Analysis of the Behavior of Inclined Anchor by Varying the Inclination and Elevation of Tie

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Abstract

Sheet pile wall system is considered one of the oldest common earth retention systems used in civil engineering projects. The common methods used in the design of sheet pile walls were based on the limit equilibrium approach using active and passive earth pressures. These methods - based on force and moment equilibrium- don't consider wall deformations, which are very important for achieving serviceability. An extensive parametric study through the finite element program, PLAXIS version 8.6 was carried out to investigate the behavior of inclined anchored sheet pile walls, studying the effect of varying the inclination of tie, and effect of elevation of tie for different sand soil types, wall height, effect of ground water table to show the effect on horizontal wall displacements, maximum wall bending moments, and anchor force for all cases. The minimum values of the wall penetration depth, unbonded length and bonded length were set to satisfy the requirements of the instructions of (FHWA). Analyses were performed using the finite element method. The analysis results show that the increase in the inclination of tie (ϴ) up to 20° decreases the maximum bending moments and maximum horizontal displacements of wall, but slightly increases the anchor force. After that, by increasing the inclination of tie (ϴ) the maximum bending moments, the horizontal displacements of wall and the anchor force increase. Generally, its recommended that the angle of inclination of tie doesn't exceed 20 degrees and for best angle of inclination 20 degrees is recommended. From observations of studying variation of tie elevation, it was concluded that increasing the elevation of tie (d/H) from the top of wall generally enhances the performance of the structure Maximum Wall Bending Moment and Maximum Horizontal Displacement decrease but increases the anchor force. And also, it was concluded that the best elevation of tie for bending moments is between 0.2 H - 0.3H from the top of the wall.
Keywords: Sheet Pile Wall, Elevation of Tie, Inclination of Tie

I. INTRODUCTION

Many authors in the literature have attempted to predict and analyze load carrying capacity of different retaining walls types. Some authors take into account the ability of sheet piles to deform considering the wall to be a flexible structure (Sahajda and Rymsza, 2008; McNab, 2002; Cherubini, 2000; Endley et al., 2000; and Valsangkar Schriver and, 1996).Others used the finite element technique in their analysis to investigate the behavior and failure mechanisms of the structure (Bilgin (2009), Warrington and Don, 2007; Krabbenhoft et al., 2005; Damkilde and Krabbenhoft, 2003; Sloan and Lyamin, 2002 and Lim and Briaud, 1999).Sheet pile walls are used for various purposes; such as excavation support system, cofferdams, and cut-off walls under dams, slope stabilization, waterfront structures, and floodwalls. Although there are several other materials (such as timber, reinforced concrete, and plastics) used for sheet piles, steel sheet piles are the most common in retaining walls. The sheet pile walls can be either cantilever or anchored depending on the wall height. While relatively shorter sheet pile walls can be cantilever, higher walls require anchors. The selection of wall type, either cantilever or anchored, is based on the function of wall, the characteristics of foundation soils, and the proximity of wall to existing structures, Bilgin (2009). The objective of this study was to investigate the maximum horizontal wall displacement, maximum wall bending moment and anchor force for two main cases, the first parameter studies the change in inclination of tie for [loose sand (LS), medium dense sand(MS) and dense sand(DS)] for wall heights 8m and 12m. Additional modeling and analysis were performed to investigate the effect of adding water table to the same types of soil at the anchor level on both sides. The second parameter studies the change of elevation of tie for the same previous cases

II. NUMERICAL MODELING AND ANALYSES

A. *Geometry and Material Properties*

A parametric study was carried out to investigate the effect of the change in inclination and elevation of tie on wall behavior for different soil conditions. Anchored sheet pile wall was studied for this parametric study. Each model has one soil layer for the entire model. Also, the groundwater table level was assumed to be at the lower line for PLAXIS MODEL in order to use dry soils which means that no excess pore water pressures are generated for all anchored sheet pile wall cases. The anchor location was assumed to be at the anchor level at 2.0 m from ground surface. The tie inclination varies from 0 up to 40 degrees from the horizontal line. The penetration depth is set to be 3 m below the wall for all cases. known that the unbonded length is 8m and the bonded length is 7 m. The soil properties used for the analyses are listed in Table 1. Three different soil types considered were dense sand (DS), medium dense sand (MS), loose sand (LS). The cases were identified with a number followed by a two-letter code. The number refers to the wall height and two-letter code indicates the soil type as given in the parentheses above. The interface elements were introduced for the considered soils to simulate the soil- structure interaction behavior so as to predict the wall behavior more accurately. Drained soil conditions were analyzed for sand soils. The material data used for sheet pile, anchors, grouted body are listed in tables 2, 3 and 4

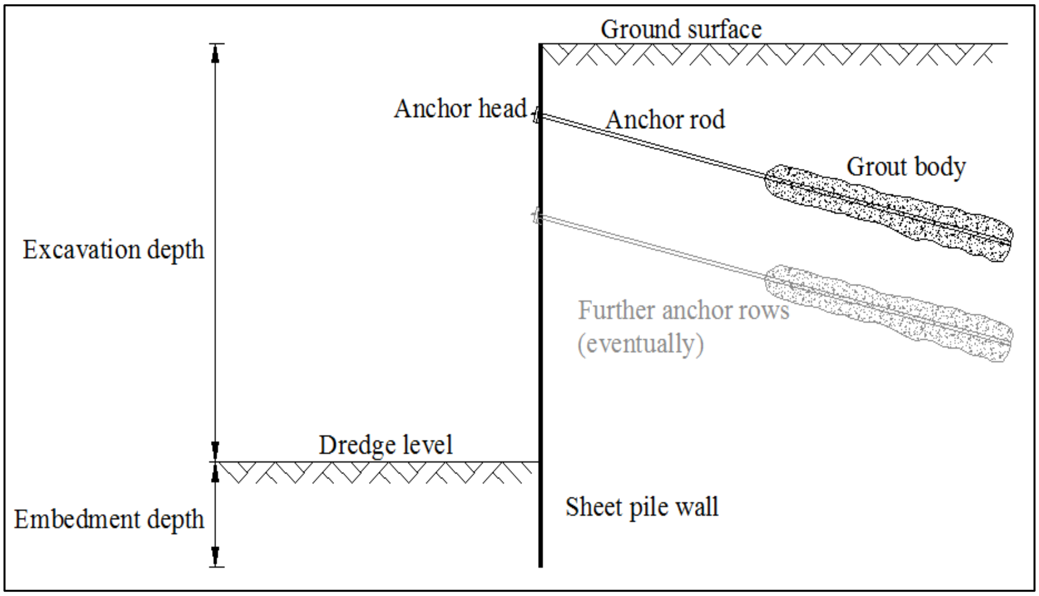

Fig. 1: Typical soil and wall profile used in parametric study

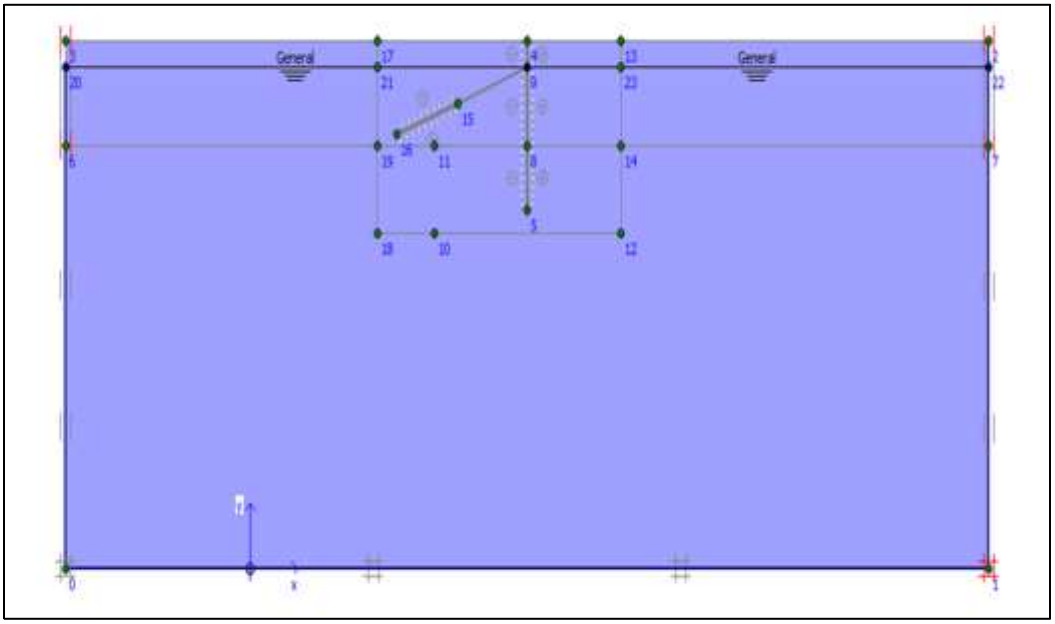

Fig. 2: Schematic of Anchored Sheet Pile Wall and Penetration Depths Analyzed for adjusted the water level to be at the anchor level on both sides of the wall

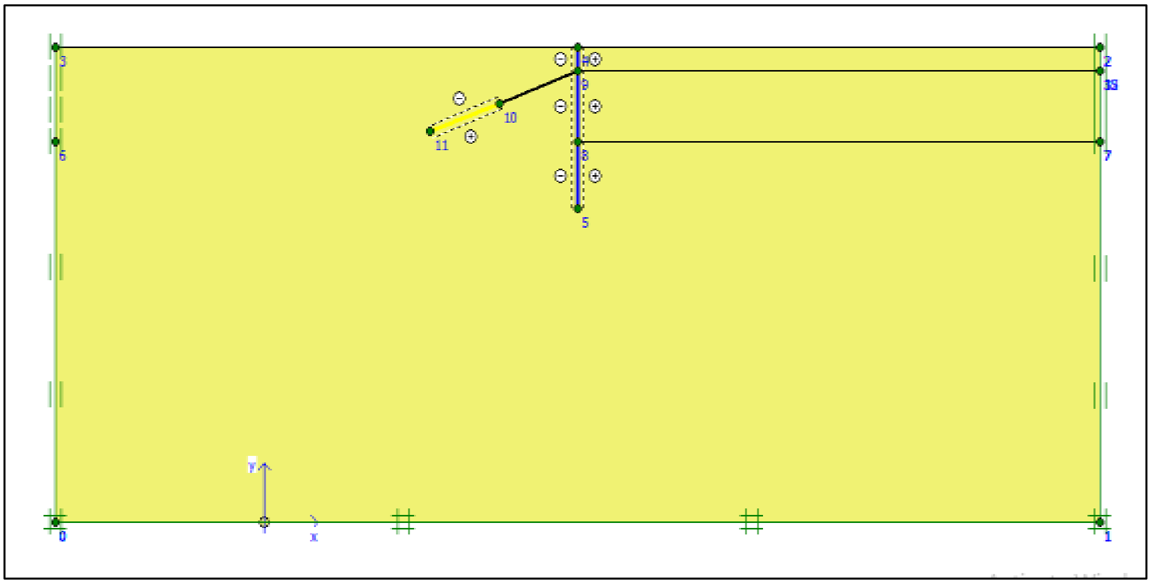

Fig. 3: Schematic of Anchored Sheet Pile Wall and Penetration Depths Analyzed

Table - 1
Material Properties for the Soil Types Studied

Parameter	Name	Loose Sand (LS)	Medium Dense Sand (MS)	Dense Sand (DS)	Unit
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	
Type of material behavior	Type	Drained	Drained	Drained	
Soil saturated unit weight	γ_{sat}	16	19	20	kN/m³
Soil unsaturated unit weight	γ_{unsat}	16	17	18	kN/m³
Young's modulus	E	2.50E+04	7.50E+04	1.30E+05	kN/m²
Friction angle	ϕ	30	36	40	°
Cohesion	C	1	1	1	kN/m²
Soil-wall interface	R_{int}	0.67	0.65	0.63	

