Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Influence of Excavation Phase on the Performance of Soil Nail System

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Abstract. Soil Nailing is one of the most recommended methods for stabilizing and strengthening the existing steep slopes and excavations, as the construction proceeds from top to bottom. In such a scenario, it is important to decide the depth of excavation at each stage for soil nail installation and to observe the behavior of the system at each phase of excavation. In this paper, efforts have been made to study the mechanism of Soil Nail system at each phase (during construction) and after the Construction. A numerical model was simulated using PLAXIS-2D considering the total depth of excavation 'H' and a number of Soil Nails (grouted) of desired length with a suitable vertical spacing. The nails and facing were modeled as plates. The depth of excavation for each phase was studied under different cases. The changes in Axial force, Bending Moment and Shear Force of the Nails and Facing, and change in total horizontal displacement of the soil system were observed. The last nail at each excavation experienced the maximum tensile force and the immediate nail of the next phase experienced a considerable reduction in force. It was also observed that the maximum Tensile forces developed in the Nails were much lesser compared to those in which excavation depth was bigger, when the nails were installed with smaller depth of excavation in a stage. Horizontal Displacement of the soil nail system was comparatively high when depth of excavation in a stage was smaller. It was inferred from the above observations and study that construction phase indeed affects the mechanism of the Soil Nail system. Stage-wise excavation and construction of the Soil Nail system with smaller depth of excavation in a stage was most preferred.

Keywords: Soil Nail, Staged construction, PLAXIS 2D, Numerical Simulation, Deep excavation

1 Introduction

Soil Nails are reinforcing, passive elements that are drilled and grouted sub horizontally in the ground to support excavations in soil, or in soft or weathered rock. It contributes to the stability of the earth-resisting systems mainly through tension as a result of the deformation of the retained soil or weathered rock mass. They transfer the tensile forces to the surrounding soil through bond stresses (shear stresses) along the grout-ground interface and ensure long term performance of the system. Soil nail walls can be used in roadway applications involving roadway cuts, road widening under existing bridge abutments, tunnel portals, repair and reconstruction of existing retaining structures (Briaud and Lim (1997)). The behavior and performance of the Soil nail system are influenced by many factors (Shivakumar Babu (2002)). Construction sequence being one such parameter, it is important to decide the depth of excavation at each stage of installation, knowing the number of nails installed at each stage and for overall system. Some researchers have done a detailed study of the reinforced earth structures, the depth of excavation to be carried out at each stage is still uncertain. Hence, efforts have been made in this paper to study the effect of depth of excavation at each stage and thus analyzing the pattern of behavior of the nail forces and deformation of the system. Elias and Juran (1991) have found that shear and bending nail strengths contribute less than 10 percent to the overall stability of the wall. Due to this relatively modest contribution, the shear and bending strengths of the soil nails are conservatively disregarded in the conventional design procedure. In this paper, the variation of flexural forces and its effect on the soil nail system is also studied

2 Methodology

In order to study the behavior and stability analysis, numerical simulations were done using PLAXIS 2D. For preliminary design values to be used in the software, FHWA (2003) Soil reference manual was considered. A 2D - 15noded - plane strain - finite element model was modeled. The model parameters are as mentioned in Table 1.

Table 1. Model/Material Parameters

Parameter	Value
Vertical height of wall, H, m	10m
Face batter, α, degrees (wrt vertical)	0
Slope of backfill, β, degrees (wrt horizontal)	0
Soil type	Dense silty sand
Cohesion, c, kPa	5
Friction angle, φ, degrees	31.5
Unit weight, γ, kN/m3	17
Modulus of elasticity of soil, Es, MPa	20
Poisson’s ratio, ν	0.3
Nail installation method	Rotary Drilled and grouted
Grade of steel	Fe415
Modulus of elasticity of nail, En, GPa	200
Nail spacing, S_V x S_H , m x m	1x1
Nail inclination (wrt horizontal), i , degrees	15
Drill hole diameter, D_{DH} , mm	100
Nail diameter, D_{DH} , mm	20

