Numerical Modeling of Grouted Soil Nails

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Abstract— **The problem of vertical excavations reinforced by the grouted nails, is analyzed using the finite element method. An extensive parametric study is performed regarding the shear strength parameters of cohesive and cohesionless soils, height of excavation, nail characteristics (length, diameter, inclination), soil-nail interaction stress, and the surcharge intensity on the backfill side. The influence of the above mentioned factors on the system behavior expressed by the global safety factor, the maximum wall lateral displacement, the maximum excavation base heave, and the maximum values of nails' internal reactions (axial force, bending moment, shear force), is studied. The study produced useful design charts for the geotechnical engineer. It is realized that, increasing the shear strength parameters of soil or decreasing the retained height leads to enhance the stability and reduce the maximum deformations and internal reactions in nails. Upper limits for the possible excavation heights, associated with soil shear characteristics, are reported. It is found that increasing nails' length leads to slight increase in stability and decrease in maximum lateral displacement, especially for low values of strength parameters. The maximum nails' axial force is proportional to their penetration length into cohesive soils. The results revealed minor effect of the soil-nail interaction stress, on the behavior, especially at high values of shear parameters. The maximum nails' axial force is inversely proportional to those stresses. Although the internal reactions in nails are proportional to their diameter, the effect of the latter on the results is limited. Maximum values of the global safety factor are attained at a nail inclination angle of (100). The maximum values of deformations, shear force, and bending moment are increased considerably beyond this threshold whereas, a reduction in maximum nails' axial force is observed. Increasing the surcharge intensity on the backfill side leads to reduce the stability and increase the maximum values of displacements and nails' internal reactions. In general, the maximum values of nails' shear force and bending moment are small, and the principal resistance is attributed to the axial forces.**

Keywords— ***Grouted Nails, Cohesive Soils, Cohesionless Soils, Soil Shear, Soil Stability***

I. INTRODUCTION

The fundamental concept of soil nailing is that soil can be effectively reinforced by installing closely spaced grouted steel bars, called 'nails' the grouted nails increase the shear strength of the overall soil mass and limit displacement during and after excavation [1]. The reinforcement forces are sustained by shear bond between the soil and the reinforcement element [2]. Soil nailing is used to provide temporary earth support and retention during excavation for new construction. The technique is also used for construction of permanent retaining walls, slope stabilization, underpinning, and protection of existing cuts. Soil nailing was also used as temporary shoring for basement excavations and as permanent and temporary earth support for excavations associated with railroads and tunnels [3]. The aim of this study is to analyze soil nailed vertical excavations, using the finite element method and perform an extensive parametric study regarding soil strength parameters, height of cuts, and nail characteristics to obtain useful design charts.

II. MODELING AND PARAMETRIC STUDY

In this study, Mohr - Coulomb yield function is used as an elastic perfectly plastic model with five basic soil input parameters, namely Young's modulus (E), Poisson's ratio (ν), friction angle (φ), cohesion (c), and the dilatancy angle (ψ). The soil is discretized into a number of two dimensional triangular elements with fifteen nodes [4]. The geometric configurations of the problem and the adopted finite element mesh is shown in Fig. 1. An extensive parametric study is performed regarding the effects of height of nailed cut (H), length of nail (L), strength reduction factor for interface (f*), diameter of nail (D), angle of nail inclination (θ), and surcharge intensity on the retained soil (q). The general skeleton of that study is illustrated in Table 1. The values in bold type represent the central values.

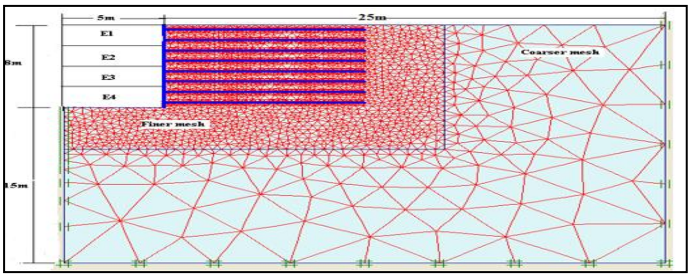

Fig. 1. The adopted finite element mesh.