Table - 2
Material Properties of Sheet Pile Wall (Plate) – Using PZ-40

Parameter	*Name*	*Value*	*Unit*
Type of behavior	*Material type*	*Elastic*	*-*
Normal stiffness	*EA*	*4.98E+06*	*kN/m*
Equivalent thickness	*d*	*0.5682*	*m*
Weight	*W*	*2*	*kN/m/m*
Poisson's ratio	*ν*	*0.15*	*-*

Table - 3
Properties of Grouted body (geotextile)

Parameter	*Name*	*Value*	*Unit*
Type of behavior	*Material type*	*Elastic*	*-*
Normal stiffness	*EA*	*3.00E+06*	*kN/m*

Table - 4
Properties of the anchor rod (node-to-node anchors)

Parameter	*Name*	*Value*	*Unit*
Type of behavior	*Material type*	*Elastic*	*-*
Normal stiffness	*EA*	*4.30E+05*	*kN/m*
Spacing out of plane	*L*	*1.5*	*m*

By using the (FHWA) instructions, the anchored sheet pile walls were designed for the wall height and three soil type combinations. The depth of wall penetration calculated and pile section selected were used in numerical modeling during the parametric study. The calculated anchor forces were also used to determine the anchor stiffness. The anchor force calculated by (FHWA) instructions and Plaxis 8.6 The design anchor stiffnesses, EA, used in the numerical analyses were obtained by multiplying the anchor area by the elastic modulus of steel. The variables and their ranges considered in the parametric study are given in TABLE 5.

B. Finite Element Software and Constitutive Model

Finite element analyses were performed using Plaxis finite element. The finite element modeling comprised two-dimensional plane strain analysis. The soil layers and the sheet pile walls were modeled using 15-node triangular elements. A finer mesh was used around the wall and the grout minimize the stress concentration around them. The excavation was simulated by removing soil in lifts. The complete excavation was performed on two steps, the anchor was installed when excavation reached the anchor level. Due to the cohesionless of the soils, the analyses were performed considering drained conditions.

C. Variables and Ranges Used in Parametric Study

Table - 5
Variables and Ranges Used in Parametric Study

Variable	*Range Considered*
Tie inclination	*0,10,20,30,40 (degrees)*
Tie elevation	*0.0H,0.1H, 0.2H, 0.3H, 0.4H, 0.5H*
Soil type	*Dense sand, medium dense sand and loose sand*
Wall height	*8m & 12m*

III. RESULTS AND ANALYSIS

A. Effect of Inclination of Tie

The Parametric study was performed to investigate the effect of inclination of tie (Θ) on anchored sheet pile wall behavior by using dense sand soil (ϕ = 40°) with the height (H= 8m). The minimum values of the wall penetration depth are set to satisfy the design requirements for anchored sheet pile wall cases, However, the upper range of inclination of tie (Θ) was determined by the design until a small or no change was observed in the wall behavior in terms of wall displacement and bending moments. These ranges of inclination of tie (Θ) are obtained by analyzing the results given by PLAXIS, and then plotting these results to see the change in wall behavior. The analysis results shown in figures 4 through 8 and discussed below.

1) Wall Displacement: and Bending Moment

The results show that as the inclination of tie (Θ) increases the maximum horizontal displacements and maximum wall bending moments decreases to reach a minimum value at Θ = 20° then increase as shown in figure 4 & 5. The wall bending moments change slightly for all cases studied.

2) Anchor Forces

The anchor force, for anchored sheet pile walls, increase with inclination of tie (Θ) increase as shown in 6. The percent change in anchor force with increasing inclination of tie (Θ) are shown in figure 8. the results in this figure show that by increasing inclination of tie (Θ) in dense sand soils for anchored sheet pile wall with height 8.0 m, about 27 percent increasing significant in anchor force values was observed.

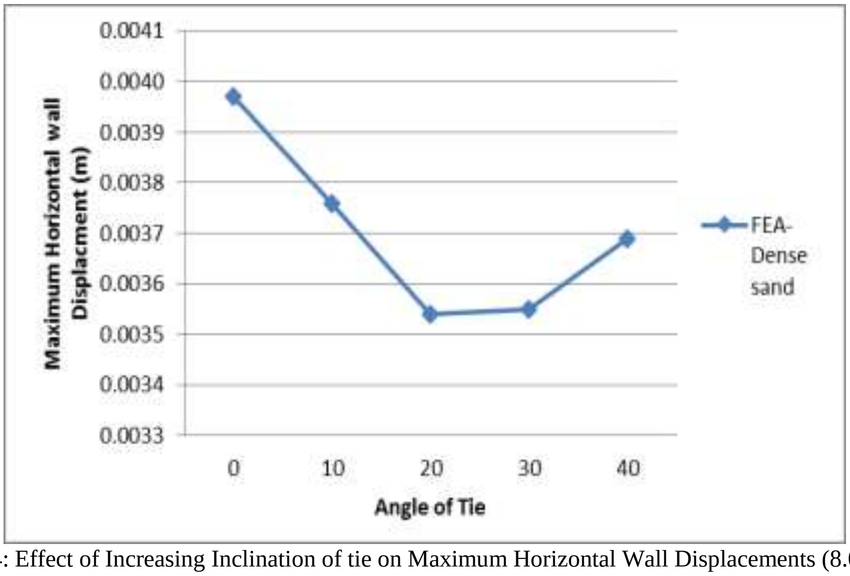

Fig. 4: Effect of Increasing Inclination of tie on Maximum Horizontal Wall Displacements (8.0DS).

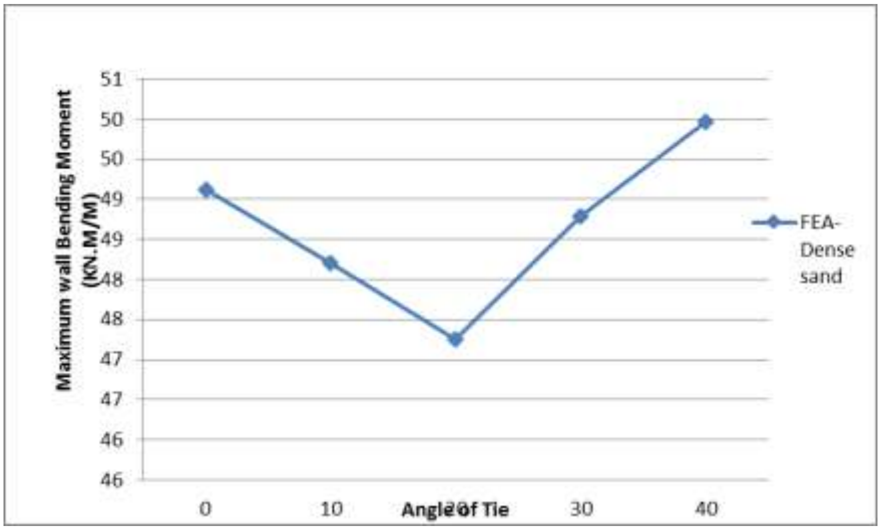

Fig. 5: Effect of Increasing Inclination of tie on Maximum Wall Bending Moments (8.0DS).

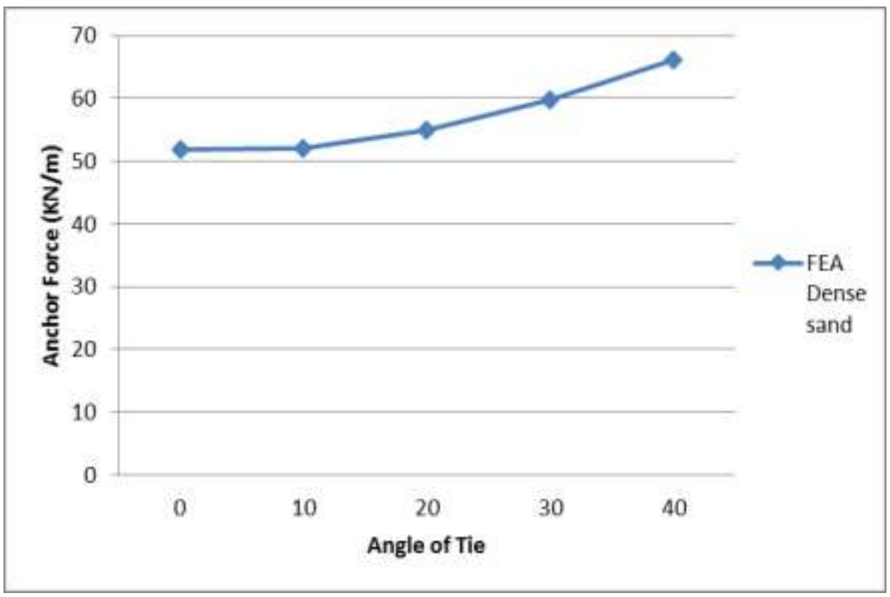

Fig. 6: Effect of Increasing Inclination of tie on Anchor force (8.0DS).