Compressive strength of grout, f_{ck} , MPa	20
Ultimate bond strength, qu , kPa	100
Modulus of elasticity of grout, E_g , GPa	22
Target Factors of Safety	
FS for global stability, FS_G	1.35
FS for pull-out, FS_P	2
FS for tensile strength, FS_T	1.8
FS for flexure failure, FS_{FF}	1.35
FS for punching shear, FS_{FP}	1.35

2.1 Conventional design procedure

The manual design procedure is based on the FHWA (2003) soil reference manual which consists of 2 parts in the design, a preliminary design and the final design. The final design includes analysis of external failure modes (global stability and sliding stability), analysis of internal failure modes (nail pullout failure and nail tensile strength failure), design of permanent facing and verification of important facing failure modes (facing flexure failure and facing punching shear failure), and influence of other site-specific considerations, such as seismic loading. In the present study only the important internal failure modes and facing failure modes are considered to assess and compare the performance of the (conventionally designed) soil nail wall. Table 2 comprises of conventional design details. It is observed that the factors of safety are greater/equal than the target assumed thus making the design procedure dependable.

Table 2. Conventional Design Summary

Description	Symbol (unit)	Formulae	Value
Normalized Bond Resistance	μ	$(quD_{DH})/(FS_{PO}\gamma_s S_H S_V)$	0.29
Normalized SN length	L/H	from the charts of FHWA(2003)	0.65
Normalized T_{max}	t_{max}		0.29
Correction for drill hole dia	C1	$C1=1.50-0.15D_{DH}+0.0065D_{DH}^2$	1.00
Correction for cohesion	C2	C2=-4.0c*+1.09	0.97
Correction for F_{OS}	C3	$C3=0.52FS_{OS}+0.30$	1.00
Correction for drill hole dia	T1	$T1=-0.3+0.4D_{DH}-0.017D_{DH}^2$	1.00
Correction for cohesion	T2	T2=-4.0c*+1.09	0.97
Corrected Length factor	L/H^*	C1*C2*C3*L/H	0.63

Corrected Tmax factor	t_{max*}	$T1*T2*T_{max}$	0.28
Length of the Nail	L (m)	rounded up	**7.00**
Maximum tension in the Nail	T_{max} (kN)	$\gamma_s S_H S_V t_{max*}$	**47.60**
Tension at face	T_o (kN)	$T_{max*}(0.6+0.2(S_{max}-1)$	**28.56**
Check for Factor of Safety for Nail			
Nominal pullout resistance/m	r_{po}(kN/m)	$\prod q_u D_{DH}$	31.42
Pullout length	Lp (m)	0.35L	2.45
Nominal pullout resistance	R_{po} (kN)	$r_{PO}*L_p$	76.98
FS for pullout	$FS_{PO}*$	R_{po}/T_{max}	**1.62**
Cross sectional area	A_t (mm²)	$(FS_T*T_{max})/f_y$	206.46
Nominal Tensile resistance	R_T (kN)	A_t*f_y	85.68
FS for tensile strength	FS_T*	R_T/T_{max}	**1.80**

Check for Factor of Safety for Facing

Type		Initial + Final Facing	
Thickness, h, mm		100 each	
Reinforcement*		WWM – 102 x 102 (reinforcement ratio 1%), 2 Waler bars of Φ10mm	
Bearing plate grade		Fe 250	
Bearing plate dimensions		225 mm x 225 mm x 25 mm	
Flexure capacity	R_{FF} (kN)	Table 6.6 of FHWA manual	80.07
Punching shear capacity	R_{FP} (kN)	Table 6.7(a) of FHWA manual	155.69
FS against flexure failure	FS_{FF}	R_{FF}/T_o	**2.80**
FS against punching shear	FS_{FP}	R_{FP}/T_o	**5.45**