TABLE 1 SKELETON OF THE PARAMETRIC STUDY.

Soil type	H (m)	L (m)	f*	D (mm)	(θ^0)	q (kPa)
Cohesive soil c=25,37.5, 50, 62.5, 75 (kPa)	4, 6, **8**,10, 12,14	6,7, 8, 9, **10**	0.47,**0.58** 0.7, 0.84	20,**25**, 28, 32	**0**, 10, 20, 30	**0**, 20, 40,60
Cohesionless soil $\varphi = 25^0$-30^0, 35^0 , 40^0	4, **6**, 8,10, 12,14	6, 7, 8,9, **10**	0.47,**0.58** 0.7,0.84	20,**25**, 28, 32	**0**, 10, 20, 30	**0**, 20, 40,60

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III. GROUTED NAILS INTO COHESIVE SOILS

Grouted nails embedded into cohesive soils with different cohesion values, are considered. The associated values of elastic parameters and soil unit weight (γ) are listed in Table 2.

c (kPa)	ν	E_s (kN/m^2)	γ (kN/m^3)
25	0.350	15000	16
37.5	0.325	22500	17
50	0.300	30000	18
62.5	0.275	47500	19
75	0.250	65000	20

IV. EFFECT OF HEIGHT OF EXCAVATION

It can be realized from Fig. 2 to 4 that, the global factor of safety increases with the increase of soil cohesion and decreases with the increase of height of nail cut. Also, maximum lateral displacement and maximum excavation base heave of wall decrease with the increase of soil cohesion and increase with the increase of height of nail cut. The maximum supported height varies from (6m) for (c=25) to (12m) for (c=62.5 kPa). Table 3 shows that, the maximum axial forces, bending moments, and shear forces decrease with the increase in soil strength and increase with the increase in height of excavation. In general the values of maximum bending moments and shear forces, are low compared to the maximum axial forces.

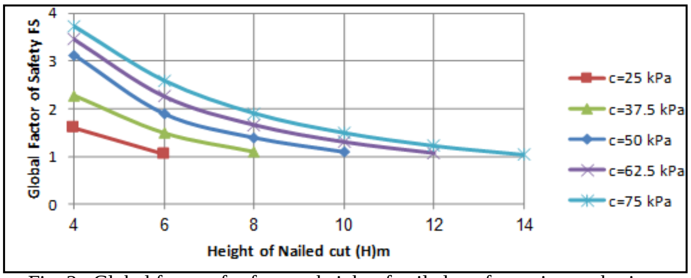

Fig. 2. Global factor of safety vs. height of nailed cut for various cohesion values

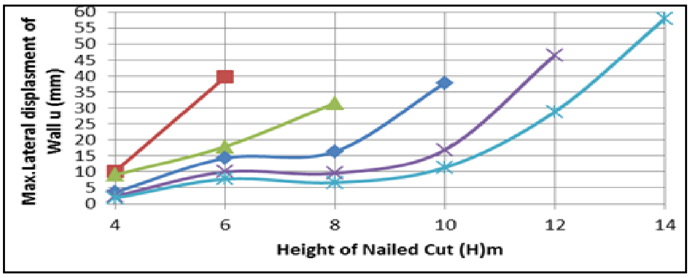

Fig. 3. Maximum lateral displacement vs. height of nailed cut for various cohesion values.

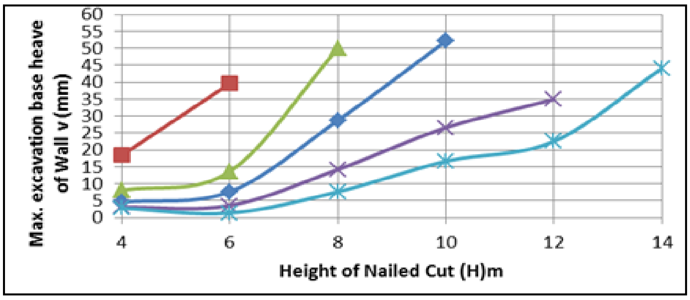

Fig. 4. Maximum excavation base heave vs. height of nailed cut for various cohesion values.