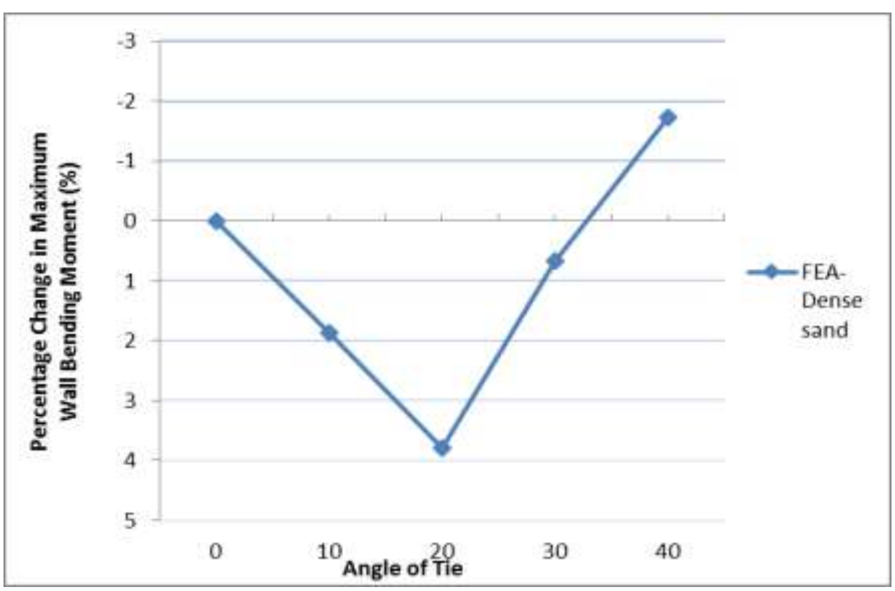

Fig. 7: Percentage Change in Maximum Wall Bending Moment with of Increasing Inclination of tie (8.0DS).

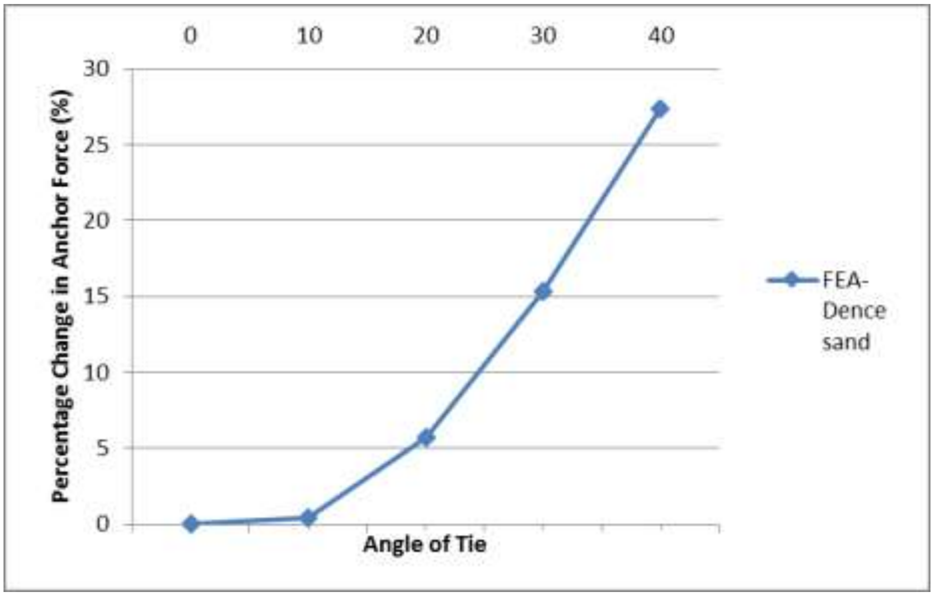

Fig. 8: Percentage Change in Anchor force with of Increasing Inclination of tie (8.0DS).

a) Effect of Soil Strength

Additional modeling and analysis were performed using medium dense sand, and loose sand soil. to investigate the effect of soil strength on the wall behavior with increasing inclination of tie (ϴ), and also to study whether the wall behavior observed for dense sand with increasing inclination of tie (ϴ)- as shown above- are similar to the walls behavior in medium dense sand or loose sand soils. Soil properties used for this parametric study were provided in (table 1).

3) The Analysis Results

The results of analysis with medium dense and loose sand soils, parallel with the results presented during first stage for dense sand soil ($\phi = 40°$), are given in figure 9, through 13. For comparative purposes. the results show that the anchored sheet pile walls in medium dense sand and loose sand soils have an identical behavior observed to those walls in dense sand soils. All the results of maximum horizontal wall displacement present in figure 9, for maximum wall bending moments in figure 10, and anchor forces in figure 11. These results display that the anchored sheet pile walls in dense sand soil, have less deformations, less bending moments, and less anchor forces with increasing inclination of tie (ϴ).

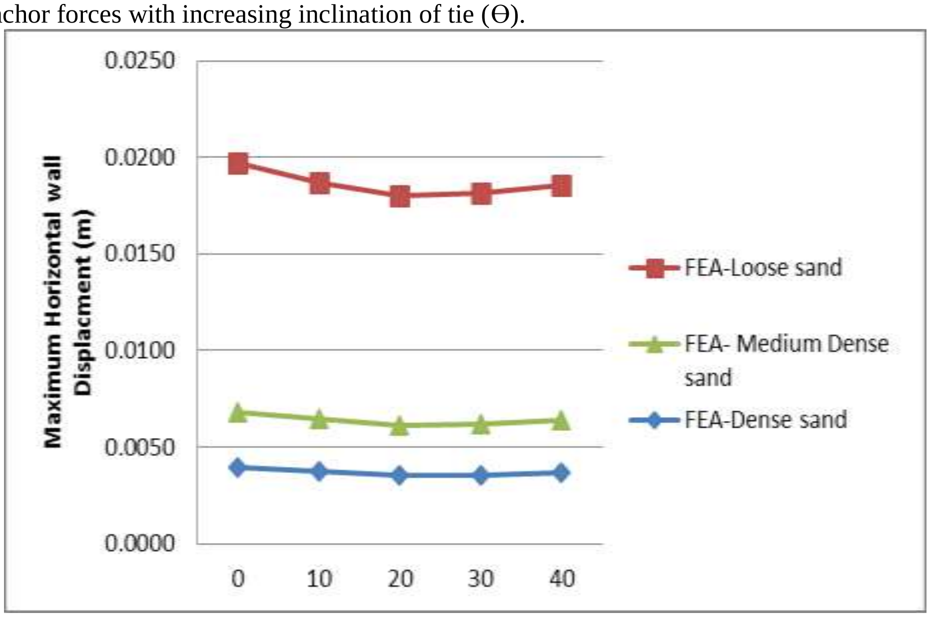

Fig. 9: Effect of Soil strength With Increasing inclination of tie (ϴ) on Maximum Horizontal Wall Displacements (Granular Soils-H=8.0).

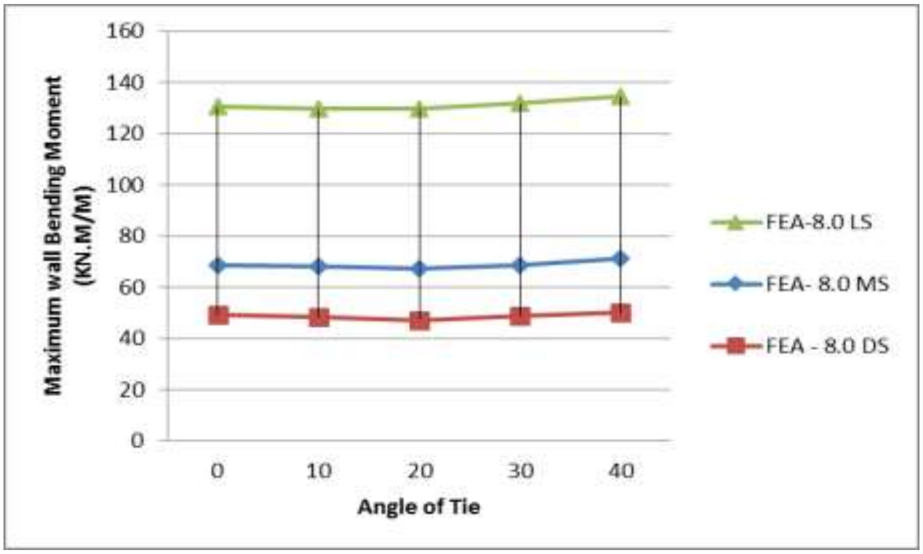

Fig. 10: Effect of Soil strength with Increasing inclination of tie (Θ) on Maximum wall Bending Moments (Granular Soils-H=8.0).

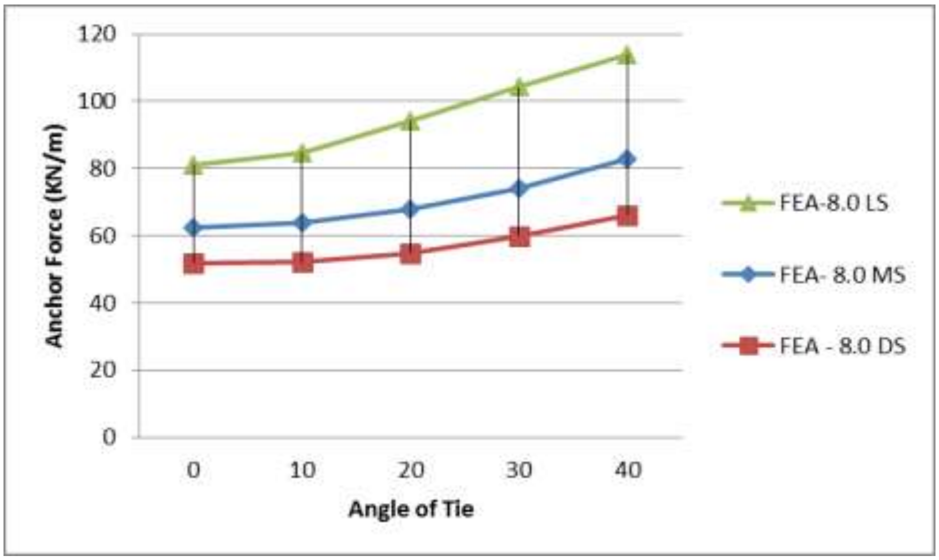

Fig. 11: Effect of Soil strength with Increasing inclination of tie (Θ) on Anchor forces (Granular Soils-H=8.0).