2.2 Numerical simulations

Using the above values from the preliminary design a model was created using PLAXIS 2D. As mentioned earlier, soil nail wall is modeled as a plane strain problem and 15-noded triangular elements are used for generating finite element mesh of appropriate density. The model considered was of total width of 30m with width of excavation kept as 5m to the left. The depth of excavation was taken as 10m and total depth of model was taken as 25m. Medium mesh density was adopted globally, which was refined to fine density in the vicinity of the soil nail wall (Fig. 1). Mesh boundaries were placed far enough so as to minimize the influence of mesh boundaries on the results of the numerical simulation. The validation is done with an already published paper and the results for axial force developed in the nails were comparable with the published information (Shivakumar Babuand Vikas Pratap Singh (2009)).The Soil nail system for 3 cases, varying the depth of excavation at each stage for each case, considered as 1m, 2m and 5m respectively are considered. The effect of other parameters is ignored in this paper. The results from the numerical simulation are summarized in Table 3.

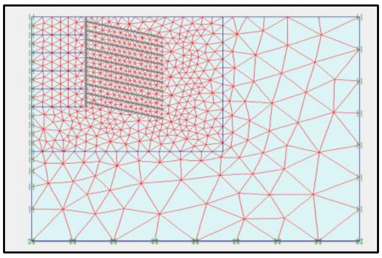

Fig. 1. Typical Finite Element Model of Soil Nail System (H=10m)

Table 3. Results from Numerical Simulation

Case		1	2	3
Depth of excavation at each stage		1m	2m	5m
Parameter	Sym-		Value	
Horizontal Displacement of the System	H (mm)	21.52	20.88	18.15
Maximum tension in the Nail	T_{max} (kN)	56.21	79.10	83.32
Error from Theoretical Value	%	+15.32	+39.82	42.87
Tension at face	T_o (kN)	51.41	70.13	74.32
Maximum Shear Force	Q (kN)	19.63	17.76	16.07
Maximum Bending moment	M (kN-m)	2.74	2.92	3.68
Pullout length	Lp (m)	6.53	6.53	6.53

FS for pullout of Nail	FS_{PO}	**3.65**	**2.60**	**2.46**
FS for tensile strength of Nail	FS_{T}	**2.31**	**1.86**	**1.75**
FS against flexure failure of face (R_{FF}=157.91kN/m^2)	FS_{FF}	**3.07**	**2.25**	**2.12**
FS against punching shear of face (R_{FP}=204.62kN/m^2)	FS_{FP}	**3.98**	**2.92**	**2.75**