TABLE 3 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS HEIGHT VALUES (C-SOIL).

c (kPa)	H (m)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	4	38.04	4.06	12.98
	6	91.44	4.30	13.57
	8	0	0	0
	10	0	0	0
	12	0	0	0
	14	0	0	0
37.5	4	29.97	3.93	11.02
	6	85.36	4.25	13.52
	8	113.97	4.32	14.09
	10	0	0	0
	12	0	0	0
	14	0	0	0
50	4	21.55	3.63	10.79
	6	82.84	3.97	13.23
	8	106.27	4.09	13.89
	10	147.64	4.16	14.91
	12	0	0	0
	14	0	0	0
62.5	4	20.03	2.64	8.33
	6	79.82	3.17	11.70
	8	102.23	3.23	13.20
	10	133.71	3.48	14.50
	12	154.23	3.85	14.94
	14	0	0	0
75	4	11.84	0.976	5.29
	6	74.51	2.75	11.22
	8	97.60	2.92	12.38
	10	131.41	3.23	13.50
	12	152.30	3.32	14.10
	14	159.49	3.41	15.16

V. EFFECT OF LENGTH OF NAILS

Fig. 5 through 7 and Table 4 show minor effect of nail length on the safety factor, maximum bending moment, and maximum shear force. The maximum lateral displacement decreases with the increase in nail length, especially for low cohesion values. Base heave and the maximum nail axial force are proportional to the nail length.

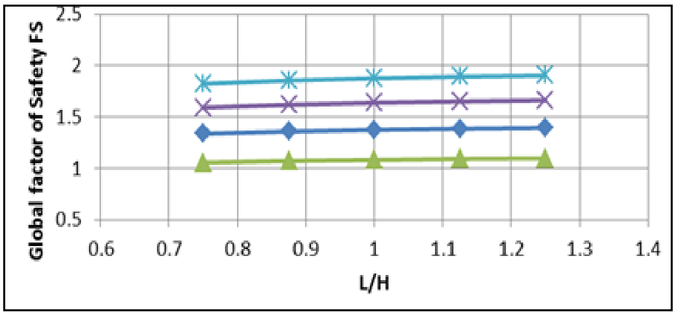

Fig. 5. Global factor of safety vs. length of nails for various cohesion values

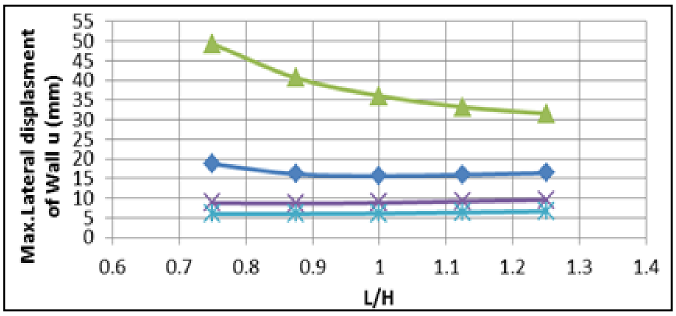

Fig. 6. Maximum lateral displacement vs. length of nails for various cohesion values.

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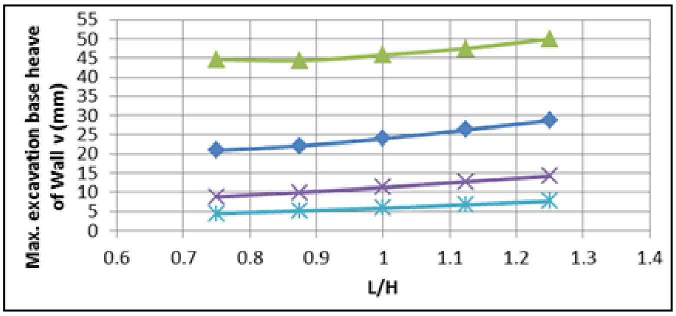

Fig. 7. Maximum excavation base heave vs. length of nails for various cohesion values.

