project properties used in the study are given in Table 2.

Table 2: Project Properties

$X_{(min)}$	$X_{(max)}$	$Y_{(min)}$	$Y_{(max)}$
0	100	0	70

3.2 Geometry and Boundary Condition

After defining the project properties, soil stratigraphy has to be defined. It is done by creating a borehole, adding and assigning respective materials and levels for different soil layers. The water head is at a depth of 4.2 m. The next step is defining structural elements. The sheet pile that is used for this study is a steel sheet pile "ISPS 2322 Z". The sheet pile wall is modeled as a plate element. The material data sets is assigned to the plates created and positive and negative interfaces are also assigned. Modeling of ground anchor is done by the combination of a node to node anchor which simulates the free anchor length and an embedded beam which simulates the grouted part. The corresponding material properties for anchor and grout bodies are then assigned. As the effect of structural parameters is not considered in the present study, same set of structural material properties have been used for all the cases considered. The vertical boundaries are fixed normally, the bottom horizontal boundary (Y_{min})is fully fixed whereas the top horizontal boundary (Y_{max}) is free.

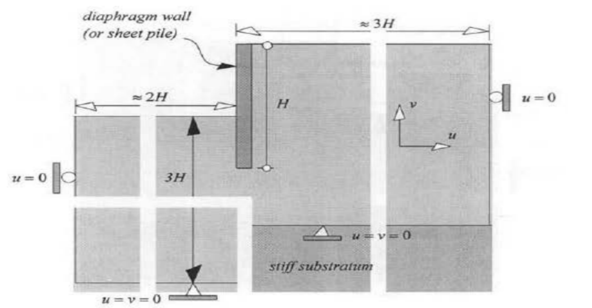

Figure 2: Typical mesh dimensions for a sheet pile wall [9]

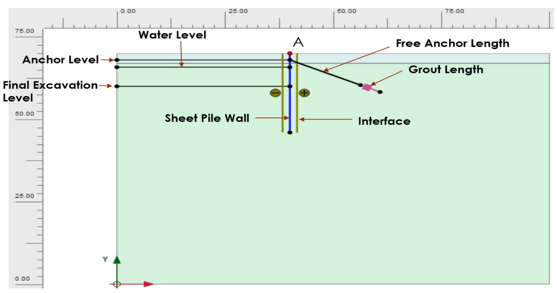

Figure 3: Geometry of the model for one of the cases considered

3.3 Mesh generation

Though the generation of a mesh using a very fine mesh provides better accuracy of results, the computation time increases greatly. So, adopting a decision to sacrifice some level of accuracy in order to maintain a better balance over time, the mesh has been generated using a medium mesh.

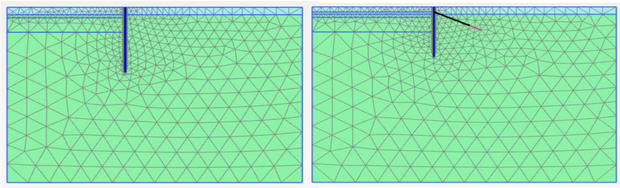

Figure 4: Generated Mesh for Cantilever Sheet Pile Wall and Anchored Sheet Pile Wall

3.4 Calculation

The number and sequence of phases in a particular calculation depend on the case considered. Table 3 and Table 4 below shows the list of cases considered. Case C16 involves varying the water table elevation from 70m to 45m for single anchored sheet pile wall having geometry as given in Table 4 for C16. Here, h is the depth of excavation, d is the embedment depth of the sheet pile, θ is the angle of inclination of the ground anchor with respect to horizontal, z is the depth at which the ground anchor is installed measured from the top of sheet pile wall, E is the excavated depth upto which soil is excavated before anchor installation, L is the free anchor length, and G is the grouted length (fixed anchor length). For the

Table 3: Cases Considered for Cantilever Sheet Pile Wall

Cases	h	d/h
C1	1m	Varying from 0.7 to 1.4
C2	2m	varying from 0.8 to 1.5
C3	3.5m	varying from 0.7 to 1.2
C4	5m	varying from 0.8 to 1.4
C5	7m	varying from 0.8 to 1.6
C6	9m	varying from 1.1 to 2.0

cantilever sheet pile wall, the first stage is the initial phase in which the generation of initial stresses occurs. The second stage involves the construction of sheet pile walls. Activation of plates and interfaces is done in this stage. When excavation level is above water table, third step is the excavation upto the final excavation depth. When the final excavation level is below water table, the third step involves the excavation above the water table level. In the fourth step, the soil is excavated up to the final excavation depth including the dewatering of the excavation. The dewatering is simulated by lowered ground water table which is defined in Flow Condition mode by drawing a new water level. In the case of the anchored sheet pile wall, the first and second phase is the same as described above. For the case, when anchor level is