3 Results and Discussion

3.1 Axial forces along Nail length

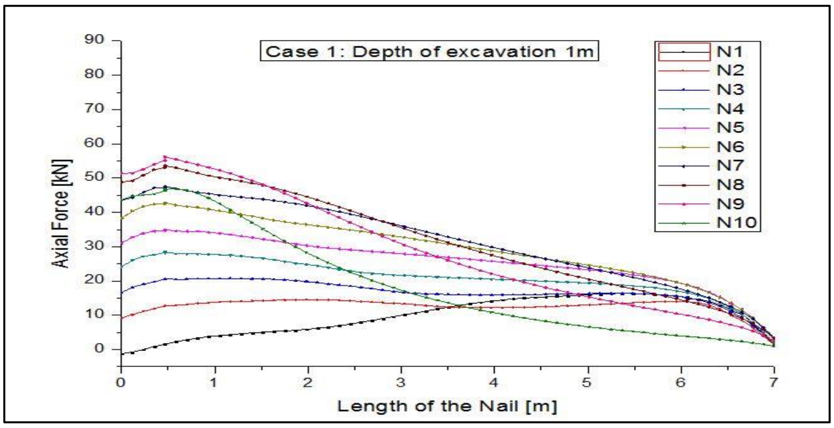

Fig. 2. Axial Force along Nail length for Case 1

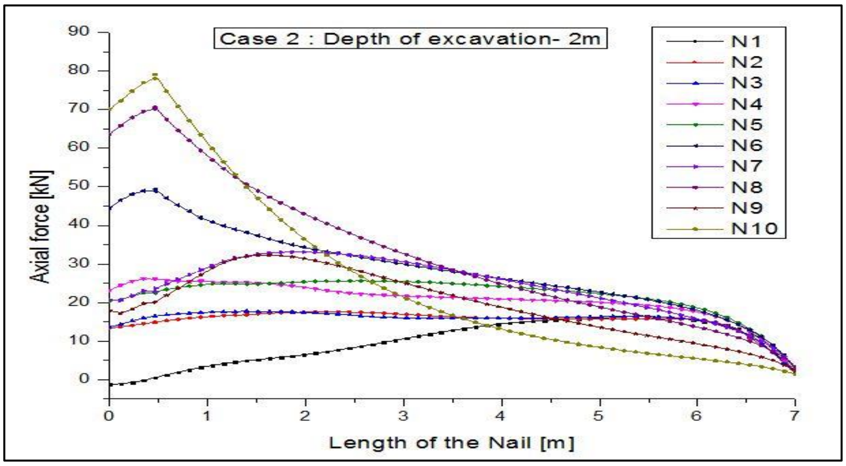

Fig. 3. Axial Force along Nail length for Case 2

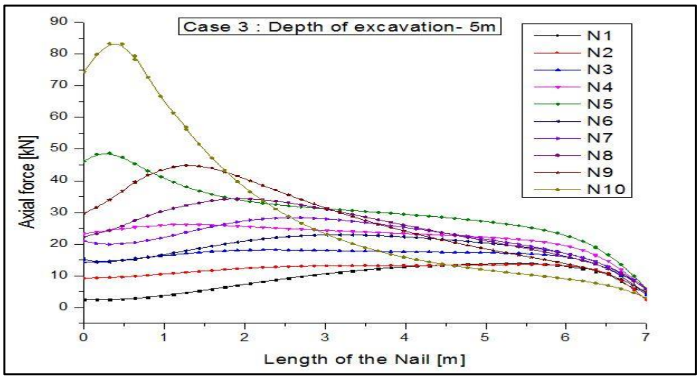

Fig. 4. Axial Force along Nail length for Case 3

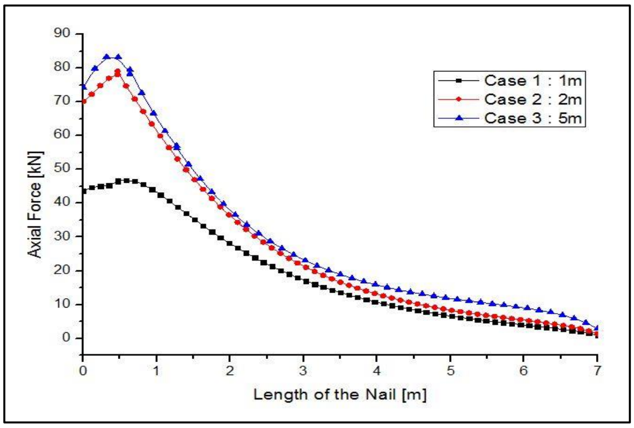

Fig. 5 Axial Force variation in Bottom-most (10^{th}) nail along the length for all three cases

Fig. 2, Fig. 3 and Fig. 4 show the axial forces developed in the nails of the Soil Nail system for cases 1 2 and 3 respectively. It is observed that Case 1, with lower depth of excavation for each stage shows lower axial force compared to Case 2 and Case 3. Also we observe that the Maximum tensile force of the system is developed for the bottommost nail of the system in Case 2 and Case 3. But for Case 1, it is maximum for the 9^{th} Nail (2^{nd} nail from the bottom) and decreases for the bottommost nail. Fig. 5 shows the Axial force for bottommost nail for all 3 cases along the length of the Nail. FHWA (2003) says that the value of Axial (tensile forces) range between 0.5 to 1.1 times of $K_a \Upsilon H S_H S_V$ i.e., between 40.43kN to 89.37kN for the model considered in this paper. The maximum Axial forces obtained from numerical simulations in all 3 cases are well within these limits. ButCase 1 giving out the lower force value suits good by yielding higher factors of safety for internal and external stabilities. Also, theoretically it is said that the axial force at Nail head (at Wall face) varying about 60% to 100% of the maximum axial force and from the simulations, it is about 90% of the maximum tensile force of the Nail for all 3 cases.

