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Numerical Study of Sheet Pile Walls to Facilitate Rural Construction

Yeetendra Kumar Bind*, N. N. Harry, Vikas Srivastava, Yogendra Kushwaha
Department of Civil Engineering, SSET, SHUATS, Allahabad, UP, India
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*yeetendra@gmail.com

ABSTRACT

Many rural structures require initial protection of construction area from waterbodieslike construction of;embankmentsto hold flood water,civil facilities near lakes or ponds, and culverts passing from catchment areas etc.Sheet pile walls is the well-known temporary structure used to facilitate the construction of water front structures in different water bodies like ponds, lakes and rivers etc. This paper is intended to formulate a simple method to study Influences of ground water variation, embedment depth and type of soil on the pressure distribution and maximum bending moment in a sheet pile wall.Depth of embedment below dredge level was first determined from commonly used classical method. Later on, Location of maximum bending moment, allowable lateral displacement and stress distribution etc were obtained from numerical analysis using PLAXIS finite element modeling. The results are presented in terms of the wall deformations and bending moments. The obtained results indicate that finite element modeling technique can yield quite safe design measure of cantilever sheet pile wall compared to classical methods.

Keywords: Cantilever sheet pile wall; Maximum bending moment; Finite element modeling.

1. INTRODUCTION

Sheet piles are thin interconnected sheet structures used for preparing a workable area for various type of construction.Though sheet piles are primarily used for providing safe construction site, however, its uses are not limited. They are also used as flood defense system to protect environment. They also help in balancing ecosystem by offering a suitable means of bank protection, cut off in flood embankments and sloe stabilization etc. The interconnection (braced cuts) may be useful in excavation near existing building to protect the lateral yielding of existing foundation, Isolating the area of bridge abutment (bulkheads) and preparing a temporary enclosures located in the waterbodies to facilitated the construction of foundation system for bridges etc.Sheet pile walls were rarely designed before beginning of the 20th Century, dating the first design methods from the early 1900's, Tsinker (1997). It was in the 1950's, when sheet pile walls were broadly established as a solution to the problems associated with deep excavations near buildings, subterranean structures or below the water table. Since then, the growing need to use scarce land efficiently, along with the specialized machinery with a greater efficiency, has led to an increase in the use of sheet pile walls. Sheet piles are steel section almost 7-30 mm thick and 400-500 mm wide and manufactured in different lengths depending on the requirement, Ergun (2008). Shapes of sheet piles also varies (like U, Z and straight line sections) and are decided by standards of different country. Edges of each sheet piles are made like the shape of an interlocking grooves so that every sheet pile may be connected together. They are inserted into the ground by hammering or vibrating.

Although design methods have been constantly reviewed and improved, but these have not changed much from past 50 years Bowles (1988), Padfield& Mair(1984) and King (1995). Despite the development of numerical methods in the last decades, the classical analytical methods are still broadly used in geotechnical engineering for the design and analysis. Many authors reviewed conventional limit-state based design methods and found that failure criteria of a cantilever sheet pile wall is slightly conservative, Day (1999) and Day (2001).

This paper is the extension of research paper titled "Numerical and analytical methods for geotechnical design of cantilever sheet pile walls", Bind *et al*. 2016. Cantilever steel sheet pile penetrating sandy and clayey layers below dredge level were analyzed in this paper. Design parameters like embedment depth magnitude and location of the maximum bending moment of the sheet pile were obtained in this research article. However, this research papers aimed to study the effect of variation of ground water table, angle of friction and type of soil on embedment depth.

2. REVIEW OF PROBLEM

The previous study analyzed sheet pile for two cases of soil layers. Case-1 is the sandy soil above and below the dredge level (but different unit weights) and case -2 is the sandy soil above the dredge level and clay soil below dredge level. Cantilever sheet pile walls are usually recommended to retain moderate heights for about 6m above the dredge line. Therefore, the present study also adopts the retained height as 6 m for the analysis. The water table is considered at the middle of the retained height. The assumed geotechnical parameters like soil friction angle and unit weights etc. for case-1 & 2 aredepicted in Fig. 1a & b.