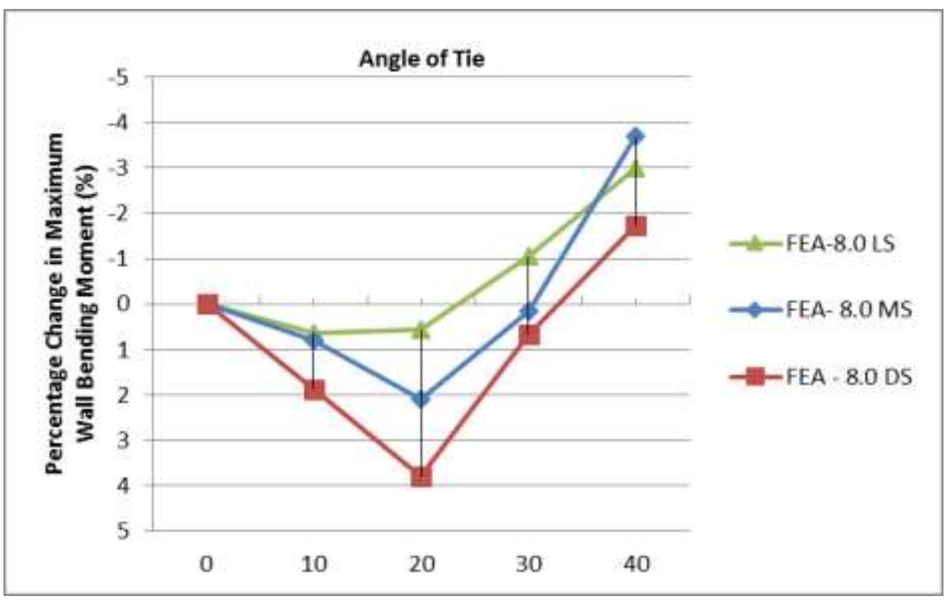

Fig. 12: Percentage Change in Maximum Wall Bending Moments with Increasing inclination of tie (Θ) (Granular Soils-H=8.0).

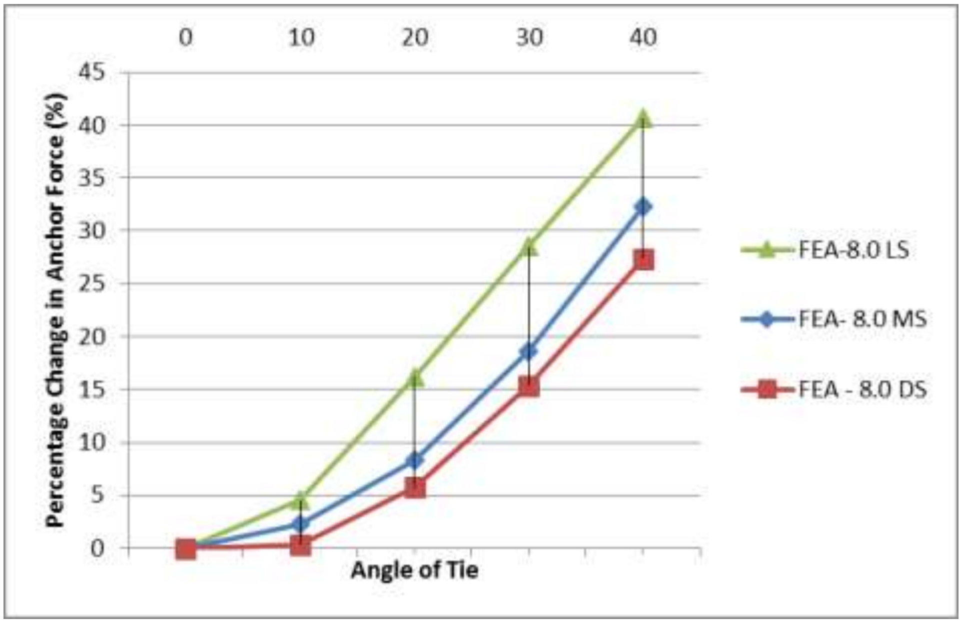

Fig. 13: Change in Anchor forces with Increasing inclination of tie (Ɵ) (Granular Soils-H=8.0).

Figures 12,13 show the percentages change in maximum wall bending moments and anchor forces in all types of sand soils. the results in figure 13 show that by increasing the inclination of tie (Ɵ) in medium dense sand and loose sand soils, more than 32 percent and 40 percent change in anchor forces were observed.

b) Effect of Wall Height (H)

The modeling and analyses were performed to investigate the effect of wall height (H) with increasing the inclination of the tie (Ɵ) on the anchored sheet pile wall behavior. This parametric study was made for 12 m high wall. the behavior was compared to the results obtained and presented earlier for the 8.0 m high wall. The results of analyses shown in Figures 14 through 19. The effect of increasing inclination of tie (Ɵ) on the wall behavior is similar for all wall heights and have similar trends, i.e. increasing the inclination of tie for H=12.0 m increases anchors forces the same as in H=8.0 m as shown in figures 17, 18 & 19.

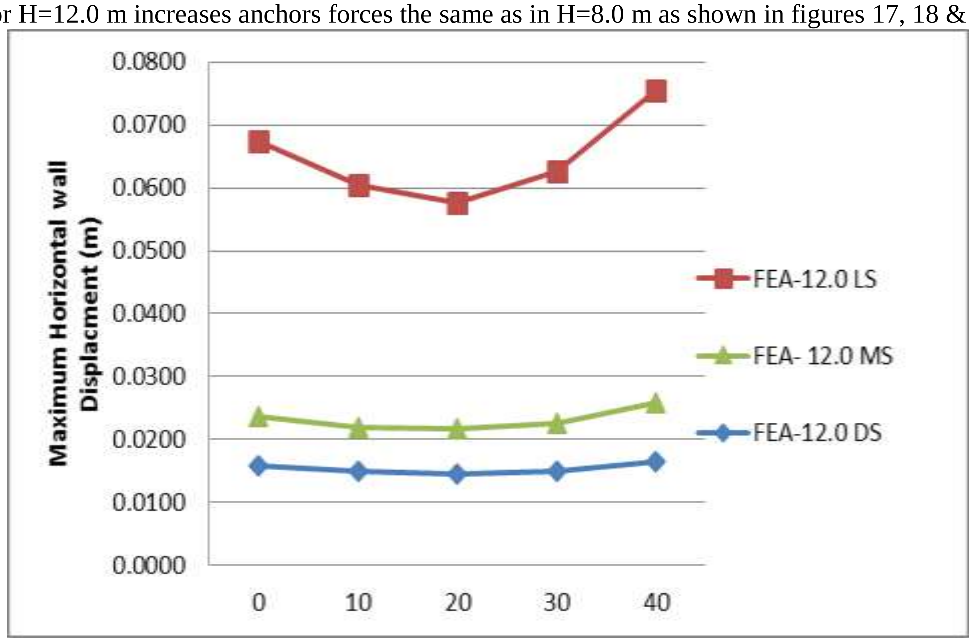

Fig. 14: Effect of Soil strength With Increasing inclination of tie (Ɵ) on Maximum Horizontal Wall Displacements (Granular Soils-H=12.0).

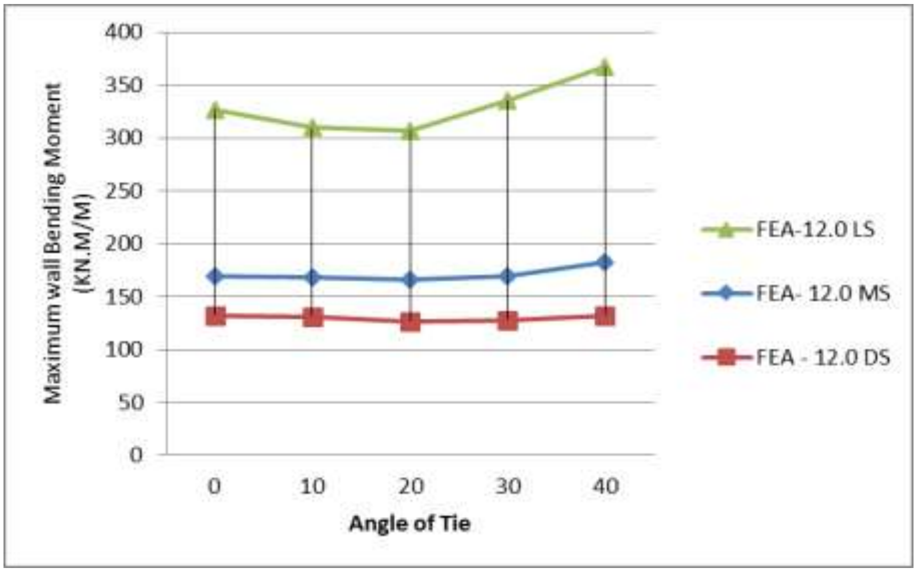

Fig. 15: Effect of Soil strength with Increasing inclination of tie (Θ) on Maximum wall Bending Moments (Granular Soils-H=12.0).

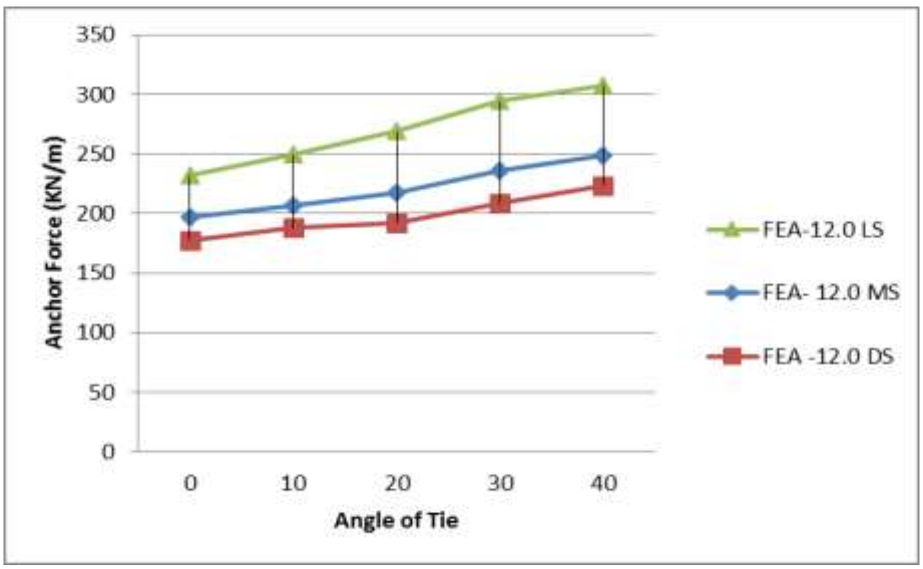

Fig. 16: Effect of Soil strength with Increasing inclination of tie (Θ) on Anchor forces (Granular Soils-H=12.0).