Table 4: Cases Considered for Anchored Sheet Pile Wall

Cases	h	d/h	z/h	θ	E/h	L/h	G/h	P
C7	10m	1	0.2	varying from 0° to 40°	Equal to z/h	1.3	0.4	200 kN
C8	10m	1	0.4	varying from 0° to 40°	Equal to z/h	1.3	0.4	200 kN
C9	10m	1	0.6	varying from 0° to 40°	Equal to z/h	1.3	0.4	200 kN
C10	10m	1	varying from 0.2 to 0.8	25°	Equal to z/h	1.3	0.4	200 kN
C11	10m	1	0.2	25°	varying from z/h to 0.8	1.3	0.4	200 kN
C12	10m	1	0.2	25°	Equal to z/h	1.3	0.4	varying from 50 to 500 kN
C13	10m	1	0.2	25°	Equal to z/h	varying from 0.5 to 2	0.4	200 kN
C14	10m	1	0.2	25°	Equal to z/h	1.3	varying from 0.05 to 0.6	200 kN
C15	10m	varying from 0.8 to 1.8	0.2	25°	Equal to z/h	1.3	0.3	200 kN
C16	10m	1.3	0.2	25°	Equal to z/h	1.3	0.3	200 kN

above water table level, third step involves excavation upto the anchor level. Fourth step is the activation of ground anchor. Then, in the fifth step excavation upto the water table level is done. Excavation upto the final excavation level is done in the sixth step including dewatering. If the ground anchor installation level is below the borehole water level, then in the third step excavation upto water table level is done. In fourth step, excavation upto the anchor level including dewatering is done. Ground anchor is activated in the fifth step. In the sixth step, excavation upto final excavation level including dewatering is done. To study the effect of water table variation, 1m excavation is done at each stage. Dewatering during excavation is done for the excavation which is carried out below the water table. The last stage in all cases is the calculation of the factor of safety.

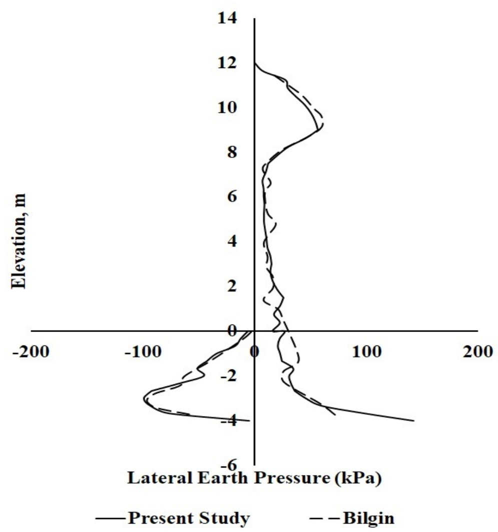

Figure 5: Lateral Earth Pressure Diagram

3.5 Model Verification

A paper by Omer Bilgin [10] is taken as reference for model verification. All the steps mentioned in [10] has been repeated and the outputs are then compared. Figure 6 shows the comparison of bending moment diagram of wall at final 2 stages of the excavation and Figure 5 shows the comparison of lateral earth pressure produced at final excavation stage for DL12 case. A good agreement has been depicted from the comparison of our result and that of [10].