3.2 Variation of Forces along the Depth of Excavation

Maximum Axial force, and Nail head Axial Force; Fig. 6 shows the variation of Maximum Axial forces of nails from nail to nail(also along the depth of excavation). It is observed that for Case 1, this variation is linear, we see a constant increase along the depth of cut and then decreases for the bottommost nail (at the final stage of excavation). For Case 2, we see that the axial force in the first nail is lesser than that of the second nail installed at that stage of excavation. Also the axial force 1st nail of the next excavation process is lesser than the axial force of the last nail of the previous stage, giving an irregular pattern as shown in Fig. 6. Similarly for Case 3, this process is repeated for every stage of excavation. The first nail of the construction process has lesser axial force and increases along the depth. But for the next stage, the 1st nail shows a decreased axial force than the last nail of the previous excavation stage as observed in Fig. 6. Also, the forces at the Nail head follow a similar pattern (Fig. 7).

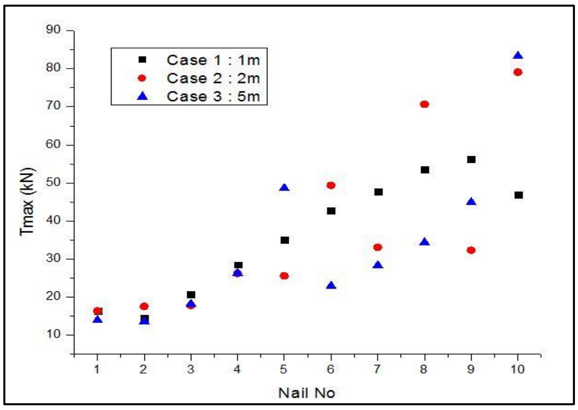

Fig. 6. Variation of Maximum axial force for each nail along the depth for all 3 cases

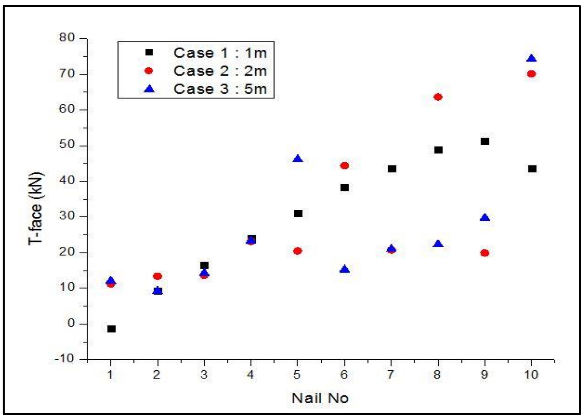

Fig. 7. Variation of axial force at Nail head of each nail along the depth for all 3 cases

Shear Force and Bending Moment; Fig. 8 and Fig. 9 show the variation of Shear force and Bending Moment alongthe length of Bottom-most Nail of the system for all 3 cases. It is observed that the flexural forces show less variation in all 3 cases. It is also observed that these forces exist only near the face and nail junction and not all along the nail. This shows the good interaction between the facing element and the nail head. Also, the values of the bending moment are negligible.

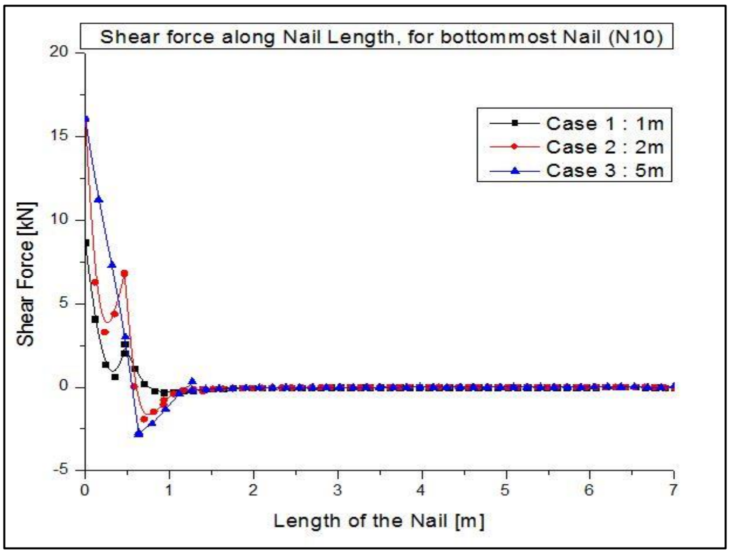

Fig. 8. Shear forcealong the Nail length for bottommost nail (N10) for all 3 cases