TABLE 4 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL LENGTH VALUES (C-SOIL).

c (kPa)	L (m)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
37.5	6 7 8 9 10	109.00 109.61 110.91 113.01 113.97	4.17 4.16 4.17 4.22 4.32	14.29 14.23 13.99 14.06 14.09
50	6 7 8 9 10	95.71 99.75 101.98 104.80 106.27	3.84 3.90 3.97 4.02 4.09	13.87 13.89 13.70 13.67 13.89
62.5	6 7 8 9 10	92.77 96.92 98.00 101.00 102.23	3.25 3.24 3.20 3.20 3.23	13.17 13.17 13.17 13.08 13.20
75	6 7 8 9 10	88.14 91.17 92.63 94.86 97.60	2.77 2.80 2.77 2.86 2.92	11.77 11.70 11.88 12.00 12.38

VI. EFFECT OF THE INTERFACE STRENGTH REDUCTION FACTOR

It can be deduced from Fig. 8 to 10 and Table 5 that, the variation in interface strength reduction factor has a negligible effect on the safety factor, maximum lateral displacement, the maximum base heave, maximum bending moment, and maximum shear force. The maximum axial force in the nails is inversely proportional to the strength reduction factor at low cohesion values.

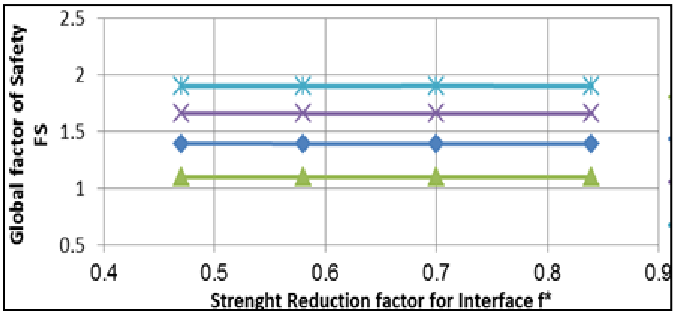

Fig. 8. Global factor of safety vs. interface strength reduction factor forvarious cohesion values.

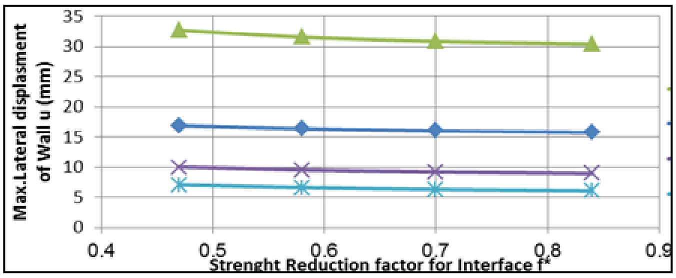

Fig. 9. Maximum lateral displacement vs. interface strength reduction factor for various cohesion values.

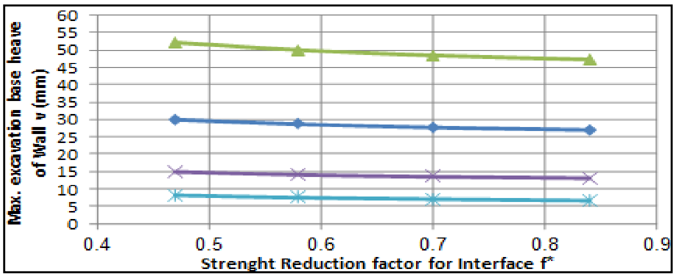

Fig.10. Maximum excavation base heave vs. interface strength reduction factor for various cohesion values.

TABLE 5 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS INTERFACE STRENGTH REDUCTION FACTORS (C-SOIL).

c (kPa)	f*	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
37.5	0.47 0.58 0.70 0.84	116.00 113.97 111.49 109.39	4.45 4.32 3.99 3.77	13.30 14.09 14.29 14.36
50	0.47 0.58 0.70 0.84	106.49 106.27 105.57 104.71	4.30 4.09 3.86 3.60	13.10 13.89 14.10 14.09
62.5	0.47 0.58 0.70 0.84	101.70 102.23 102.11 101.86	3.36 3.23 3.06 2.91	12.44 13.20 13.60 13.85
75	0.47 0.58 0.70 0.84	96.70 97.60 97.64 97.35	3.11 2.92 2.74 2.59	11.85 12.38 12.63 12.75

VII. EFFECT OF NAIL DIAMETER

Fig. 11 to 13 and Table 6 reveal a slight reduction in the safety factor and increase in all other responses, with the increase in nail diameter.

