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Influence of Surface roughness, Nail inclination and L/H Ratio in the Stability of Nailed Earth Wall

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***Abstract*— Soil nailing is a modern in situ soil reinforcement technique. It can be used to retain excavation or to stabilize slopes. Soil nailing has gained worldwide acceptance in both theory and practice due to its economy, technical advantages, construction speed, insufficient availability of land in metro cities and subsoil constructions. The stability of the nailed wall mainly depends on flexural rigidity of the nail material and on L/H ratio of the nail. The other parameters on which the stability depends are diameter of the nail, spacing of the nail, surface roughness of the nail, nail inclination and the position of loading from the face of the nailed earth wall. Therefore, this work aims to study the effect of all the above mentioned parameters in the stability of nailed earth wall. Series of tests were carried out on a model nailed wall in the laboratory, to study the influence of the above parameters. The loadings were positioned at 50 mm, 125 mm and beyond the nail length from face of the wall. Downward inclination of the nail towards backfill surface roughness of the nail and reduction in horizontal spacing of the nail, improved the stability of the nailed soil structure. To check the stability of nailed earth wall irrespective of L/H ratio loading at 0.25 H from the face of the wall was recommended. Increase in L/H ratio from 0.7 to 0.8 increases the stability in greater degree. The optimum L/H ratio recommended for nailed earth structure is 1.0**

Keywords—Nailed earth wall, L/H ratio, Surface roughness, Spacing of nails, Stability, Nail inclination.

I. INTRODUCTION

Soil nailing is an insitu-reinforcement technique to treat unstable natural soil slopes. Soil nailing is typically used to stabilize existing slopes or excavations where top to bottom construction is advantageous compared to other retaining wall systems. Soil nailing technique was developed in early 1960s, partly from the techniques for rock bolting, multi-anchorage systems, and partly from reinforced fill technique (FHWA, 1998). New Austrian Tunneling Method introduced in the early 1960s was the premier prototype to use steel bars and shotcrete to reinforce the ground. With the increasing use of the technique, semi-empirical designs for soil nailing began to evolve in the early 1970s. The first systematic research on soil nailing, involving both model tests and full-scale field tests were carried out in Germany in mid-1970s. Subsequent development work was initiated in France and the United States in the early 1990s. Constructing a soil nailed wall involves reinforcing the soil as work progresses in the area being excavated by the introduction of passive bars, which essentially work in tension. These are usually parallel to one another and slightly inclined downward. These bars can also work partially in bending and shear. In order to keep the soil from caving in between the bars, some sort of facing needs to be installed. Some sort of shotcrete reinforcement with a welded wire mesh generally makes this.

Zhang et al. (2001) conducted a model tests of soil nailing on steep cuttings of unsaturated silty clay. Length of nails and density of soil are considered. Some of the observations made are, for the same vertical spacing, increase in L/H ratio increases the stability of nailed wall. The failure surface of nailed cuttings is deeper than the cuttings without reinforcement and use of shorter length causes external stability problem.

Dhamodhar (2007) conducted model tests on nailed soil wall using dry cohesion less sand, to understand the influence of bending stiffness in failure mechanism. Steel bars of diameter 4 mm, 6 mm and 8 mm were used in this experiment. The loadings were positioned at different distance from face of the wall and these loads were applied at different sequence. The behavior of different nail during excavation and loading are observed. It was concluded that the performance of wall with rigid steel nail was comparatively better than the flexible nails on same wall condition.

Hong et al. (2003) summarized the pullout tests that were conducted on single and double nail in a model sand box. The authors considered parameters like surface roughness, L/D ratio of nails, the overburden pressure and distance between two nails. The test results showed that the apparent friction between soil and nail interface depends up on the surface roughness of nail. Group efficiency was used to evaluate the effectiveness of nail when installed within a group. The test results proved that the group efficiency of double nail system was depend upon the surface roughness and has a linear relationship with nail distance.

Rawat and Gupta (2016) reported the response of the unreinforced and the soil nailed slopes under increasing surcharge by conducting model tests. There was a gradual

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increase of load at the wall, to observe the load vs settlement behavior and failure pattern for each slope angle. It was found that soil slope of 45 degrees with nail inclination of 0 degree had the maximum stability.

Gunawan et al. (2017) carried out a stability analysis of nailed earth wall by varying L/D ratio, slope angle and angle of internal friction. From the analysis it was concluded that use of larger diameter nail is more effective in stability, however the diameter of nail may be decided based on factor of safety.

The factors influencing the stability of the nailed earth wall are,

i. Length of the nail
ii. Downward inclination of nail
iii. Surface roughness of the nail
iv. Horizontal spacing of the nail
v. Arrangement of nail pattern
vi. Flexural rigidity of the nail material
vii. Loading position

Though there are lot of research studies about influences of L/H ratio, there is no comprehensive studies about the influence of L/H ratio, nail inclination and surface roughness of nail in the stability of nailed earth wall by varying the loading position from the face of the wall. Hence attempts are made in this study to understand the influence of L/H ratio, nail inclination and surface roughness.

II. MATERIALS AND METHODS

The details about the experimental facility and test media are discussed in this section.

A. Experimental facility:

In the experimental investigation, there are difficulties to exactly replicate the procedure that are practiced in the field. The main objective of the experimental investigation is to observe the failure pattern for different nail inclination, surface roughness and surcharge location. Hence nailed soil wall is constructed as briefed below and loaded to observe the stability of nailed earth wall. It is assumed that the difference in the procedure in the field and laboratory will not have or have a little effect on the failure pattern and failure mechanism. Experimental facility that are available to carry out model test on nailed structures consists of

- Model tank
- Instrumentation
- Loading System
- Facing and Facing – Nail Connection.

1.Model tank:

The tank that is to be used in this study was made up of 4 mm Mild steel sheets welded together and stiffened with suitable angle sections. The size of the tank was 1.5m x 0.5m x 0.6m. It was placed on a wooden stand of 300 mm height. Both the longer sides of the tank were made of acrylic sheet of thickness 8mm to reduce the friction. One of its shorter faces was provided with 5 holes of 12 mm diameter to fix the measuring equipment's.