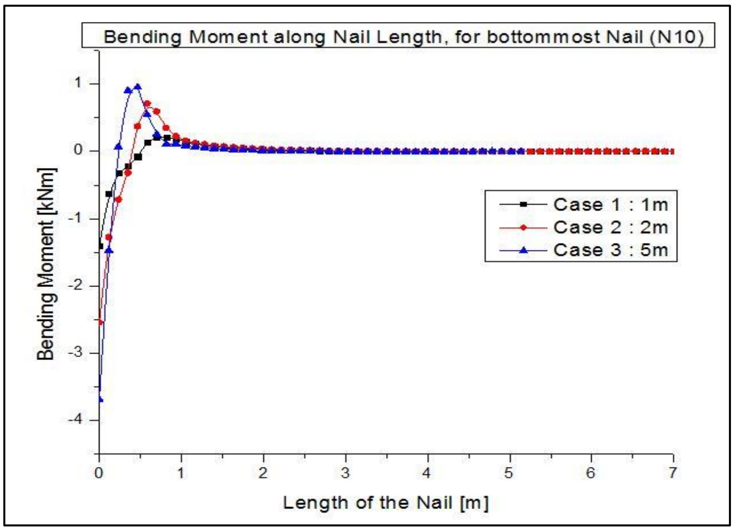

Fig. 9. Bending Moment along the Nail length for bottommost nail (N10) for all 3 cases

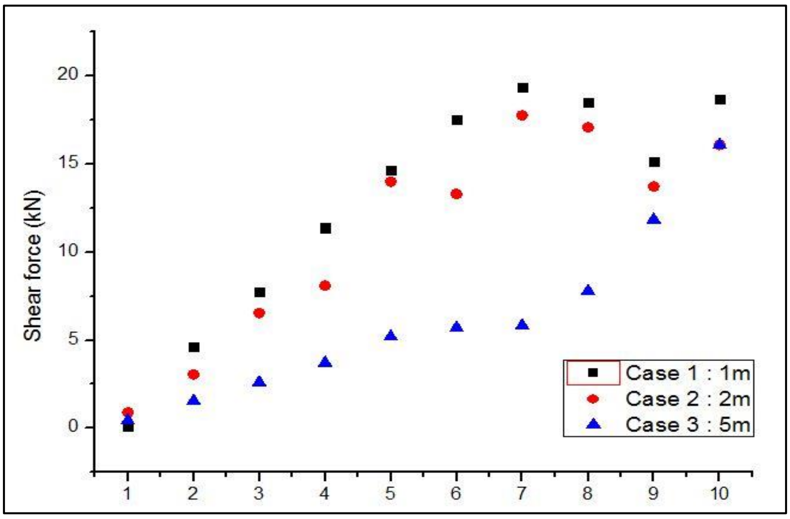

Fig. 10. Variation of Maximum Shear force of Nails along the depth for all 3 cases