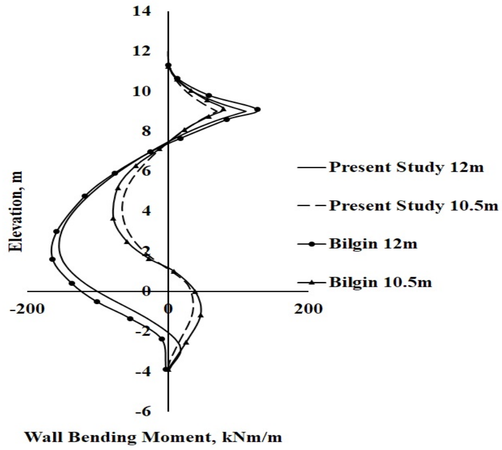

Figure 6: Wall Bending Moment Diagram

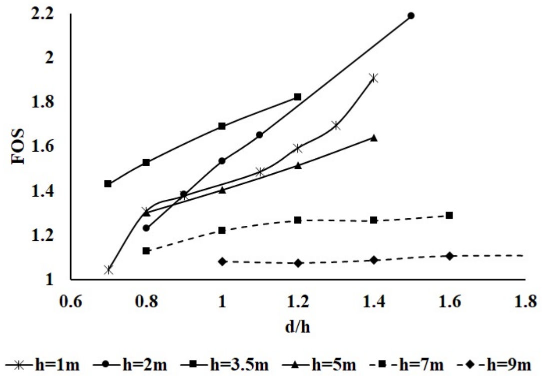

Figure 7: Graph of Factor of Safety verses d/h

The graphs obtained shows that the factor of safety increases with the increase in embedment depth but the rate of increase is lower for deeper excavation. For excavation depth of 1m and 2m, slightly different nature of graphs are obtained. This is because, the soil profile consists of silty layer upto 3m depth from top. Hence, for 1m and 2m excavation depth, the passive resistance is provided either completely by the silty layer or partly by silty and partly by bottom clayey layer depending on the embedment depth.

4. Results and Discussions

In this section, the results obtained from the Plaxis for different cases listed in Table 3 and Table 4 are analyzed and the effect of various parameters on the factor of safety and horizontal displacement of the wall top is studied in detail.

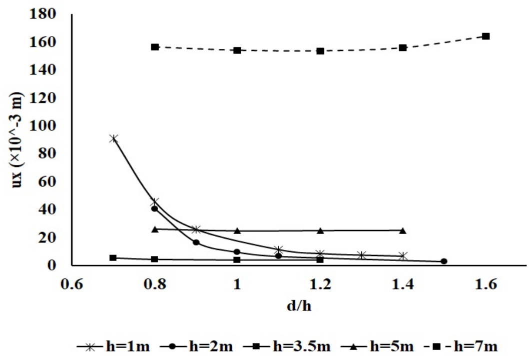

Figure 8: Graph of ux verses d/h

4.1 Effect of embedment depth in cantilever sheet pile wall

A range of cases have been considered to determine the influence of embedment depth in cantilever sheet pile wall. The aim here is to understand how the factor of safety and wall movement is affected by the embedment depth for different depth of excavation. During numerical simulation, the ratio of depth of embedment and the depth of excavation is varied and the result obtained is shown in Figure 7 and Figure 8.

4.2 Effect of angle of inclination of ground anchor in anchored sheet pile wall

Three cases (C7, C8 and C9) are studied to observe the effect of the angle of inclination of ground anchor in anchored sheet pile wall. Figure 9 and Figure 10 shows the results obtained on varying θ from 0° to 40° for respective cases.

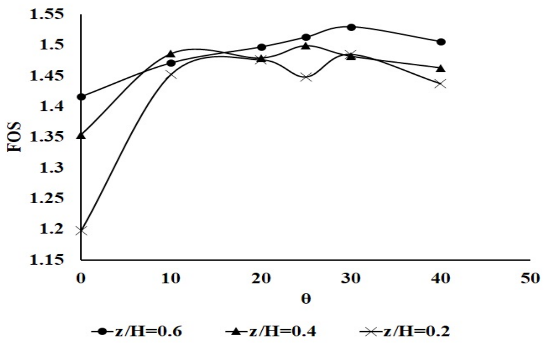

Figure 9: Graph of FOS verses θ

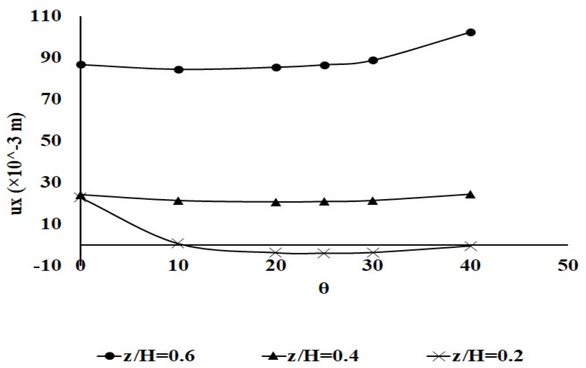

Figure 10: Graph of u_x verses θ

In all the cases, it has been found that maximum value of factor of safety and minimum value of horizontal displacement is obtained for a range of $\theta = 10°$ to $\theta = 30°$.

4.3 Effect of installation position of ground anchor in anchored sheet pile wall

The variation of factor of safety and horizontal displacement based on the installation position of ground anchor from the ground surface is shown in Figure 11 and Figure 12.