2. Instrumentation:

When the load was applied, the structure may move both vertically and horizontally. The arrangements are made to measure the vertical movements of soil and to measure the horizontal movements of nails by measure of dial gauges / LVDT.

For vertical settlement measurement, two dial gauges of 50 mm maximum range were kept at the two ends of the wooden block. These dial gauges were fixed on the sides of the tank using magnetic base. The average of the two readings was taken to obtain the average settlement.

Measurement of Horizontal Displacement was a difficult task since the nail ends were inside the soil and the measuring instruments could not be placed the soil. Hence an arrangement was provided to extend the nail movement to the outside of the tank, where the dial gauges were fixed. This arrangement consisted of a wooden frame of H-shape, which could be placed inside the excavation side of the structure. The vertical member of this frame was provided with five 10mm diameter mild steel pipes of length 500mm. These pipes were fixed tightly to the frame at vertical spacing of 100mm, the first one being placed at 50mm from the top level of the tank. A smooth, electro plated mild steel rod of 3.5 mm diameter and length 700 mm moved freely inside each 10mm rod with the help of two bushes kept at each of its ends. One end of the 3.5 mm rod was provided with a wooden piece of 25mm width, 20mm thickness and 50mm length as shown in figure 3.3. This wooden piece had a slot of 8 mm width and 8mm depth through which the nail heads could move freely. This arrangement provided 2 degrees of freedom for the movement of nail heads. Since the nail head moved horizontally as well as vertically, this arrangement facilitated the vertical movement of the nail through the slot and simultaneously measured the horizontal movement of it. The other end of this 3.5 mm rod extended outside of the tank, where the dial-gauges were fixed and the horizontal displacements were recorded.

3.Loading System:

The loading method selected was such that it suits the actual field conditions. A wooden block of size 480mm x 140 mm x 65 mm was kept over the model structure at a suitable distance from the face of the cut. The block was rigid and distributed the applied load equally over its entire area. The load was applied on the block by loading frame arrangement.

4. Facing and Facing – Nail Connection:

The facing has to be continuous, perfectly fitting the irregularities of the cut slope surface, and flexible enough to withstand ground displacement during excavation. The facing material was designed not to play a structural role but to restrict the flow of backfill material. Polythene sheets were used because of its flexibility. In order to arrest the soil flow between the consecutive nails, polythene sheets were used to cover the cut face. These polythene sheets were kept intact by the use of cardboard pieces of size 75 mm x 50 mm. Plastic bush of size 15mm diameter was fixed at the nail head using glue. This bush held the cardboard pieces in position and

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eventually, the soil mass also. Figure 2.1 shows the schematic diagram of the model tank.

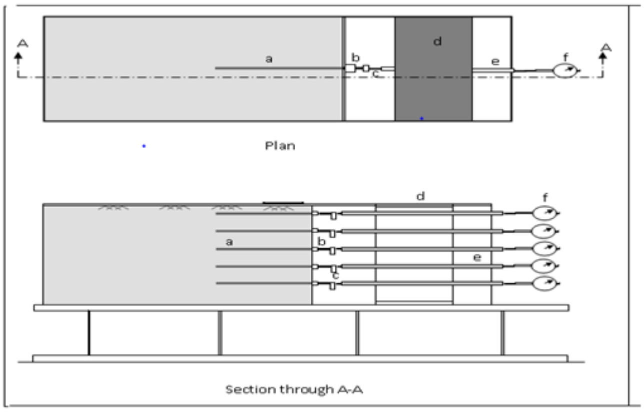

Fig. 2.1. *schematic diagram of model tank*

a .Nail b. Nail head c. Mild steel rod d. Wooden frame e. Mild steel pipe f .Dial gauge g. Loading

B. Test media:

Medium dry sand, classified as SP in the Unified Soil Classification System, was used as test media. The minimum dry densities of the sand were determined to be 1.5 g/cc. Fig. 2.2 presents the average grain size distribution curve for the sand used in this analysis. The properties of sand are listed in table I.

TABLE I PROPERTIES OF SAND

Property	**Symbol and units**	**Values**
Specific gravity	G	2.66
Coarse sand	%	06
Medium sand	%	75
Fine sand	%	19
Effective size	D_{10}	0.40
Coefficient of uniformity	C_u	1.63
Coefficient of curvature	C_c	0.96
Classification	SP	Poorly graded
Angle of internal friction at 1.5g/cc	ϕ	34
Angle of internal friction at 1.6g/cc	ϕ	39

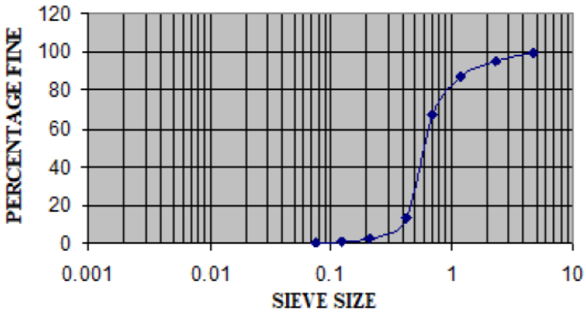

Fig. 2.2 *Grain size distribution*

C. Experimental procedure:

Preliminary tests were conducted to understand the difficulties during experimental investigation. The procedures that are followed are briefed below. The entire width of the tanks was divided into three parts and nails were provided at the center of each part, which resulted in a horizontal spacing of 167 mm. Similarly, the entire height of the structure was divided into 5 parts and nails were provided at each of its centers, which resulted in a vertical spacing of 100mm.Height of the structure was selected as 500mm. The nail diameter of present study was 8mm.The experiment was done with loading positioned at 50mm (Condition 1), 125mm (Condition 2), loading at nail length +50mm from the face of the wall (Condition 3).