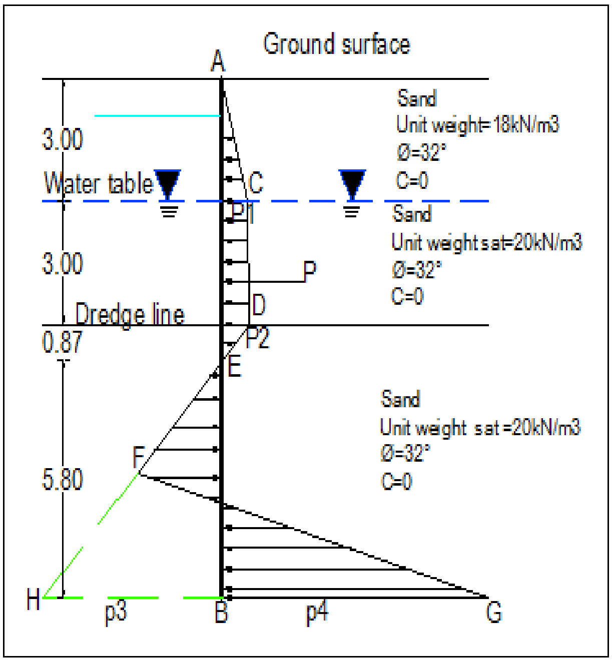

Fig. 1(a): Cantilever sheet pile in sandy soil (case-1).

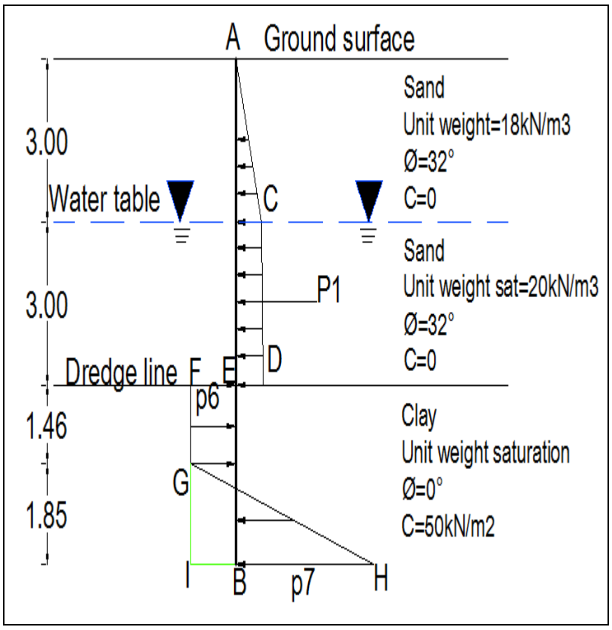

Fig. 2(b): Cantilever sheet pile in clay soil (case-2).

Full method also known as UK method assuming active state in the back of the wall and the extent of active state distributed above the rotation point, whereas passive state considering in front of the wall between the dredge line and the rotation point, gave net pressure distribution as shown in Fig.1a & 1b.

For detailed method of determination of pressure distribution diagram, embedment depth (D) and maximum bending moment using classical approach kindly refer Bind et al 2015. Using classical method, the embedment depth and maximum bending moment were calculated as 6.67m &444.09KN-mrespectively for case 1 and 3.30m &222.24KN-m respectively for case 2.

3. FORMULATION OF PROBLEM

Finite element analysis is relatively faster compared to classical approach. Therefore, no. of variables/treatment were increased in FEM analysis to get benefited from its robust calculative power. The major response parameter was embedment depth while, retained height, angle of friction and ground water conditions were adopted as shown in Table- 1. It can be seen from Table- 1 that total 3^3=27 and 3^3 * 1= 27 combination were possible for case 1 and 2 respectively. However, only one combination from each case is discussed here.