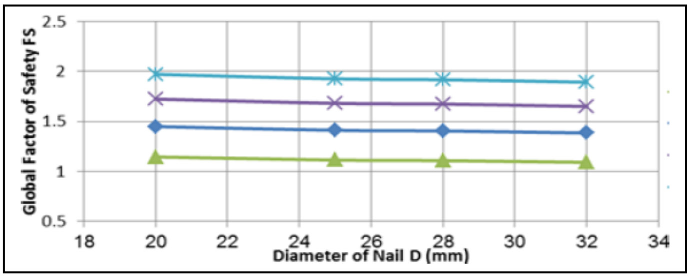

Fig. 11. Global factor of safety vs. diameter of nail for various cohesion values.

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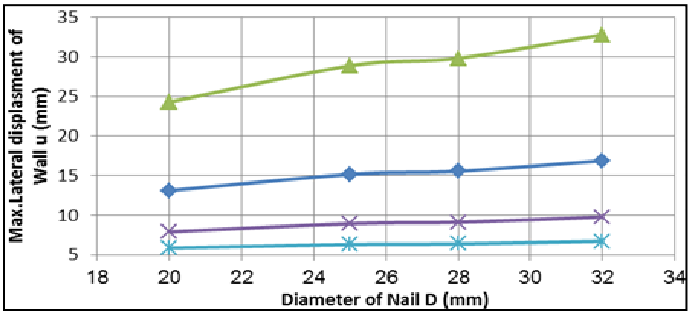

Fig.12. Maximum lateral displacement vs. diameter of nail for various cohesion values.

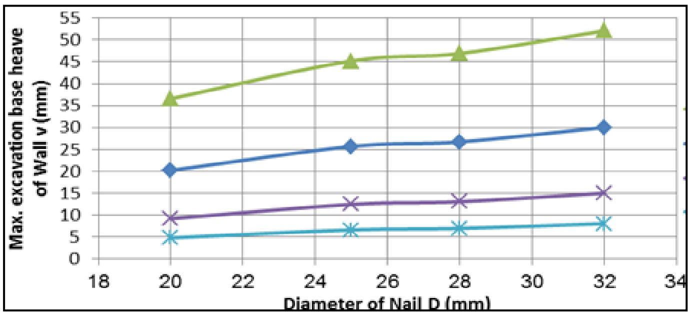

Fig.13. Maximum excavation base heave vs. diameter of nail for various cohesion values.

TABLE 6 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL DIAMETER VALUES (C-SOIL).

c (kPa)	D (mm)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
37.5	20	97.57	1.80	9.07
	25	108.98	3.40	12.58
	28	111.67	3.78	13.40
	32	117.90	4.77	15.02
50	20	94.26	1.66	8.84
	25	103.24	3.22	12.00
	28	105.29	3.58	13.23
	32	109.17	4.61	14.89
62.5	20	88.91	1.34	8.21
	25	98.92	2.57	11.67
	28	101.10	2.87	12.49
	32	105.34	3.67	14.10
75	20	81.71	1.09	6.94
	25	93.39	2.26	10.61
	28	95.98	2.55	11.41
	32	101.31	3.35	13.53

VIII. EFFECT OF ANGLE OF NAIL INCLINATION

A threshold at an inclination angle of (10^0) is detected from Fig.14 to 16 and Table 7. A maximum safety factor is reached at this value. The maximum displacements, bending moment, and shear force are increased beyond this value, especially for low cohesion values. The maximum axial force is reduced beyond an inclination angle of (10^0).