Fig.2.3. *View of the model nailed wall*

Fig. 2.4. *Arrangements made for application of Load*

The minimum dry densities of the sand were determined to be 14.45 kN/m^3. The overall view of model nailed earth wall constructed for the detailed experimental investigation is shown in figure 2.3. Figure 2.4 shows the arrangements made for application of load on the nailed earth wall. The load was increased in stages. At one particular load, it was observed that the settlement is continuously increasing even though the applied load remains constant. This load is defined as failure load. For the experimental investigation the tests were in the model nailed wall by using dry sand for different L/H ratio, Nail inclination and surface roughness of nail and are summarized in the table II.

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TABLE II EXPERIMENTAL PROGRAM ON DIFFERENT L/H RATIO OF NAIL WALL, NAIL INCLINATION AND SURFACE ROUGHNESS IN NAILED WALL

Aim	**To study the effect of L/H Ratio of nail in nailed Wall.**	**To study the effect of nail inclination in nailed wall.**	**To study the effect of surface roughness in nailed wall.**
Nails used	High Yield Strength Deformed Steel.	High Yield Strength Deformed Steel.	High Yield Strength Deformed Steel and Mild Steel.
Length of the Nail	500mm, 450mm, 400mm, 350mm, and 300mm.	400mm.	400mm.
Nail Inclination	0 degree	0 degree and 10 degree	0 degree

III. RESULTS AND DISCUSSION

One of the convenient ways of predicting the behaviour of full scale nailed structures is by conducting model tests in laboratory, simulating the field conditions. The trends and behaviour pattern observed in the laboratory model test can be used in formulating mathematical relationship to estimate the load carrying capacity of the nailed structures.

1. Effect of L/H ratio of nail in nailed wall:

Based on the experimental investigation the following results are discussed in this section.

i. Applied pressure Vs Settlement
ii. Applied pressure Vs Nail displacement
iii. L/H ratio Vs Ultimate pressure
iv. Nail displacement along the length of nail with respect to wall height

Applied pressure Vs Settlement:

The applied pressure vs vertical settlement for loading at a distance of 50mm (condition 1), 125mm from face of wall (condition 2) and 50mm from nail end (condition 3) is shown in figure 3.1 to 3.3.

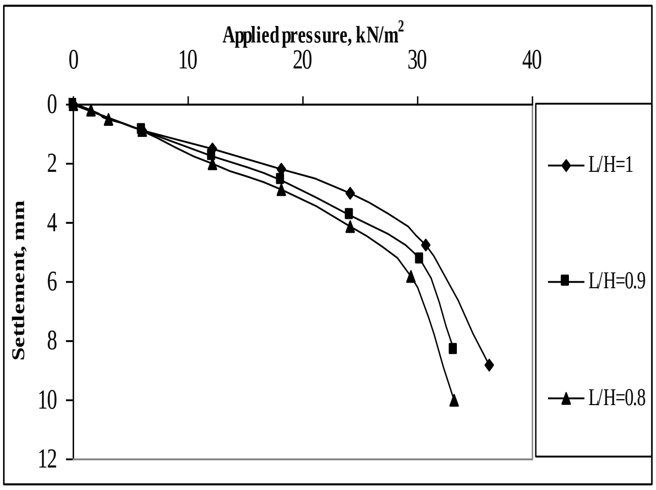

Fig. 3.1. *Applied pressure Vs Vertical settlement, loading at 50 mm from face of the wall*

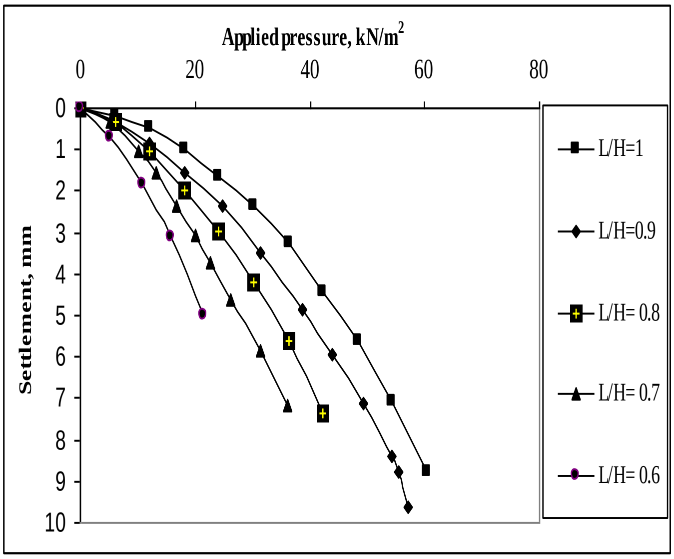

Fig. 3.2 *Applied pressure Vs Vertical settlement, loading at 50 mm from face of the wall*

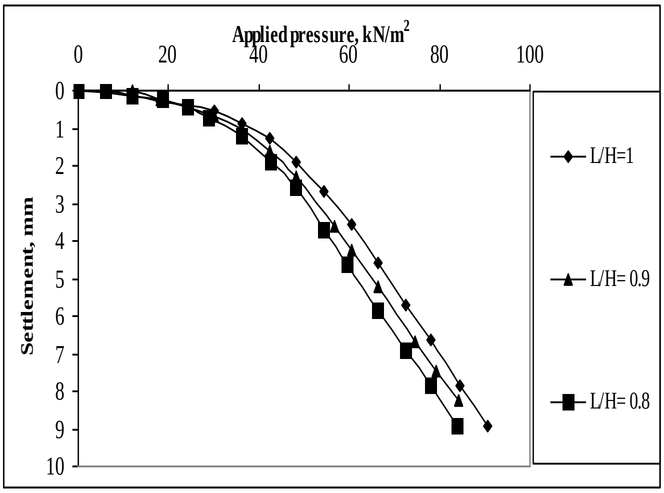

Fig. 3.3 *Applied pressure Vs Vertical settlement, loading at 50 mm from nail end*

The applied pressure Vs nail displacement for different loading points and L/H =1.0 are shown in figure 3.4 to 3.6

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Applied pressure Vs Nail displacement:

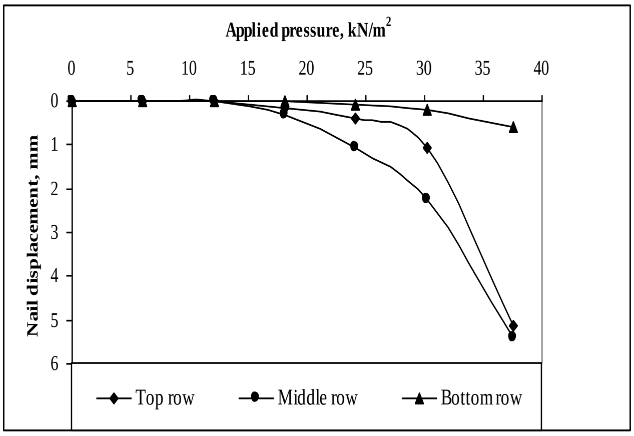

Fig.3.4 *Applied pressure Vs Nail displacement for loading at 50 mm from face of the wall, for L/H ratio of 1.0*

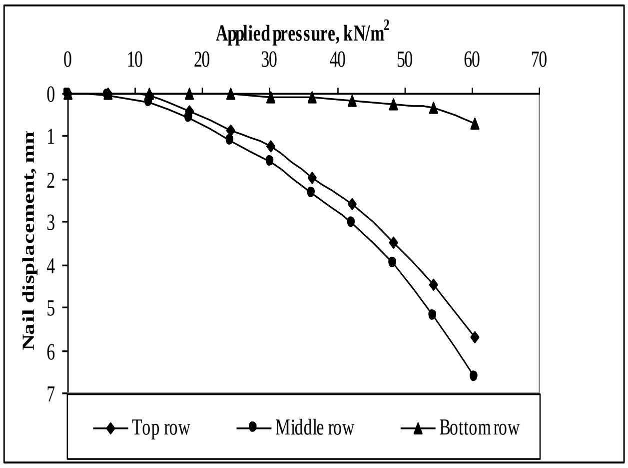

Fig. 3.5 *Applied pressure Vs Nail displacement for different levels, loading at 125 mm from face of the wall for L/H ratio of 1.0*

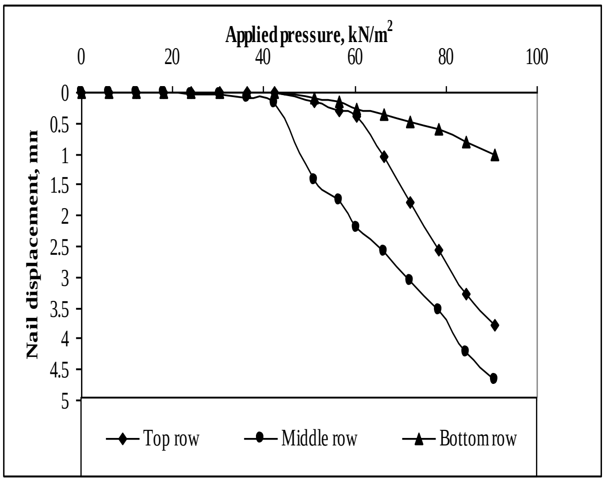

Fig.3.6 *Applied pressure Vs Nail displacement for different levels, loading at 50 mm from end of nail for L/H ratio of 1.0*

L/H ratio Vs Ultimate pressure:

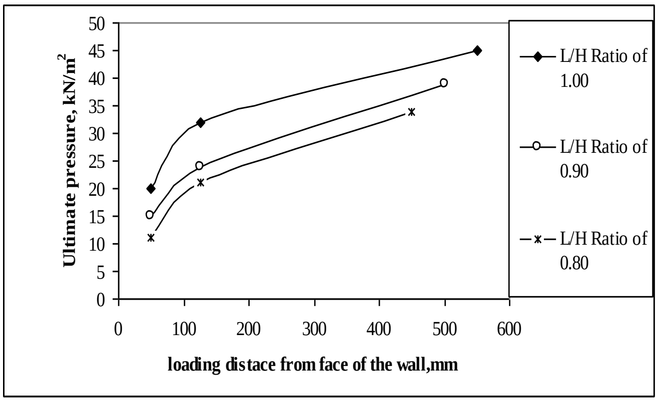

Fig.3.7 *Variation of ultimate pressure on loading position based on vertical settlement*

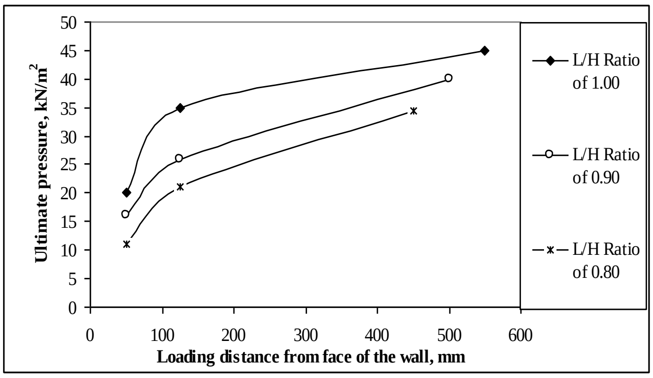

Fig. 3.8 *Variation of ultimate pressure on loading position based on maximum displacement*

Nail displacement Vs Wall height:

The maximum nail displacements for different loading conditions and are shown in Figures 3.9 to 3.11.