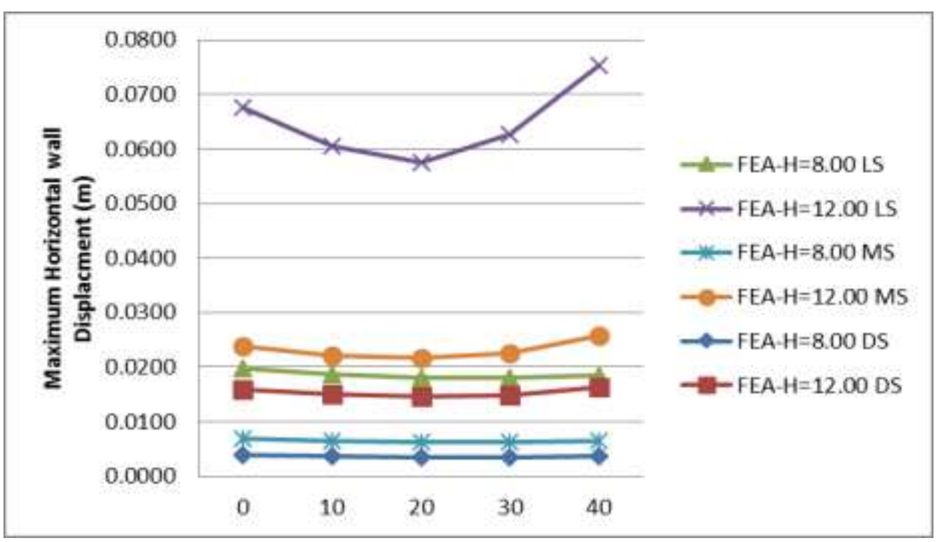

Fig. 17: Effect of Wall Height with Increasing inclination of tie (Θ) on Maximum Horizontal Wall Displacements (Granular Soils-H=12.0 and H=8.0).

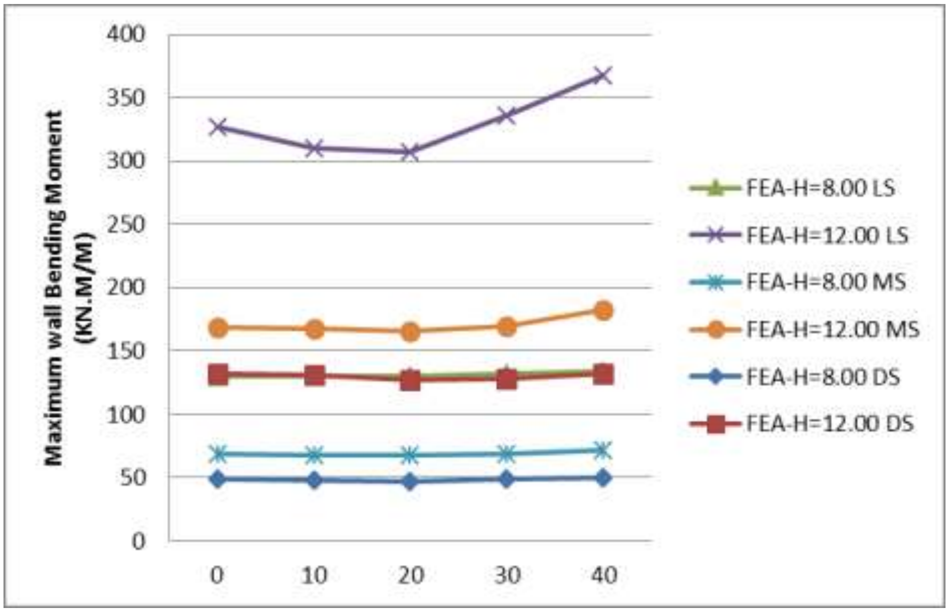

Fig. 18: Effect of Wall Height with Increasing inclination of tie (Ө) on Maximum wall Bending Moments (Granular Soils-H=12.0 and H=8.0).

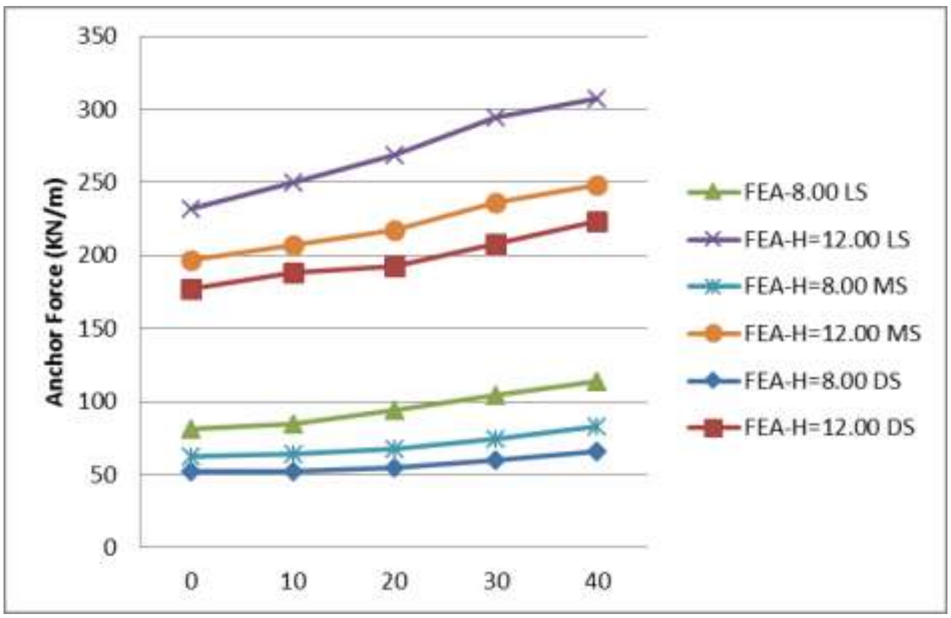

Fig. 19: Effect of Wall Height with Increasing inclination of tie (Ө) on Anchor forces (Granular Soils-H=12.0 and H=8.0).

B. Effect of Elevation of Tie

The Parametric study was performed to investigate the effect of Elevation of tie (d/H) on anchored sheet pile wall behavior by using dense sand soil (ϕ = 40°) with the height (H=8.0 m). The minimum values of the wall penetration depth were set to satisfy the design requirements for anchored sheet pile wall cases. However, the upper range of Elevation of tie (d/H) was determined by the design until a small or no change was observed in the wall behavior in terms of wall displacement and bending moments. These ranges of Elevation of tie (d/H) were obtained by analyzing the results given by PLAXIS, and then plotting these results to see the change in wall behavior.

1) The Analysis Results

Results of maximum horizontal wall displacements, maximum wall bending moments, and anchor forces with increasing of Elevation of tie (d/H), for the 8.0 m anchored sheet pile wall in dense sand soil, are shown in figures 20 through 24 and discussed below.

2) Wall Displacement and Wall Bending Moments

The results show that as the Elevation of tie (d/H) increases the maximum horizontal displacements and maximum wall bending moments decreases as expected as shown in figure 20 and figure 21

3) Anchor Forces

The anchor force in anchored sheet pile walls increases with increasing the Elevation of tie (d/H) as shown in Figure 22. The percent change in anchor force with increasing Elevation of tie (d/H) is shown in figure 24. the results in this figure show that the increase in the Elevation of tie (d/H) in dense sand soils for anchored sheet pile wall with height 8.0 m, causes about 39 percent significant increase in anchor force values.

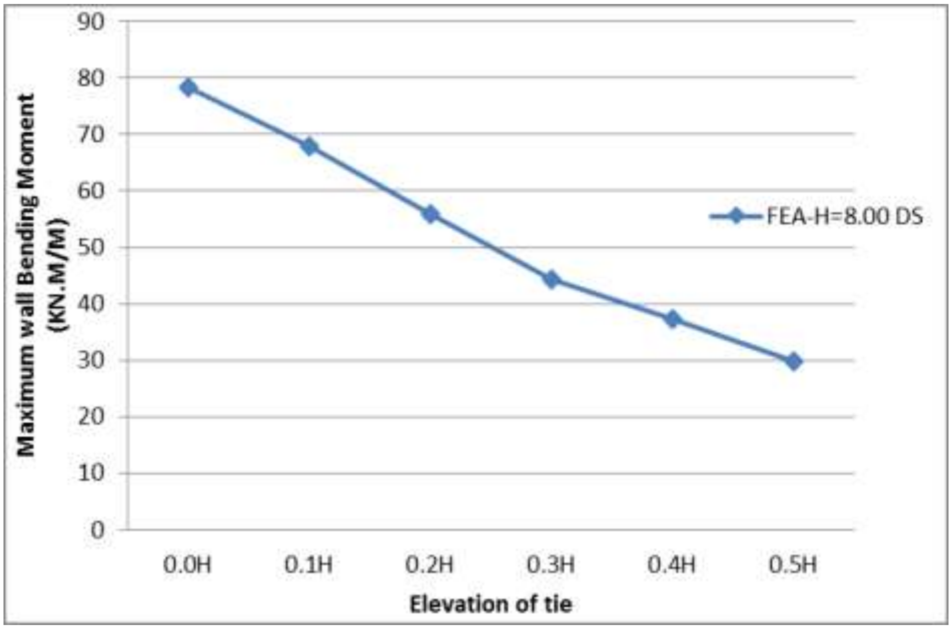

Fig. 20: Effect of increasing elevation of tie on Maximum Horizontal Wall Displacements (8.0DS).