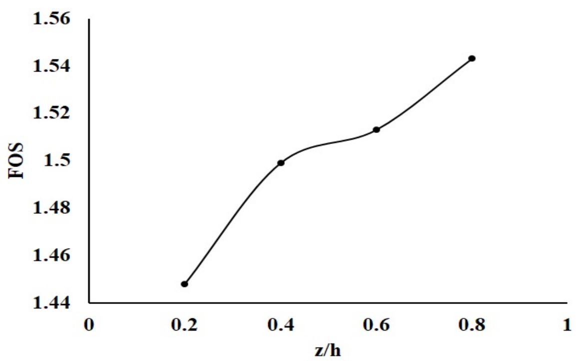

Figure 11: Graph of FOS verses z/h

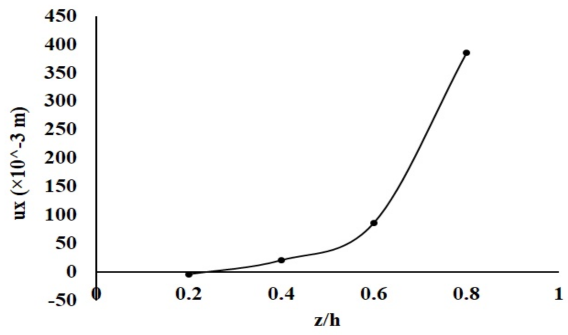

Figure 12: Graph of u_x verses z/h

The results shows that there is slight increase in factor of safety when the ground anchors are installed near to the final depth of excavation. However, there is sharp increase in horizontal displacement when z/h is greater than 0.4.

4.4 Effect of depth excavated before the ground anchor installation

The effect of depth excavated before the ground anchor installation can be observed in Figure 13 and Figure 14. The trend of effect on factor of safety suggests a decrease in FOS with increased E/h ratio and also, there is the sharp increase in the horizontal displacement with late installation of anchor.

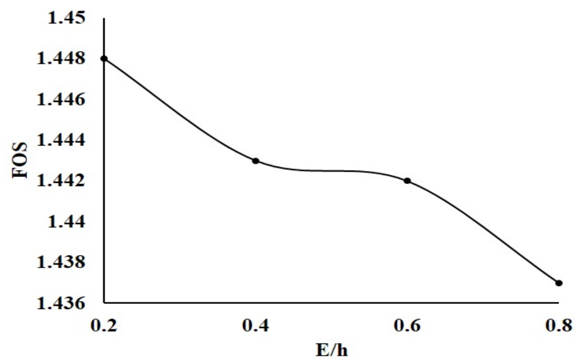

Figure 13: Graph of FOS verses E/h

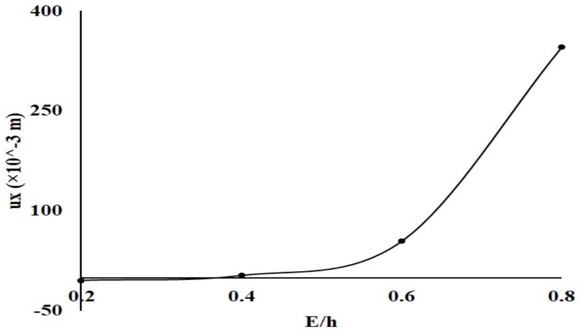

Figure 14: Graph of u_x verses E/h

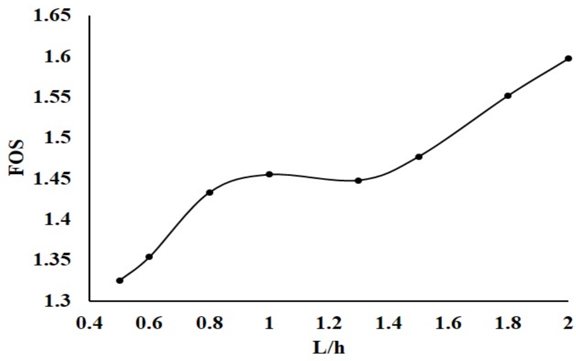

Figure 16: Graph of FOS verses L/h

4.5 Effect of pre-stress force on anchor

The value of pre stress force on anchor is varied from 50kN to 500kN and the result obtained is summarized in Figure 15. The result clearly suggests that there is not much influence of pre-stressing force on factor of safety, however, the horizontal displacement decreases almost linearly with the increase in pre-stressing force.