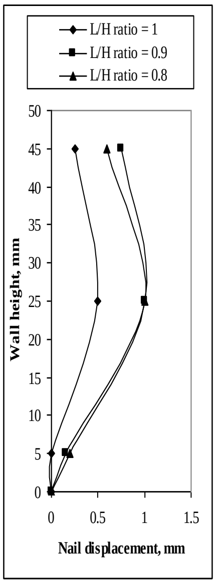

Fig 3.9 Loading at 50 mm from face of wall

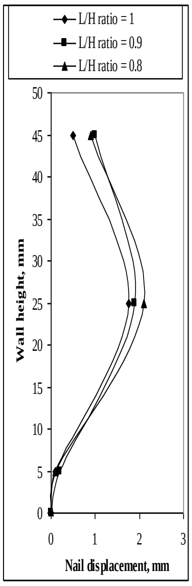

Fig 3.10 Loading at 125 mm from face of wall

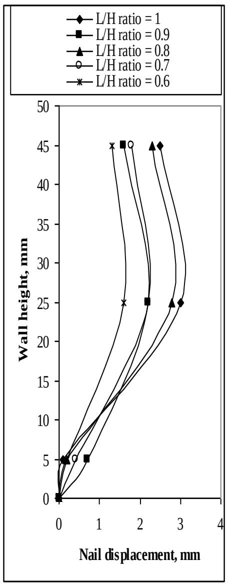

Fig 3.11 Loading at 50mm from nail end

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TABLE III *ULTIMATE PRESSURES FOR DIFFERENT L/H RATIO AND LOADING LOCATION*

Description		**Loading position**										
		Condition 1			**Condition 2**					**Condition 3**		
		L/H Ratio			**L/H Ratio**					**L/H Ratio**		
		0.80	**0.90**	**1.00**	**0.60**	**0.70**	**0.80**	**0.90**	**1.0**	**0.80**	**0.90**	**1.00**
Based on vertical settlement of surface	Ultimate pressure, kN/m²	9	10	12	10	14	22	30	34	40	46	52
	Vertical settlement of surface, mm	1.5	1.6	1.6	1.8	2.1	3	3.25	2.75	1.5	1.6	1.5
Based on maximum nail displacement	Ultimate pressure, kN/m²	10	14	18	15	22	27	33	39	46	48	54
	Maximum nail displacement	0.65	0.65	0.65	1.9	2	2	2.1	2.2	0.5	1.5	1.25

From the figure 3.7, 3.8 and table III the observation made on summarized below:

The increment of ultimate pressure for L/H ratio of 0.6 to 0.7is less and is high for the interval of 0.7 to 0.8and moderate for the interval of 0.8 to 1.0. Increment of L/H ratio beyond 1.0 shall not increase the ultimate pressure.

Increase of L/H ratio, increases the ultimate pressure for different loading positions. The observation is common for the ultimate pressure based on vertical settlement and maximum nail displacement. The ultimate pressure is relatively higher for maximum nail displacement then the vertical settlement due to loading.

The loading is very near to the face of the nailed wall, the L/H ratio of the nail has only marginal effect on the load carrying capacity of the wall. When the loading is away from face of the wall, the pressure increased linearly with increase in L/H ratio of the nail. The maximum increment is for loading at 125 mm from face of the wall. For loading at distance equal to length of nail and 50 mm from end of nail, the nailed portion of the wall support the loading and ultimate pressure is high.

2. Effect of nail inclination:

Based on the experimental investigation the following results are discussed in this section.

i. Applied pressure Vs Settlement
ii. Nail inclination Vs Ultimate pressure
iii. Nail displacement along the length of nail with respect to wall height

Applied pressure Vs Settlement:

The applied pressure vs vertical settlement for loading at a distance of 50mm (condition 1), 125mm from face of wall (Condition 2) and 50mm from nail end (condition 3) for different nail inclination is shown in figure 3.12 to 3.14.

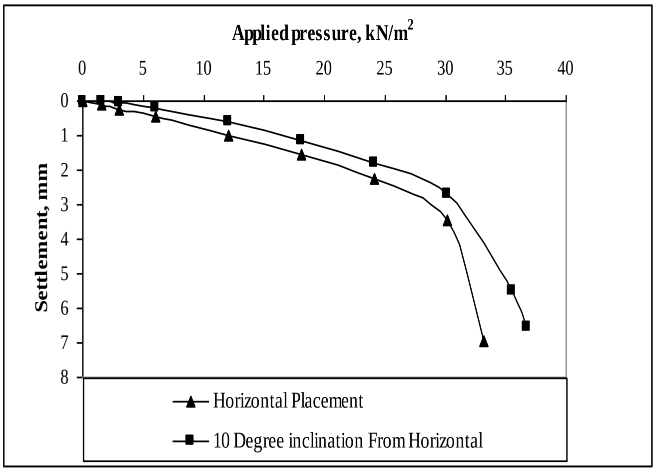

Fig. 3.12 *Applied pressure Vs Vertical settlement loading at 50 mm from face of the wall*

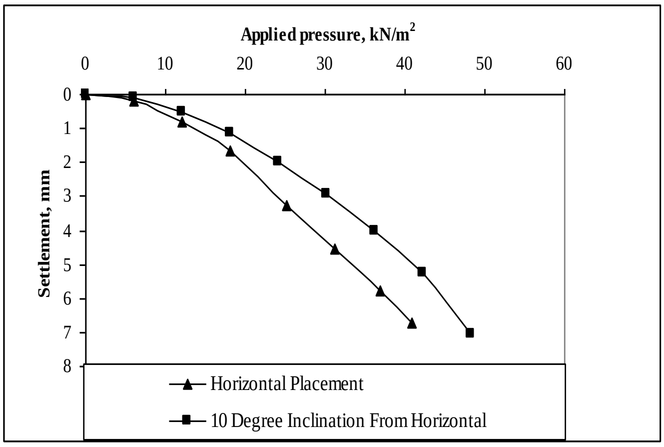

Fig 3.13 *Applied pressure Vs Vertical settlement, loading at 125 mm from face of the wall*