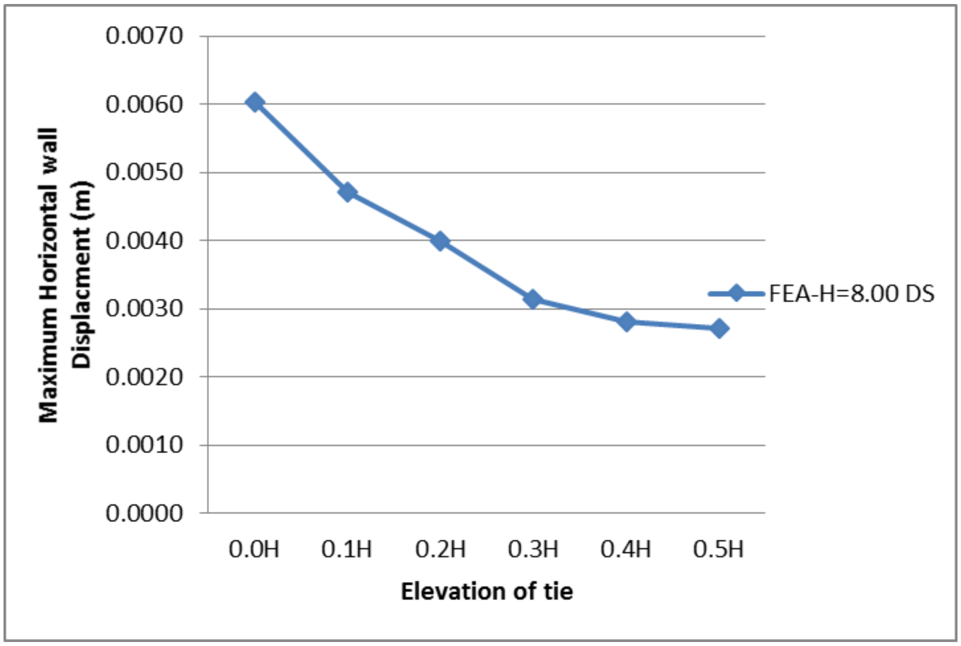

Fig. 21: Effect of increasing elevation of tie on Maximum Wall Bending Moments (8.0DS).

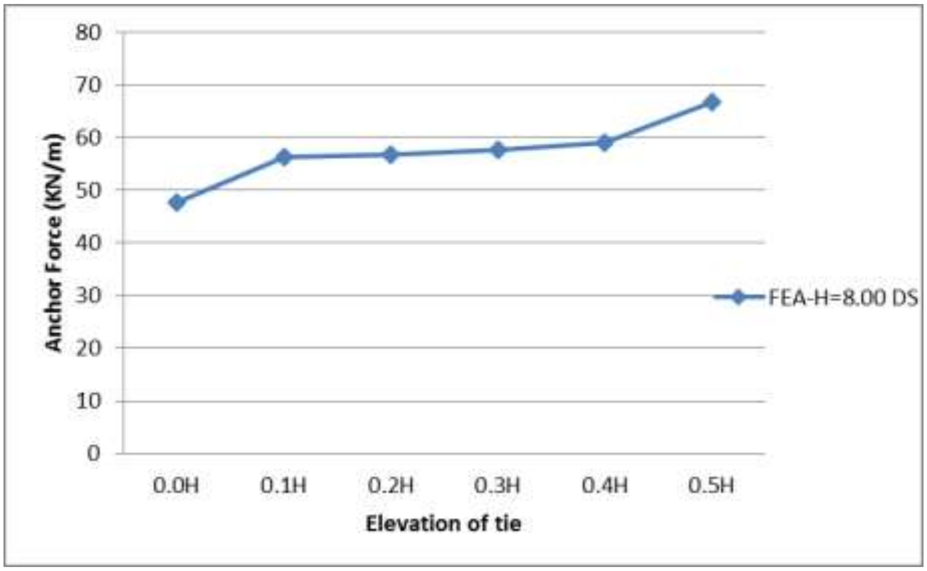

Fig. 22: Effect of Increasing elevation of tie on Anchor force (8.0DS).

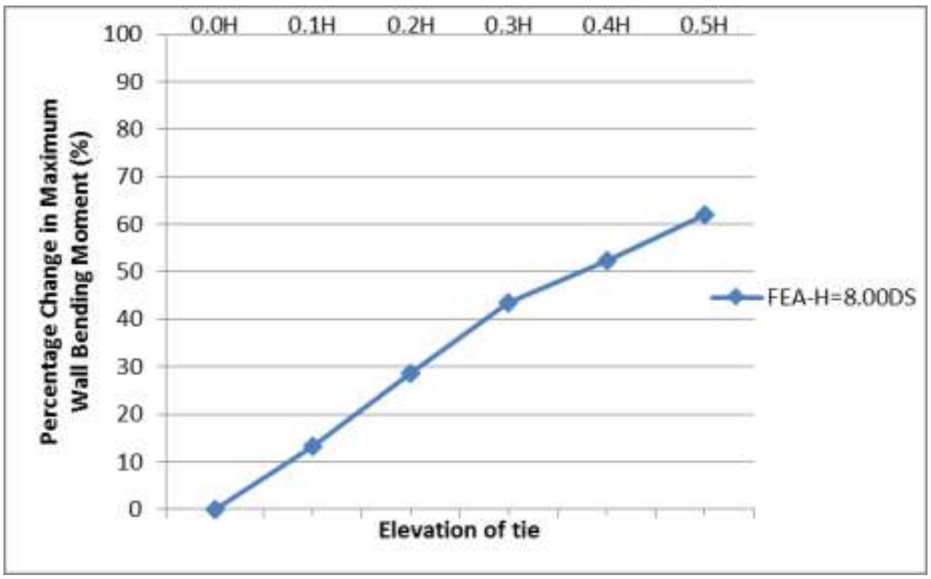

Fig. 23: Percentage Change in Maximum Wall Bending Moment with of increasing elevation of tie (8.0DS).

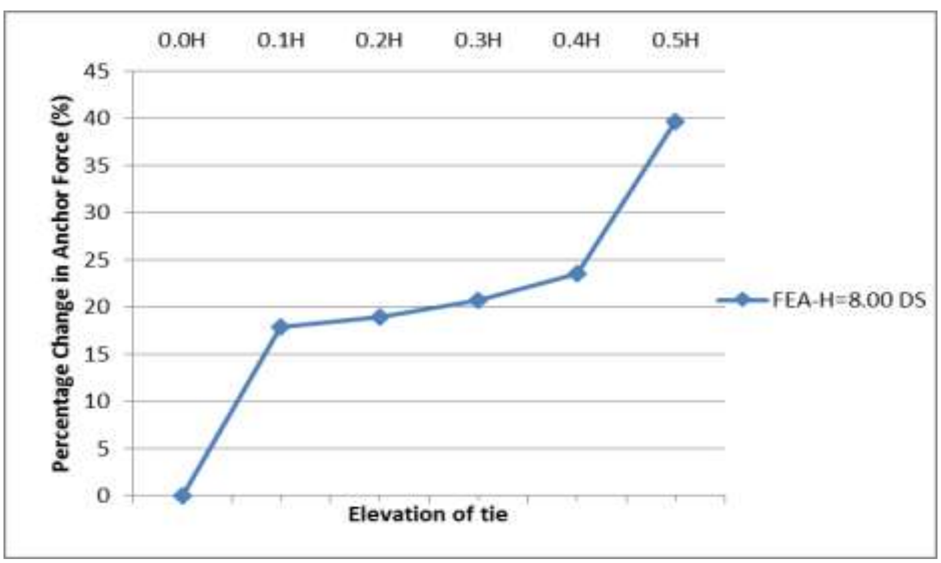

Fig. 24: Percentage Change in Anchor force with of increasing elevation of tie (8.0DS).

a) Effect of Soil Strength

Additional modeling and analysis were performed using medium dense sand, and loose sand soil. to investigate the effect of soil strength on the wall behavior with increasing elevation of tie (d/H).and also, to study whether the wall behavior observed for dense sand with increasing elevation of tie (d/H) -as shown above- are similar to the walls behavior in medium dense sand or loose sand soils. Soil properties used for this parametric study were provided in (table 1).

1) The Analysis Results

The results of analysis of medium dense and loose sand soils, parallel with the results presented during first stage for dense sand soil (ϕ = 40°), are given in figure 25, through 27 for comparative purposes. The results show that the anchored sheet pile walls in medium dense sand and loose sand soils have an identical behavior. All the results for maximum horizontal wall displacement are shown in figure 25, for maximum wall bending moments in figure 26, and anchor forces in figure 27. These results display that the anchored sheet pile walls in dense sand soil, have less deformations, less bending moments, and less anchor forces with increasing elevation of tie (d/H).

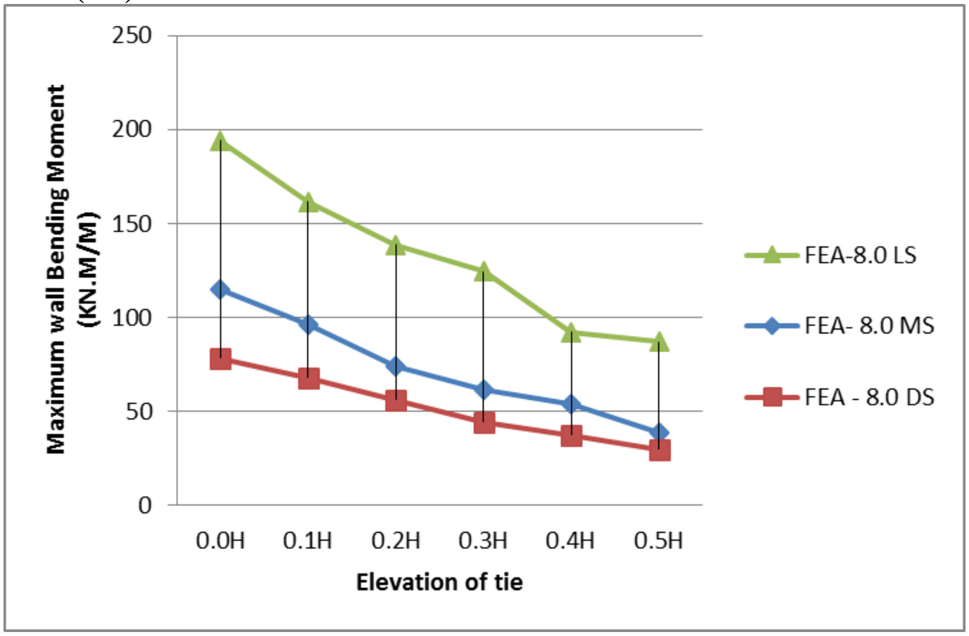

Fig. 25: Effect of Soil strength With Increasing elevation of tie (d/H) on Maximum Horizontal Wall Displacements (Granular Soils-H=8.0).