Table 1. Selected values of variables.

Parameters for Case 1 & 2			Parameters for Case 1
Retained Height (m)	**Angle of Friction (Degree)**	**Ground water table**	**Cohesion (kN/m²)**
6.0	30.0	Top	
4.5	35.0	Middle	37.5
3.0	40.0	Bottom	

4. FINITE ELEMENT METHOD

The continuously increasing complexity in the analysis of a sheet pile wall supported by multiple rows of anchors led the use of numerical techniques like finite element analysis in the field of retaining structures. Latter on finite element analysis was successfully applied in several other retaining structures. Potts &Fourie (1984) and Powrie (1996) applied FEM technique on propped walls.

4.1 Numerical Approach

PLAXIS two-dimensional Finite Element computer program was used to perform deformation and stability analysis. Real situations may be modeled either by a plane strain or by an ax symmetric model.

4.1.1 Model Geometry

The first step consists of the creation of the geometry of the model. On the general settings window, shown in Figure 5.1, the user can select the general model used (plane strain), the element type (15-node triangle) and the dimensions. Set of lines creating a closed polygonal can be used as soil vicinity in which soil properties were applied. No. of polygons were created to represent various layers of soil. Sheet pile walls and interfaces were modeled from Diaphragm 30 element resembling "Plate". Back and front of the wall can be quickly created in Plate element. Model geometry and boundary conditions representing case 1 & 2 are depicted in Fig. 2a & 2b.

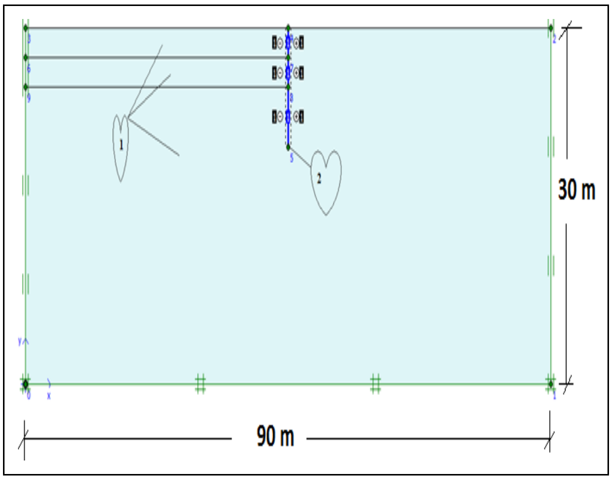

Fig. 2a: Model Geometry case1. (1) Clusters. (2) Sheet pile wall.

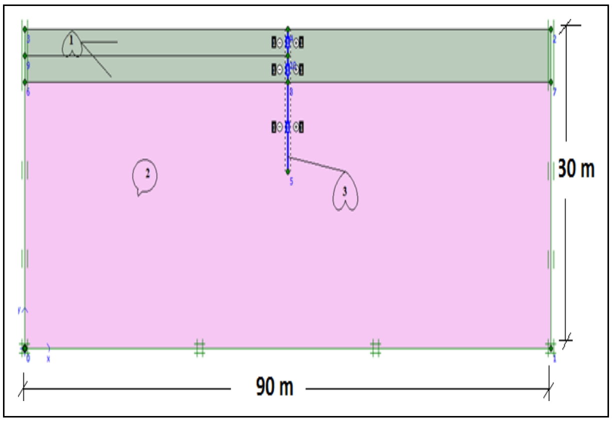

Fig. 2b: Model Geometry case2. (1 and 2) Clusters. (3) Sheet pile wall.