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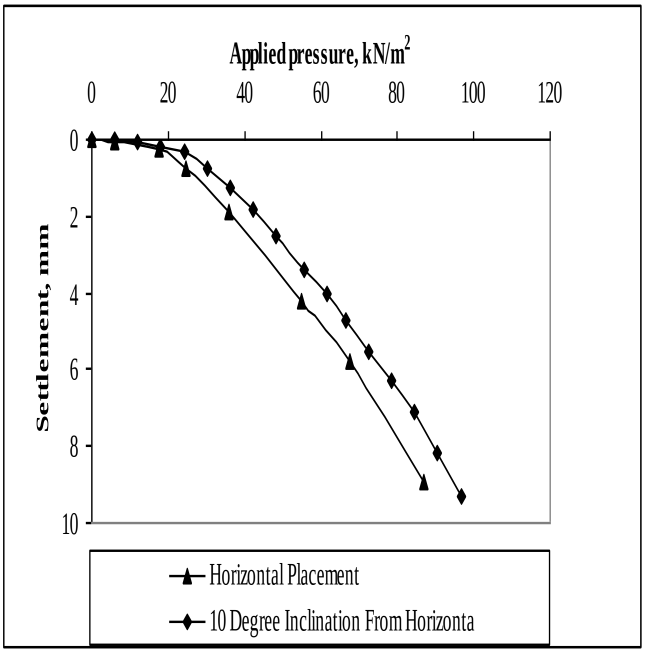

Fig 3.14 *Applied pressure Vs Vertical settlement, loading at 50 mm from nail end*

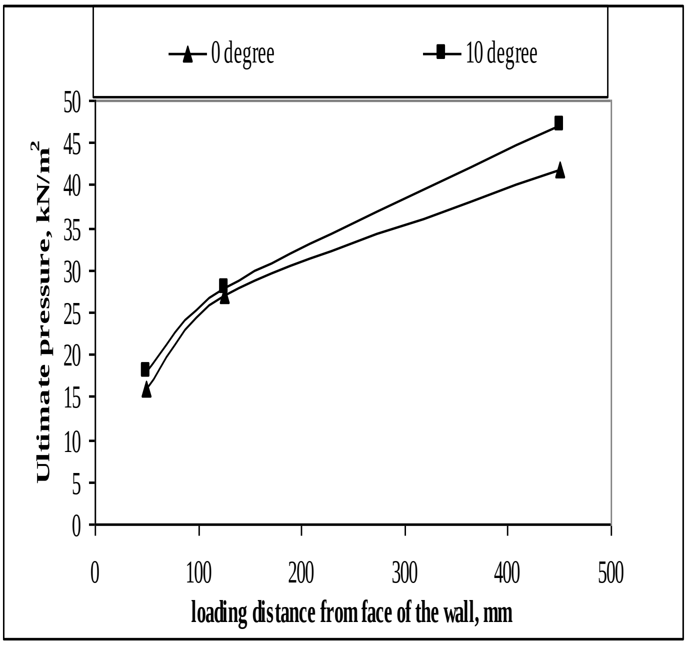

Fig. 3.16 *Variation of ultimate pressure on loading position of wall based on maximum nail*

Nail inclination Vs Ultimate pressure:

The ultimate pressure for different L/H ratio for different loading conditions are shown in figure 3.15 and 3.16 and are summarized in table IV

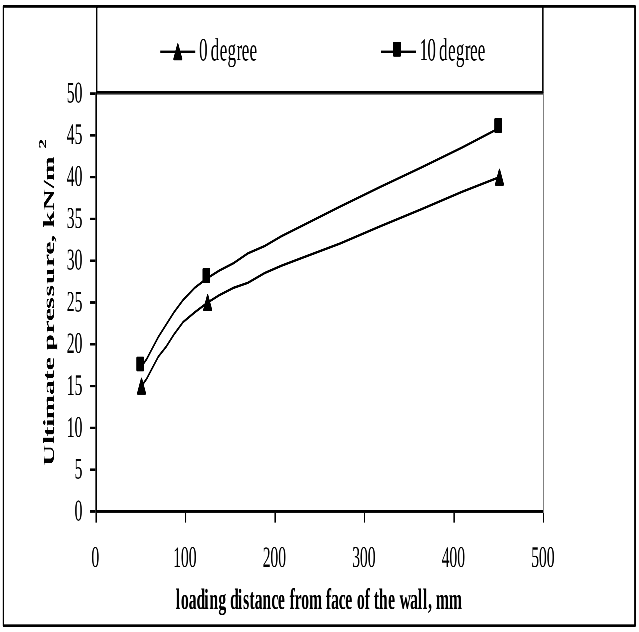

Fig. 3.15 *Variation of ultimate pressure on loading position of wall based on vertical settlement*

Nail displacement Vs Wall height:

From table, the maximum nail displacements for different loading conditions and are shown in Figure 3.17

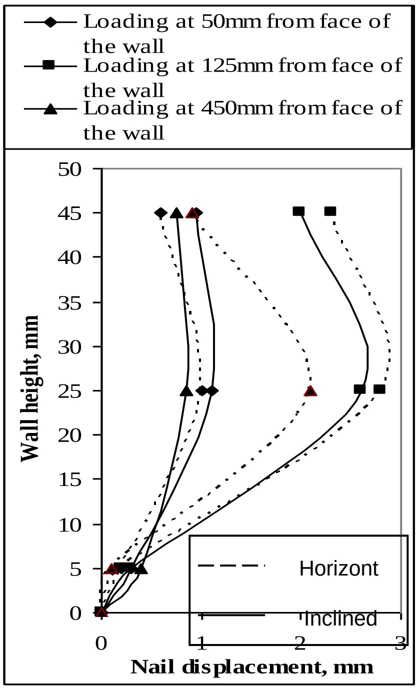

Fig 3.17 *Maximum nail displacements, for 10^0 inclination*

TABLE IV ULTIMATE PRESSURE FOR INCLINED NAILS

Description		Loading position					
		Condition 1		Condition 2		Condition 3	
		Inclination of the Nail from horizontal		Inclination of the Nail from horizontal		Inclination of the Nail from horizontal	
		0°	10°	0°	10°	0°	10°
Based on vertical settlement of surface	Ultimate pressure, kN/m²	15	17.5	25	28	40	46
	Vertical settlement of surface, mm	1.2	1.0	2.8	3.3	2.8	2.8
Based on middle nail displacement	Ultimate pressure, kN/m²	16	18	27	28	42	47
	Middle nail displacement, mm	1.4	1.35	3.2	2.2	0.9	0.85

From the figure 3.14, 3.15 and table IV the observation made on summarized below:

The increase in ultimate pressure with increasing horizontal inclination of nails from 0^0 to 10^0 for loading at 50 mm from face of the wall is 2.5 kN/m^2, for other load cases also there is a increment in the ultimate pressure.