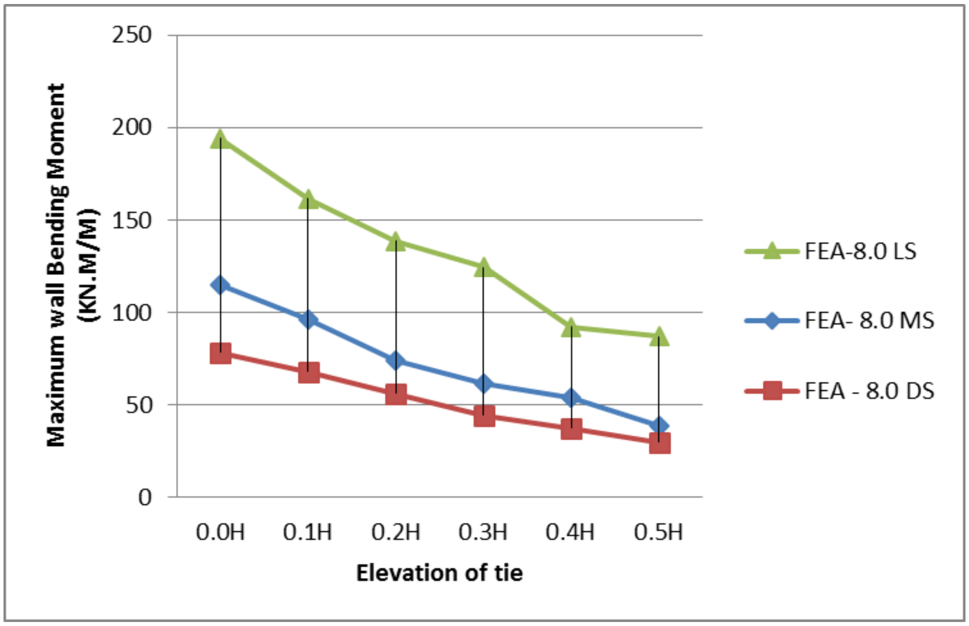

Fig. 26: Effect of Soil strength with Increasing elevation of tie (d/H) on Maximum wall Bending Moments (Granular Soils-H=8.0).

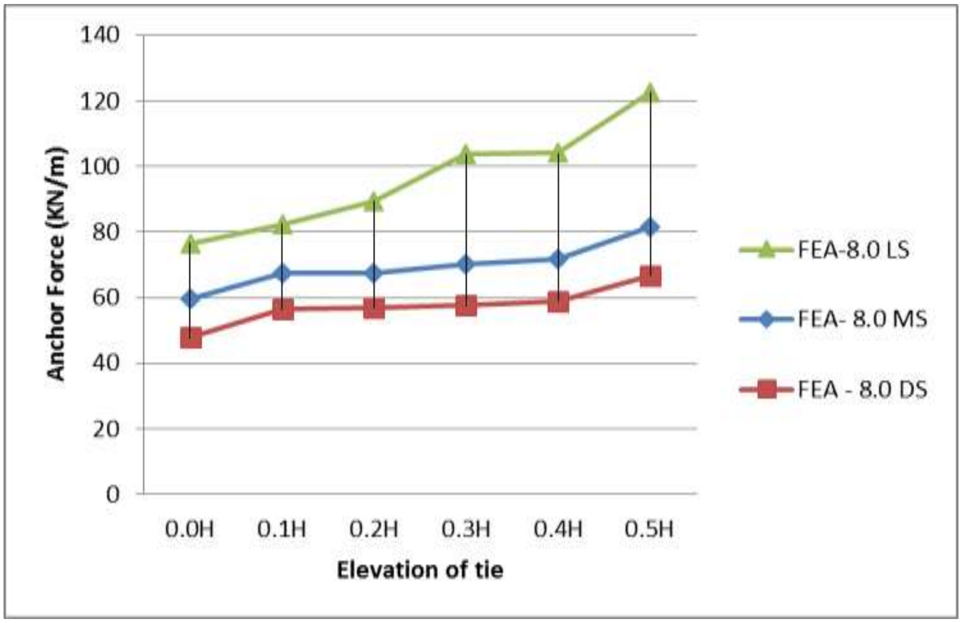

Fig. 27: Effect of Soil strength with Increasing elevation of tie (d/H) on Anchor forces (Granular Soils-H=8.0).

b) Effect of Wall Height (H):

The modeling and analyses were performed to investigate the effect of wall height (H) with increasing elevation of tie (d/H), on the anchored sheet pile wall behavior. This parametric study was conducted for 12 m high wall and the behavior was compared to the results obtained and presented earlier for the 8.0 m high wall. The results of analyses obtained for 12 m high walls, along with the results of 8.0 m high walls, in sand soil types are shown in Figures 28 through 33

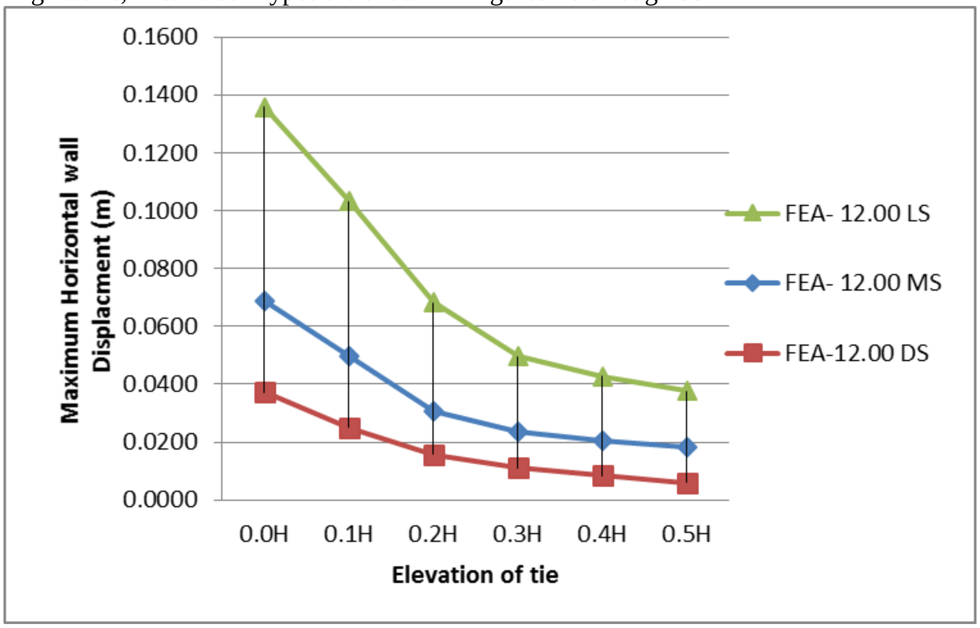

Fig. 28: Effect of Soil strength With Increasing elevation of tie (d/H) on Maximum Horizontal Wall Displacements (Granular Soils-H=12.0).

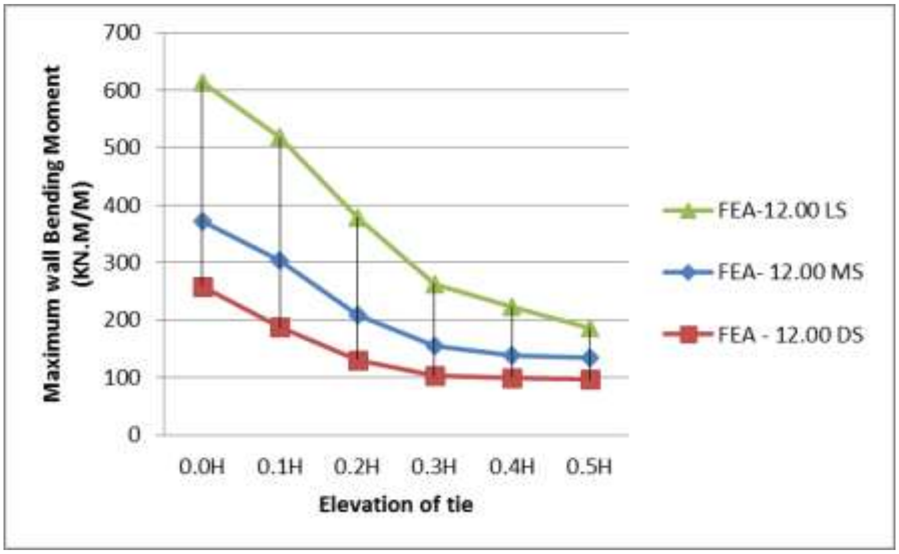

Fig. 29: Effect of Soil strength with Increasing elevation of tie (d/H) on Maximum wall Bending Moments (Granular Soils-H=12.0)

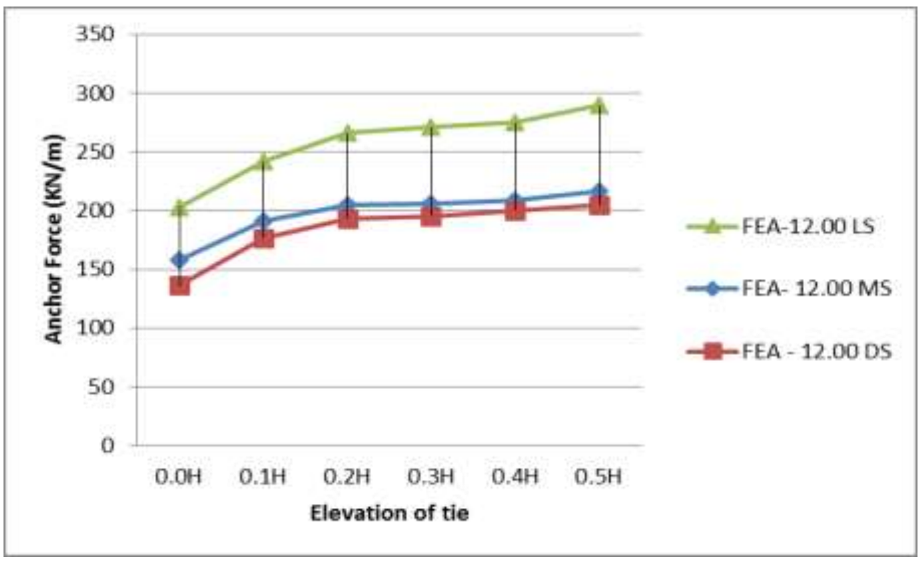

Fig. 30: Effect of Soil strength with Increasing elevation of tie (d/H) on Anchor forces (Granular Soils-H=12.0).