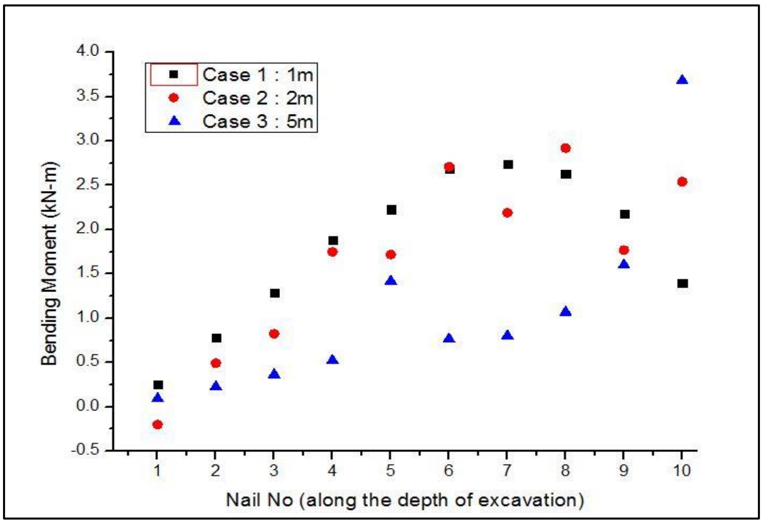

Fig. 11. Variation of Maximum Bending Moment of Nails along the depth for all 3 cases

In Fig. 10 and Fig. 11, we can see the maximum shear force and bending moment for each nail plotted against the nail no along the depth of excavation. We see that these forces for case 1 follow a similar pattern of the axial forces in Case 1 and thus linearly varying. But for case 2 and 3 as discussed before, it is dependent on the depth of cut at each stage. This also suggests that there is good interaction between the soil, nail and facing element in Case 1 than in cases 2 and 3. Also as mentioned earlier, Shear and bending forces contribute less than 10% in the performance of the soil nail system. It only can be considered for designing the facing element.

3.3 Horizontal Displacements

In general soil undergoes deformation in 2 directions, horizontal and vertical. Vertical (upward) displacements are nothing but the basal heaving property of the soil in case of soil nail system. In this paper, only horizontal displacement of the soil at the face of the wall is considered and studied. Fig. 12 gives the horizontal displacement of the Soil Nail Wall. We observe that the displacement is slightly higher in Case 1 compared to cases 2 and 3. Juran (1985) states that the displacement of the vertical cut to be approximately 0.2% of the height of the wall, which accounts to 20mm for 10m height wall considered in this paper. Even though the displacement of the system in Case 1 is slightly higher, i.e., 21.52mm the system is stable compared to the other 2 cases when considered the factors of safety.

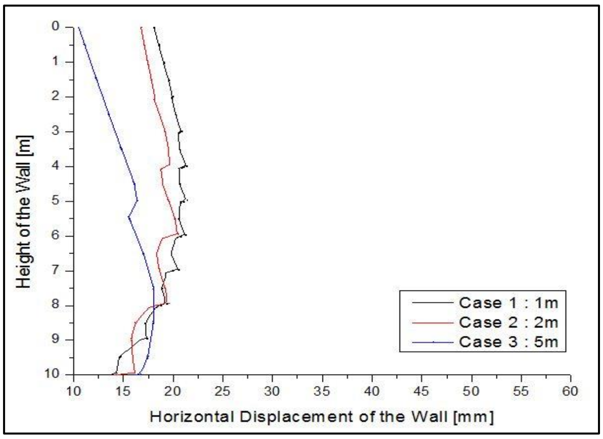

Fig. 12. Horizontal Displacement of the Wall in all 3 cases (displacement-away from wall)

4 Conclusions

Axial forces developed in nails are due to the frictional resistance or bond shear resistance between the soil and the nail. Lower axial force means the higher bond shear resistance developed between soil and nail interface, thus keeping the soil nail system intact. From the observations made above, the axial forces in Case 1 are much lesser than Case 2 and Case 3. The Axial force obtained in Case 1 also has a less error compared to theoretical than the other two cases. Further, the variation of axial forces along the depth of excavation is constant or it gradually increases down the excavation depth where as in cases 2 and 3 we observe the variation alternatively and depth dependent respectively. We also observed that the nail head axial forces also follow the same pattern as that of the maximum tensile forces of the system and are about 90% of the maximum forces.

The factors of safety for Case 1 is higher than those of Case 2 and Case 3. The factors of safety for internal stability (Against nail pullout strength and Nail tensile strength) are higher in Case 1 proving that lower axial forces always yield higher factors of safety. Also the face flexural and shear resistance is also higher in Case 1 than in Case 2 and Case 3 for each stage. The shear force variation of the nails shows a good interaction between the soil nail and facing element.

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