Increase of inclination of nails, increases the ultimate pressure for different loading positions. The observation is common for the ultimate pressure based on vertical settlement and maximum nail displacement. The ultimate pressure is relatively higher for maximum nail displacement than the vertical settlement due to loading.

For loading at 50 mm and 125 mm from face of the nailed wall, the nail inclination has only marginal effect on the load carrying capacity of the wall. When the loading is away from face of the wall, the increment is for loading at 450 mm from face of the wall. The increase in resistance for inclined nail is due to additional rotation required by the nail to move vertically and horizontally.

3. Effect of surface roughness of nail:

Based on the experimental investigation the following results are discussed in this section.

i. Applied pressure Vs Settlement
ii. Surface condition Vs Ultimate pressure
iii. Nail displacement along the length of nail with respect to wall height

Applied pressure Vs Settlement:

The applied pressure Vs Settlement characteristic for surface roughness of nail in nailed soil wall for different loading locations are shown in fig 3.18 to 3.20.

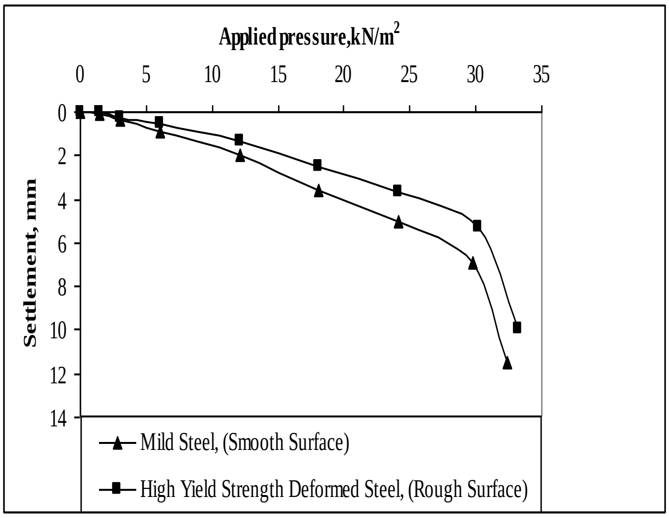

Fig 3.18 *The applied pressure Vs Vertical settlement, loading at 50 mm from face of the wall*

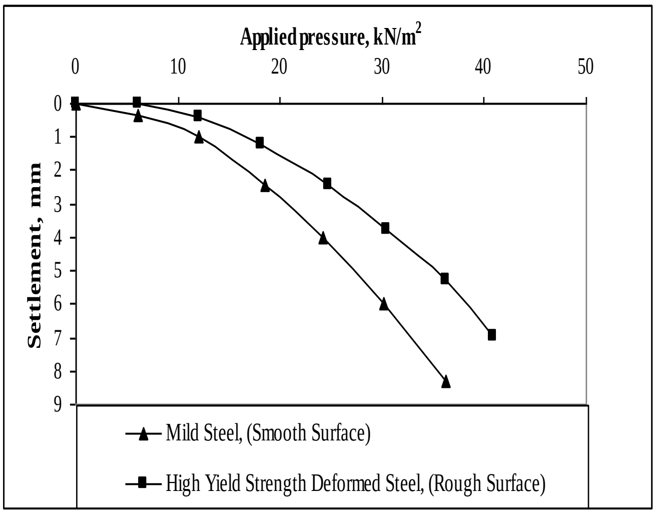

Fig 3.19 *The applied pressure Vs Vertical settlement, loading at 125 mm from face of the wall*

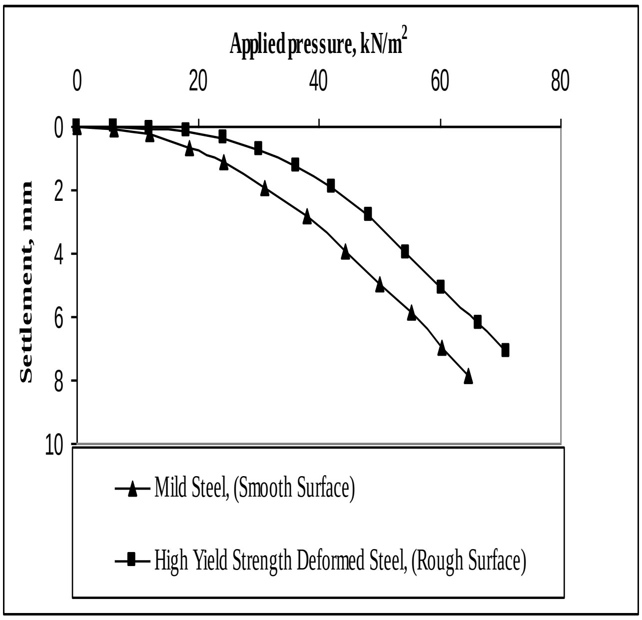

Fig 3.20 The applied pressure Vs Vertical settlement, loading at 125 mm from face of the wall

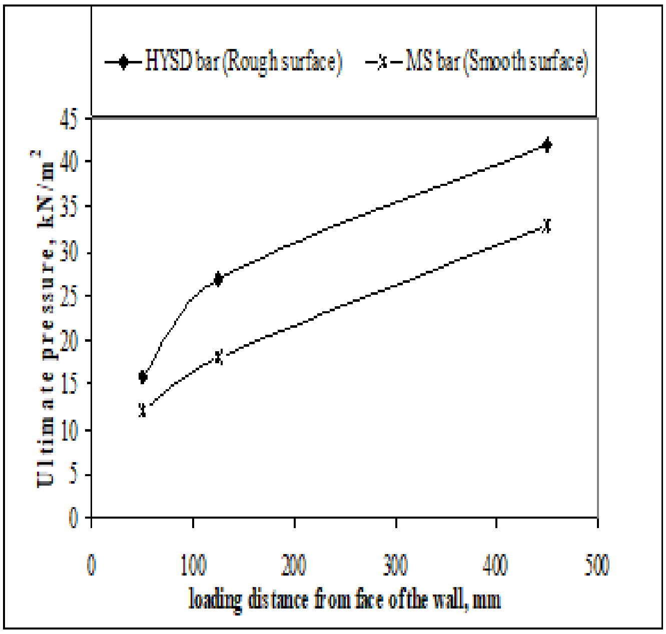

Fig 3.22 *Variation of ultimate pressure on loading distance from face of the wall (Based on maximum nail displacement)*

Surface condition Vs Ultimate pressure:

The ultimate pressure for different L/H ratio for different loading conditions are shown in figure 3.21 and 3.22 and are summarized in table V.