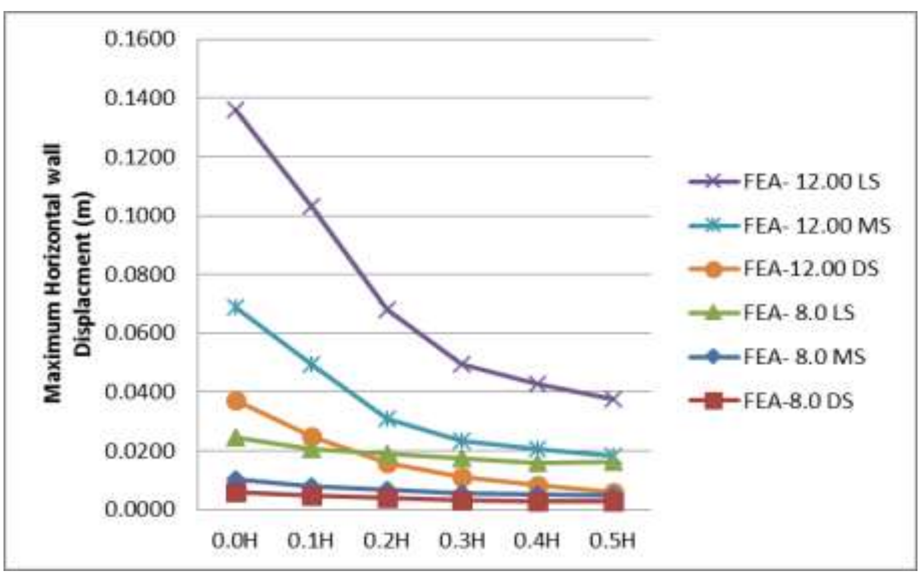

Fig. 31: Effect of Wall Height with Increasing elevation of tie (d/H) on Maximum Horizontal Wall Displacements (Granular Soils-H=12.0 and H=8.0).

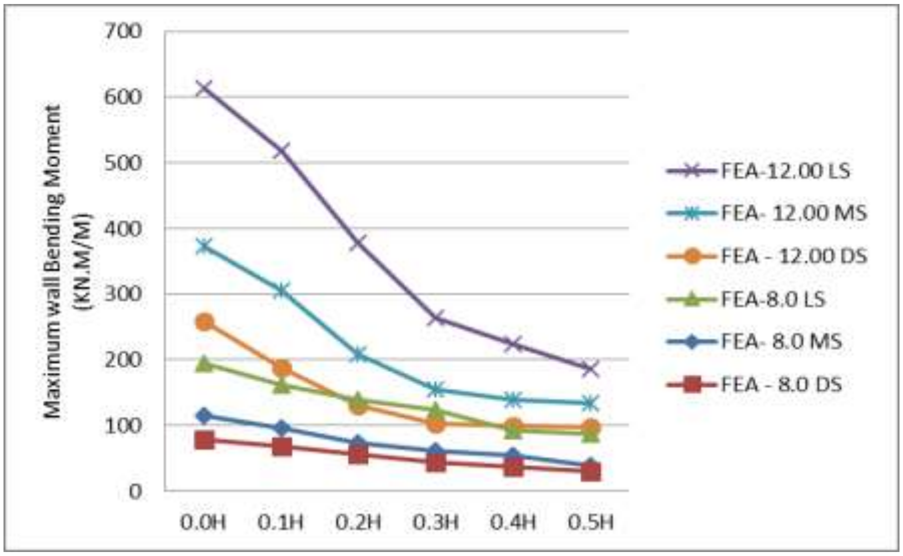

Fig. 32: Effect of Wall Height with Increasing elevation of tie (d/H) on Maximum wall Bending Moments (Granular Soils-H=12.0 and H=8.0).

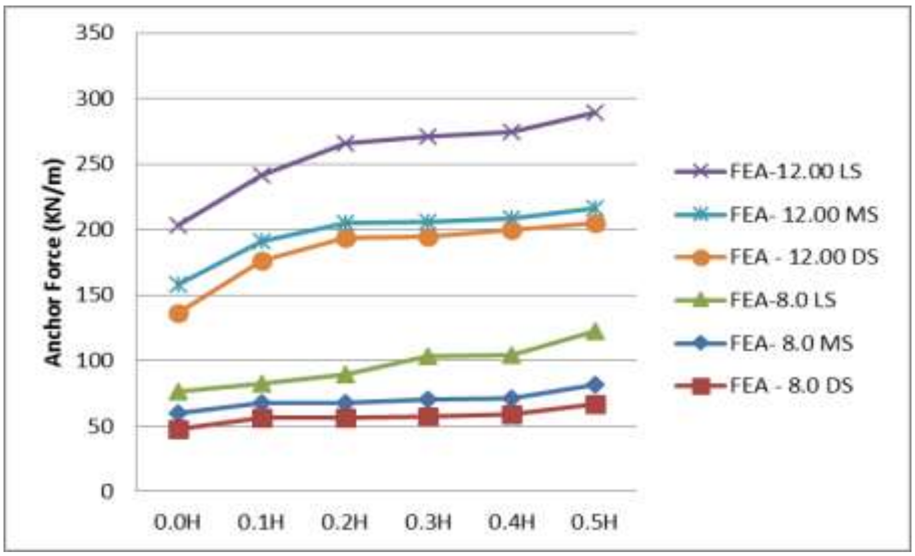

Fig. 33: Effect of Wall Height with Increasing elevation of tie (d/H) on Anchor forces (Granular Soils-H=12.0 and H=8.0).

The effect of increasing elevation of tie (d/H) on the wall behavior is the same for all wall heights and have similar trends, i.e. increase the elevation of tie (d/H) for H=12.0 m increase anchors forces as the same for H=8.0 m as shown in figures 34 & 35 .

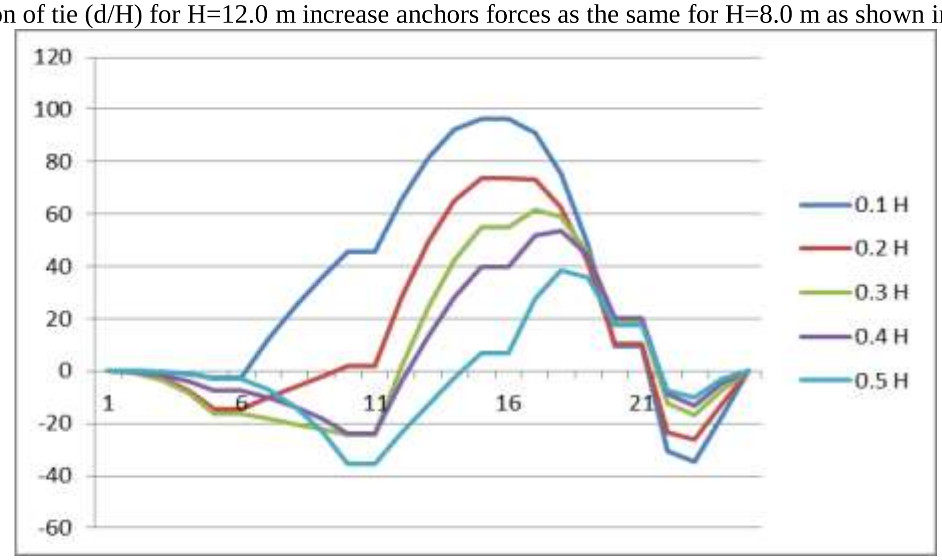

Fig. 34: Bending Moments for SPW with different elevation of tie (d/H) (Medium dense Soil- H=8.0).

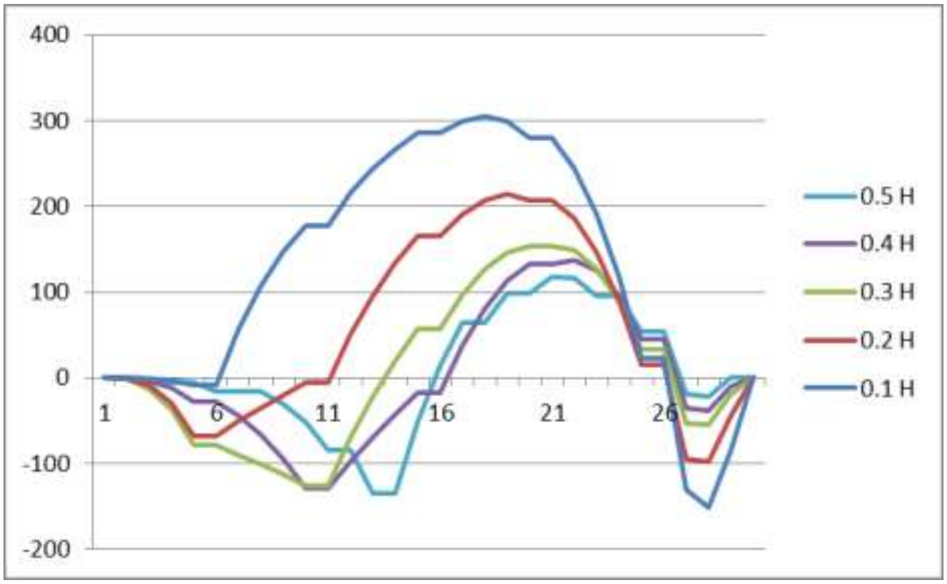

Fig. 35: Bending Moments for SPW with different elevation of tie (d/H) (Medium dense Soil- H=12.0).

IV. CONCLUSION

From previous observations, the results show that by increasing inclination of tie (Ө) in dense sand soils for anchored sheet pile wall with height 8.0 m, about 27 percent significant increase in anchor force values was observed. for medium dense sand and loose sand soils, more than 32 percent and 40 percent change in anchor forces were observed. It is also noticed that the effect of increasing inclination of tie (Ө) on the wall behavior is the same for all wall heights and have similar trends, i.e. increasing the inclination of tie for H=12.0 m increases anchors forces as the same for H=8.0 m. Also, the results show that the increase of (Ө) to 20° leads to decreasing the maximum bending moments and maximum horizontal displacements of wall, but slightly increases the anchor force. after that, increasing the inclination of tie (Ө) increases the maximum bending moments, horizontal displacements of wall and anchor force. Generally, its recommended that the angle of inclination of tie doesn't exceed 20 degrees. and for best angle of inclination 20 degrees is recommended. From previous observations of studying variation of tie elevation. increasing the elevation of tie (d/H) from the top of wall generally enhances the performance of the structure as Maximum Wall Bending Moment a Maximum Horizontal Displacement decrease. but the anchor force increases. And also, it can be concluded that the best elevation of tie for bending moments is between 0.2 H - 0.3H from the top of the wall. Also, increasing the elevation of tie (d/H) along the wall decreases the positive maximum bending moments and increases the negative maximum bending moments. And also, the effect of tie elevation on the Maximum Horizontal Displacement is more significant for relatively high wall (12 m). For example, when the elevation of tie (d/H) increases, the reduction in maximum horizontal displacement reaches almost four times

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