4.1.2 Material Properties

Drained type soil material with Mohr-Coulomb material model was selected for both cases. The material properties were applied to each soil layer after completing material sets. The other parameters selected in both cases are described in Table 2. The at-rest coefficient was manually introduced in initial stress generation phase. PLAXIS enables entering into various other properties, which are not discussed here since they were insignificant for undertaken problem. In addition,properties can vary as per the requirement. Plates are structural elements, similar to beam, and therefore a bending stiffness (EI) and an axial stiffness (EI) must be introduced. Table 3 represents the assumed parameters for Diaphragm 30 element.

Table 2. Soil parameters.

Mohr-Coulomb		Case(1) Loose sand	Case(2) Medium Clay
Type		Drained	Drained
γ_{unsat}	[kN/m³]	17.00	17.50
γ_{sat}	[kN/m³]	19.00	19.50
k_x	[m/day]	1.000	0.001
k_y	[m/day]	1.000	0.001
e_{init}	[-]	0.500	0.500
c_k	[-]	1E15	1E15
E_{ref}	[kN/m²]	18000.000	5000.000
μ	[-]	0.280	0.450
G_{ref}	[kN/m²]	7031.250	1724.138
E_{oed}	[kN/m²]	23011.364	18965.517
c_{ref}	[kN/m²]	0.00	37.50
ø	[°]	30.00	0.00
ψ	[°]	0.00	0.00
E_{inc}	[kN/m²/m]	0.00	0.00
y_{ref}	[m]	0.000	0.000
$c_{increment}$	[kN/m²/m]	0.00	0.00
$T_{str.}$	[kN/m²]	0.00	0.00
$R_{inter.}$	[-]	1.00	1.00
Interface permeability		Neutral	Neutral

4.1.3 Discretization

The subsequent calculations required the discretization of the problem and it was achieved by the meshing. The coarse mesh was generated in the preliminary analysis. Then, points or areas (with concentrations of stress) where better accuracy was desired, were found. The global mesh of the model in these areas were adjusted. Fine meshes provides better accuracy, however, computing time increases considerably. Therefore, accuracy of results were compromised (up to certain extent) to achieve a better balance over time. Initial water pressure and initial effective stresses were specified once after completion of meshing. An illustration of generated mesh for case 2 is given in Fig 3 below.

Table 3. Beam element parameters.

Element	EA	EI	w	μ	Mp	Np
	[kN/m]	[kNm²/m]	[kN/m/m]	[-]	[kNm/m]	[kN/m]
Diaphragm 30	4.118E7	1.38E5	10.00	0.00	1E15	1E15

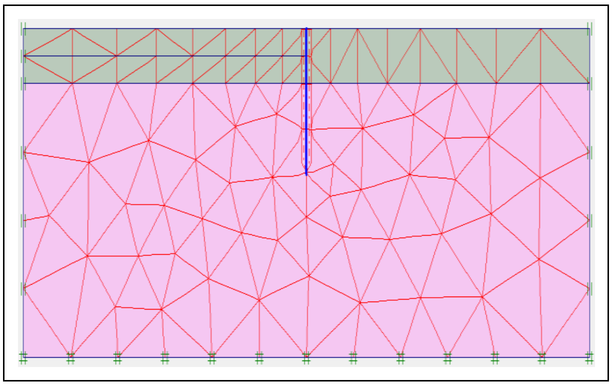

Fig. 3: Generated mesh for clay soil.

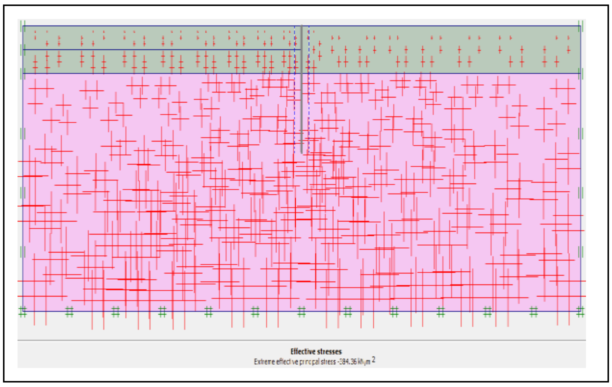

Fig. 4: Initial effective stresses clay soil.