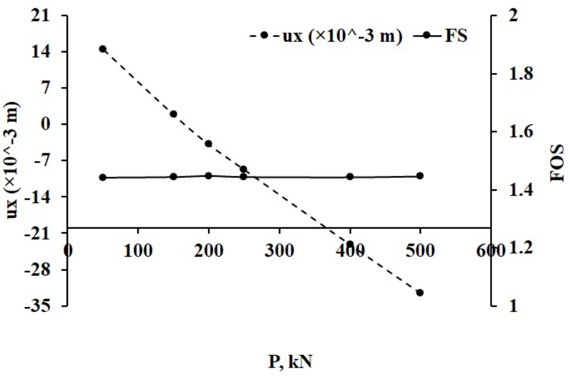

Figure 15: Graph of FOS and u_x verses P

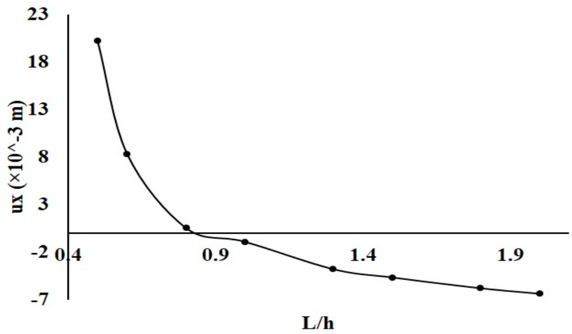

Figure 17: Graph of u_x verses L/h

As per [8], in order to prevent the transfer of load from anchor bond zone to the "no-load" zone (zone between the wall and critical failure surface), the grouted portion of anchor should be placed sufficiently, a minimum distance of $h/5$ or 1.5m, behind this zone. In our case, the no load zone is extended upto around 6m. So, for our case of h=10m, the unbonded anchor length less than 8m affect greatly on the stability and servicability of sheet pile wall.

4.6 Effect of free anchor length

The increase in free anchor length of ground anchor results increase in FOS and decrease in horizontal displacement as seen in Figure 16 and Figure 17. However, it is found that after $L/h > 0.8$ the slope at which horizontal displacement decreases is very low compared to that for $L/h < 0.8$.

4.7 Effect of grout length

The increased grout length results increase in FOS and decrease in u_x as shown in Figure 18 and Figure 19. It can be clearly seen that, for $G/h > 0.1$, the rate at which u_x decreases is very low compared to the rate for $G/h < 0.1$. The FOS increases rapidly upto the ratio of 0.2.

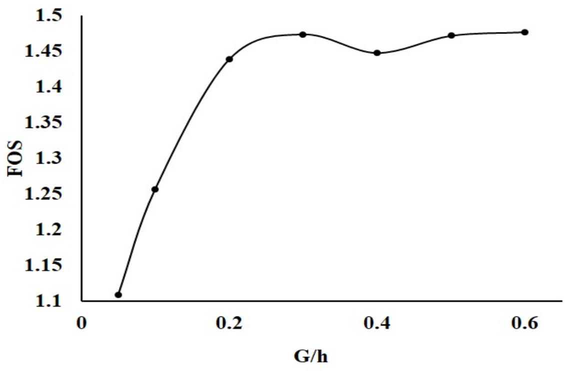

Figure 18: Graph of FOS verses G/h

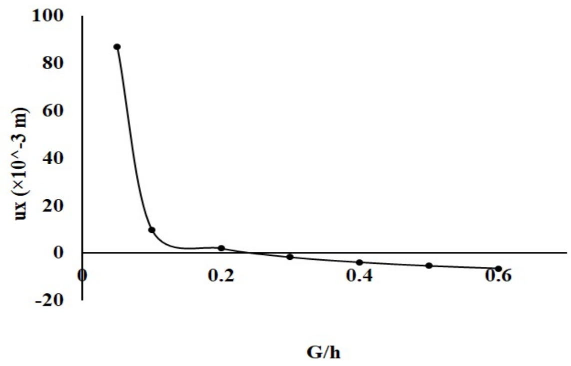

Figure 19: Graph of u_x verses G/h

4.8 Effect of embedment depth in anchored sheet pile wall

With the increase in embedment depth, the factor of safety increases whereas the horizontal displacement is decreased which can be seen in Figure 20.