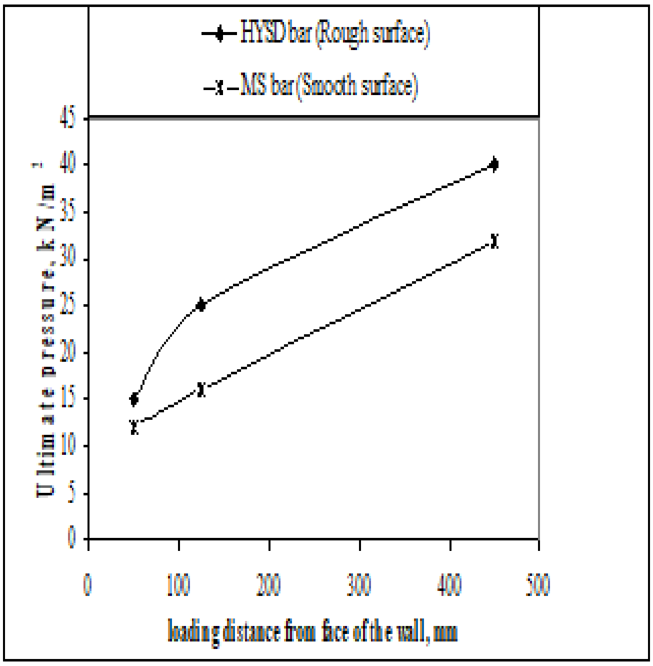

Fig 3.21 *Variation of ultimate pressure on loading distance from face of the wall (Based on vertical settlement)*

Nail displacement Vs Wall height:

The maximum nail displacements for different loading conditions and are shown in Fig 3.23.

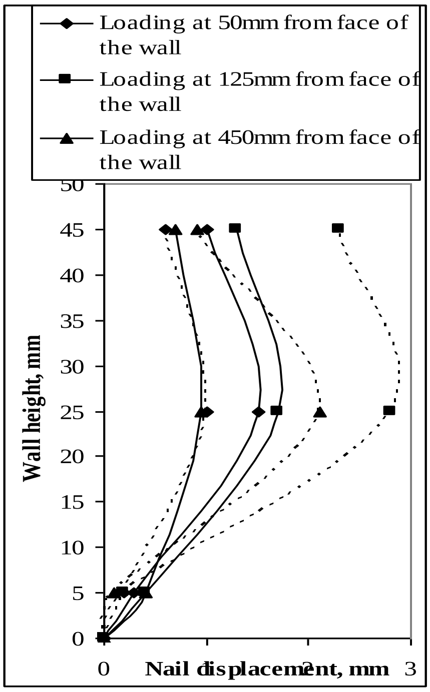

Fig.3.23 *Maximum nail displacements for Mild steel rod*

TABLE V SUMMARY OF RESULTS WITH VARYING THE SURFACE ROUGHNESS OF THE NAIL AND LOADING POSITION OF WALL FOR L/H RATIO OF 0.8

Description		Condition 1		Condition 2		Condition 3	
		Mild steel rod (Smooth surface)	**HYSD rod (Rough surface)**	**Mild steel rod (Smooth surface)**	**HYSD rod (Rough surface)**	**Mild steel rod (Smooth surface)**	**HYSD rod (Rough surface)**
Based on vertical settlement of surface	Ultimate pressure, kN/m^2	12	15	16	25	32	40
	Vertical settlement of surface, mm	2.0	2.5	3.0	3.0	3.0	2.0
Based on maximum nail displacement, mm	Ultimate pressure, kN/m^2	12	16	18	27	33	42
	Middle nail displacement, mm	1.50	1.50	3.0	2.0	2.0	3.0

From the figure 3.21, 3.22. 3.23 and table V the observation made on summarized below:

There is increase in ultimate pressure with increasing surface roughness of nails. Increase of surface roughness of nails, increases the ultimate pressure for different loading positions. The observation is common for the ultimate pressure based on vertical settlement and maximum nail displacement. The ultimate pressure is relatively higher for maximum nail displacement then the vertical settlement due to loading. For the loading 50 mm from the face of the Wall, the surface nail has only marginal effect on the load carrying capacity. But loading 125 mm from face of the wall, influence of surface roughness in load carrying capacity is comparatively high.

IV. CONCLUSION

The important observation made from this study are listed below.

a) Influences of L/H ratio

For better stability of nailed wall, the optimum L/H ratio of nail should be equal to 1.0 and the loading should be at 0.25 H from face of the wall. The optimum loading location is almost constant irrespective of L/H ratio. The nail movement is maximum for the middle row of nails and slightly greater than the top row nail movement. The nails used in this laboratory study are rigid and failure of the nailed wall due to soil failure

b) Inclination of nails

10^o down ward inclination of nails towards the backfill increased the ultimate pressure by 12% and hence increase the stability of nailed wall. The increased resistance due to the additional movement required to mobilize the maximum resistance.

Increase of 50% to 56% of ultimate pressure was observed for the same magnitude of vertical settlement and lesser nail movement due to surface roughness. The increment in the yield strength and surface roughness increases the pullout resistance and hence the stability of nailed wall increases.

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