5. RESULTS & DISCUSSION

Effect of three parameters namely retained height, frictional angle and ground water level on deformation and stability were observed. Assumed parameters facilitated calculation of embedment depth, stress distribution and bending moment etc. from classical and finite element approach.

5.1 Results from Classical Approach

The pressures p_1, p_2, p_3& p_4 acting per meter square area of the sheet pile wall and the embedment depth have already been reported in Fig.1 for case 1. Using classical method embedment depth and maximum bending moment were calculated as 6.67m and 444.09KN-mrespectively for case-1 and 3.30m and 222.24KN-m respectively for case 2.

5.2 Results from FEM Using PLAXIS

After filling all the details of FEM, the initial stresses were generated in the cantilever sheet pile model penetrating sandy and clayey soil and is presented for clayey soil (case 2) in Fig.4. Similarly, pore water pressure was also generated for both cases and is shown for sandy soil (case-1) in Fig. 5. It can be seen that effective stresses and pore water pressure were gradually increasing with increasing depth.

It can be seen that entire region is made from blue color representing sandy soil. Fig.4 illustrates the deformation of mesh and subsequent deformation of sheet piles after application of loading.

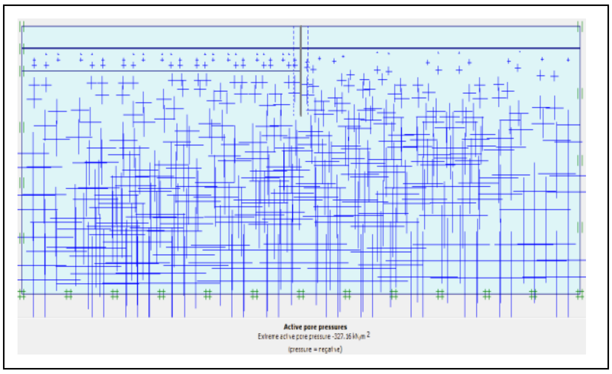

Fig. 5: Initial pore water pressure for sand soil

The results of embedment depth and displacements (in conjunction with Table 1) obtained from FEM analysis for case 1 & 2 is presented in Table 4 and 5 respectively. It can be observed that embedment depth and displacement decreases with increasing angle of friction in case of sand. However, displacement increases with increasing angle of friction when sand is located above dredge level and clay is located below dredge level. In addition, embedment depth also increases with an increase in angle of friction in sand located above dredge line. Plot of total displacement can be seen in Fig. Embedment depth increases with decreasing water table in both cases since lower water table decreases lateral pressure from both sides resulting instability from both sides.

Plot of total displacement (mean shading) can be seen in Fig. 6a for case 1. The location and magnitude of total displacement is also provided in the figure. The dark red to light blue color shows highest to lowest total displacements. Fig. 6b shows the displacement due to stresses tending to produce deformation in cantilever sheet pile at the front face.

Table 4. Variation of embedment depth and displacements for sandy soil.

Retained Height	Phi (Degree)	Ground water table					
		Top		Middle		Bottom	
		Embedment Depth	Displacement	Embedment Depth	Displacement	Embedment Depth	Displacement
6.0	30.0	5.5	0.0010	6.5	0.0080	7.5	0.0080
	35.0	4.5	0.0003	5.5	0.0020	6.0	0.0020
	40.0	5.5	0.0010	5.5	0.0004	5.5	0.0004
4.5	30.0	3.0	0.0020	4.5	0.0010	4.5	0.0020
	35.0	3.0	0.0001	3.0	0.0003	3.0	0.0030
	40.0	3.0	0.0001	3.0	0.0001	3.0	0.0001
3.0	30.0	2.0	0.0003	2.5	0.0020	2.5	0.0010
	35.0	1.5	0.0001	2.0	0.0001	2.0	0.0001
	40.0	1.5	0.0001	2.0	0.0003	2.0	0.0003

Table 5. Variation of embedment depth and displacements for clay soil.