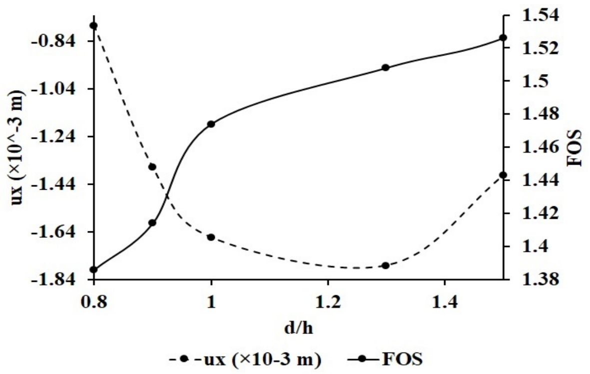

Figure 20: Graph of FOS and u_x verses d/h

4.9 Effect of water table variation

The water table elevation is varied from 70m to 45m and the results obtained are shown in Figure 21. The figures indicates that the factor of safety increases for lowered water table. However, the trend of increase of FOS when water elevation is decreased from ground level upto dredge level (60m) is different from the trend it follows when water elevation further decreases from dredge level to 45m. Also, the decrease in water elevation below 55m doesn't affect the factor of safety of sheet pile wall. Figure 21 suggests that decrease in water table beyond dredge level doesn't result much effect on the lateral displacement of the top of wall.

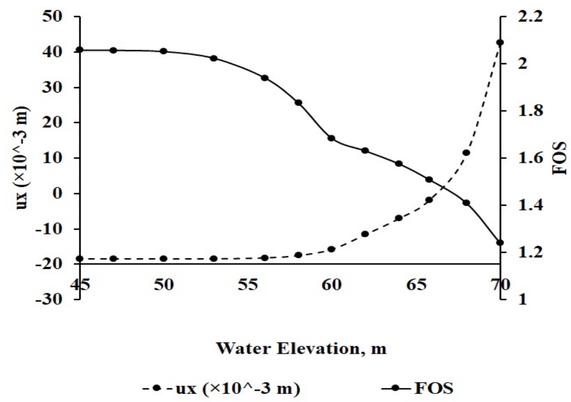

Figure 21: Graph of FOS and u_x verses $WaterElevation$

5. Conclusions

For the soil considered in this study, cantilever sheet pile wall seems to perform well for excavation depth upto 5m, with a minimum embedment depth equal to 1.1 times the excavation depth, above which anchored sheet pile wall is required. For single anchored sheet pile wall, angle of inclination between 10° and 30° results greater value of factor of safety and lower value of deflection. Installation of anchor close to the final excavation depth and late installation of anchor results more deflection. So, installation of an anchor at z/h=0.2 immediately after excavation reaches this position proves beneficial. Pre-stress force on anchor has significant contribution in the deflection control. The obtained results from varying unbonded anchor length support the concept of choosing the length of unbonded anchor based on the location of critical potential surface as suggested by [8]. The position of ground water table affect both the factor of safety and lateral displacement of sheet pile wall but the effect is negligible when the GWT is half of the excavation depth below the dredge level.

References

[1] Leila Eskandari and Behzad Kalantari. Basic types of sheet pile walls and their application in the construction industry–a review. *Electronic Journal of Geotechnical Engineering*, 16, 2011.

[2] Braja M Das and Nagaratnam Sivakugan. *Principles of foundation engineering*. Cengage learning, 2018.

[3] Kristian Krabbenhoft, Lars Damkilde, and Sven Krabbenhoft. Ultimate limit state design of sheet pile walls by finite elements and nonlinear programming. *Computers & structures*, 83(4-5):383–393, 2005.

[4] Ömer Bilgin. Lateral earth pressure coefficients for anchored sheet pile walls. *International journal of geomechanics*, 12(5):584–595, 2012.

[5] Chang-Yu Ou, Pio-Go Hsieh, and Dar-Chang Chiou. Characteristics of ground surface settlement during excavation. *Canadian geotechnical journal*, 30(5):758–767, 1993.

[6] Michael Long. Database for retaining wall and ground movements due to deep excavations. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(3):203–224, 2001.

[7] Christian Moormann. Analysis of wall and ground movements due to deep excavations in soft soil based on a new worldwide database. *Soils and Foundations*, 44(1):87–98, 2004.

[8] FHWA FHWA. Geotechnical engineering circular no. 4: Ground anchors and anchored systems, 1999.

[9] F Azizi. Applied analyses in geotechnics; e & fn spon, 2000.

[10] Ömer Bilgin. Numerical studies of anchored sheet pile wall behavior constructed in cut and fill conditions. *Computers and Geotechnics*, 37(3):399–407, 2010.