Retained Height	Phi (Degree)	Ground water table					
		Top		Middle		Bottom	
		Embedment Depth	Displacement	Embedment Depth	Displacement	Embedment Depth	Displacement
6.0	30.0	3.0	0.007	6.5	0.010	10.0	0.012
	35.0	4.0	0.007	7.0	0.010	10.5	0.012
	40.0	4.5	0.008	8.0	0.012	11.0	0.009
4.5	30.0	2.0	0.005	3.0	0.006	5.0	0.007
	35.0	3.0	0.004	4.0	0.006	5.5	0.008
	40.0	4.0	0.006	7.0	0.008	12.0	0.009
3.0	30.0	2.0	0.002	3.0	0.003	3.0	0.004
	35.0	1.5	0.003	3.0	0.004	5.0	0.005
	40.0	3.0	0.003	3.0	0.005	5.0	0.006

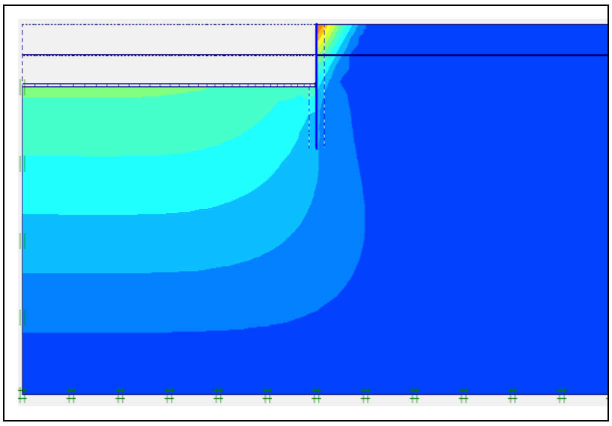

Fig. 6a: Plot of total displacements (mean shadings) for case 1.

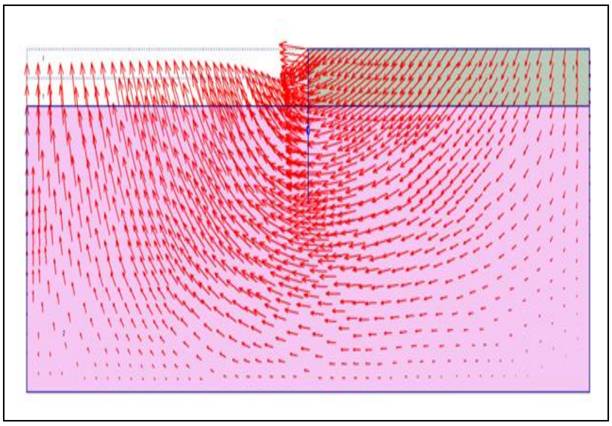

Fig. 6b: Plot of total displacements (arrows) for case 2.

The direction of effective stresses can also be seen in the Fig. 7 & 8 for case 1 & 2 respectively. It can be observed that near sheet piles, the direction of effective stresses are disturbed (neither horizontal nor vertical) compared to Fi. 4. The probable explanation for this is the presence of sheet pile wall. Away from sheet pile, the direction of effective stresses remain undisturbed.

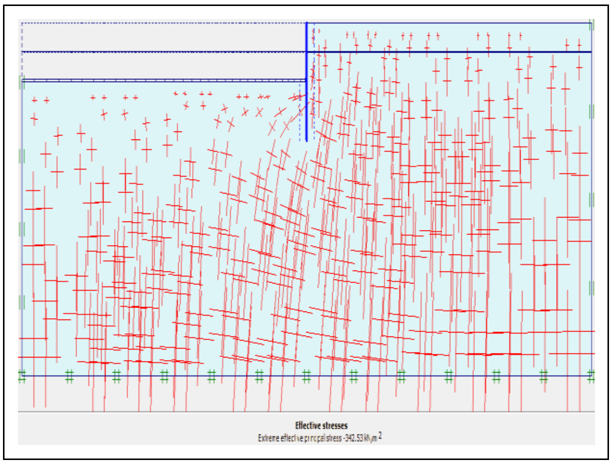

Fig. 7: Plot of effective stresses for case 1 (principal directions).

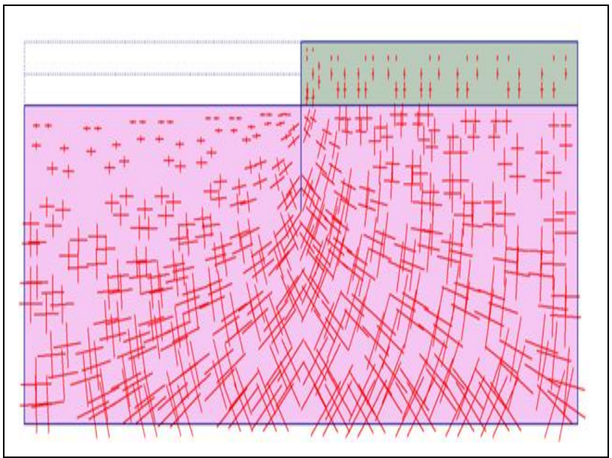

Fig. 8: Plot of effective stresses for case 2(principal directions).

The maximum total displacement in beam penetrating sandy soil was *130.69x10-*^{3}m. However, maximum horizontal and vertical displacements were -*124.51x10*$^{-3}$ m *39.72x10-*^{3}m respectively at the front direction of the sheet pile. The total, horizontal and vertical displacements are illustrated in Fig. 9.

The maximum values of axial force, shear force and bending moment were obtained as *-44.08 kN/m, -89.88 kN/m and -282.07*kN-m/m length of wall respectively.Fig.10 illustrates the distribution of axial force, shear force and bending moment throughout the length of the wall.

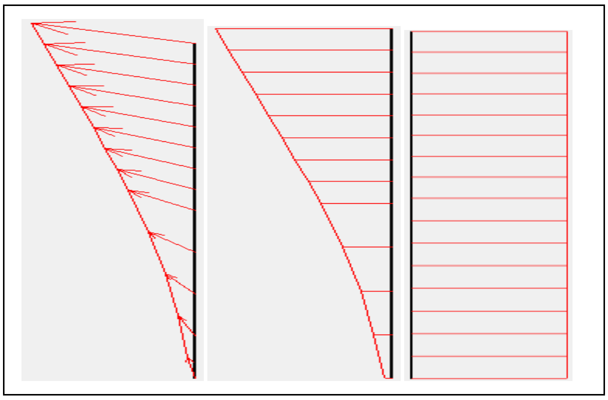

Fig. 9: Total, Horizontal and vertical displacements in beam (case 1).

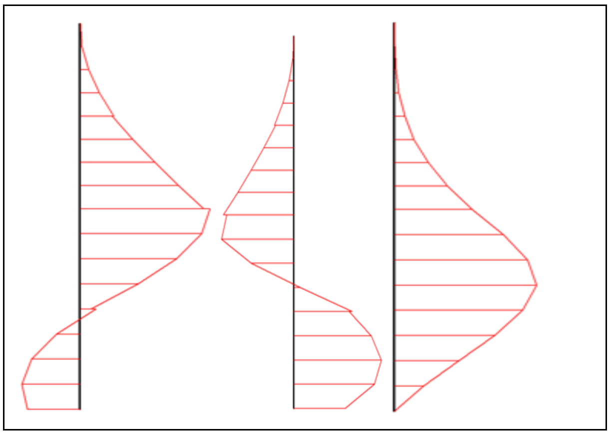

Fig. 10: Axial forces, shear forces and bending moments in beam (Case 1).

The extreme total displacement obtained in beam was *259.66x10-3*m, However, extreme horizontal displacements was *-258.62x10-3* m at the front direction of the sheet pile for case 2 Fig.11. The extreme values of axial force, shear force and bending moment were obtained as *-110.92* kN/m *79.59* kN/m *-189.91* kN-m/mlength of wall respectively.Fig.12 illustrates the distribution of axial force, shear force and bending moment throughout the length of the wall for case 2.

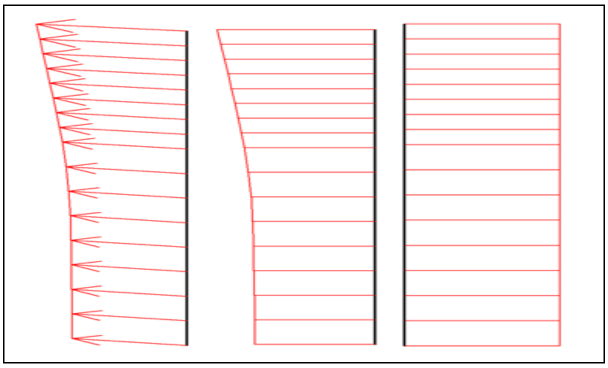

Fig. 11: Total, horizontal and vertical displacements in beam (case 2)

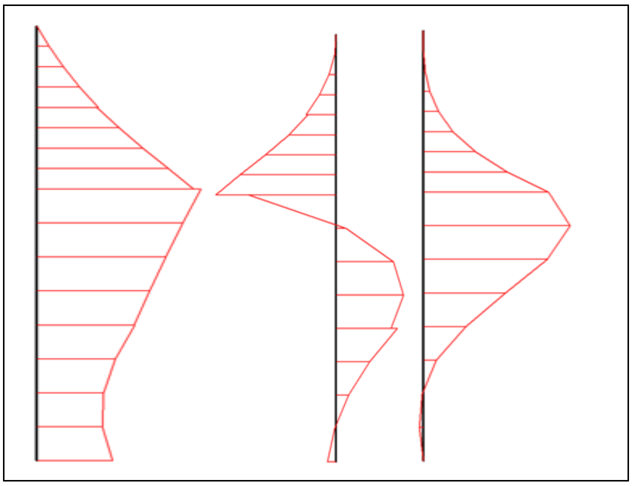

Fig. 12: Axial forces, Shear forces and Bending moments in beam (Case 2).

Displacements, forces, magnitude and location of maximum bending moment etc. reported above only for few combinations of retained height, water table and soil type (angle of friction) using FEM approach since it was not possible to provide these values for all cases.

6. CONCULSION

An elastic-plastic material with two dimensional strain was used in PLAXIS to model actual soil condition. The primary assumption considered each layer of soil as homogeneous material following Mohr-Coulomb failure criterion. A sufficient size of geometry (30 m X 90 m) was used to demonstrate the stress distribution in the vicinity of soil. Analysis of cantilever sheet pile through classical method penetrating sandy and clay soil showed substantial involvement of time and human expertise. Whereas, numerical analysis gives fast and more precise results. The lateral displacement from numerical analysis was within the limit of allowable lateral displacement. However, classical methods are either incapable or involve very complex calculation in determining the same.

PLAXIS showed that embedment depth decreases when water table is situated on both side of wall (front and back) at great height that is near to ground level since it dispenses the stresses uniformly on the surface of sheet pile, which enhances the stability. Plots and values of displacements shows that at the top of the sheet pile, the displacement is highest and it goes on decreasing towards the bottom. The effective stresses diagram shows that near to sheet pile the effective stresses get disturbed due to disturbances created from the installation of sheet pile. However, effective stresses remain undisturbed far away from the sheet pile. The model is useful in flood defense system used to protect environment from hazard.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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