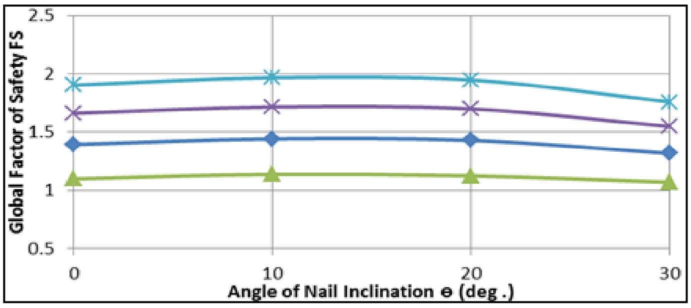

Fig.14. Global factor of safety vs. angle of nail inclination for various cohesion values.

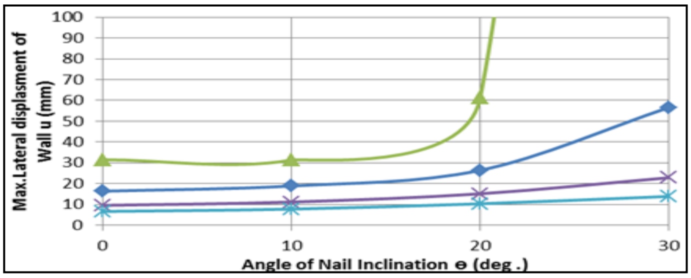

Fig.15 Maximum lateral displacement vs. angle of nail inclination for various cohesion values.

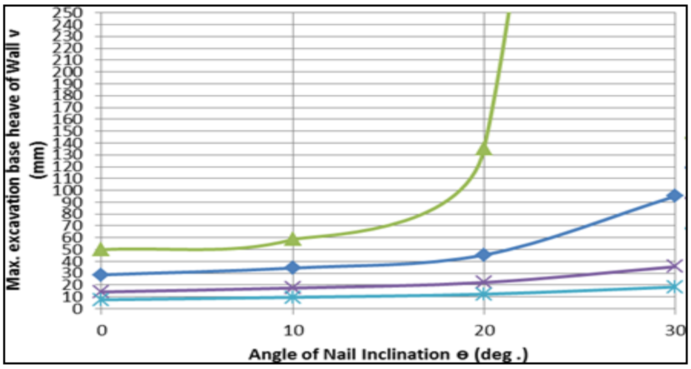

Fig.16. Maximum excavation base heave vs. angle of nail inclination for various cohesion values.

TABLE 7 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL INCLINATION ANGLES (C-SOIL).

c (kPa)	θ (degree)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
37.5	0	113.97	4.32	14.09
	10	110.00	6.98	19.96
	20	100.20	29.81	72.89
	30	94.00	141.30	174.20
50	0	106.27	4.09	13.89
	10	106.91	6.50	19.40
	20	86.47	13.39	35.12
	30	75.24	42.10	104.11
62.5	0	102.23	3.23	13.20
	10	100.66	5.25	17.78
	20	77.63	9.31	25.44
	30	47.63	23.05	66.13
75	0	97.60	2.92	12.38
	10	94.34	4.54	16.10
	20	72.43	7.51	21.13
	30	29.78	15.13	44.91

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IX. EFFECT OF SURCHARGE INTENSITY

It is apparent from Fig.17 to 19 and Table 8 that, the safety factor is inversely proportional to the surcharge intensity on the backfill side, whereas the maximum displacements and the maximum axial force are proportional to the surcharge intensity. The effects on maximum bending moment and maximum shear force are negligible.

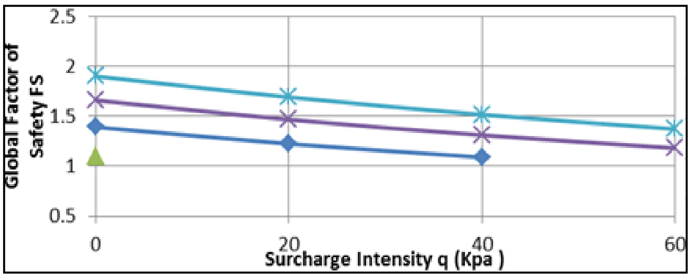

Fig. 17. Global factor of safety vs. surcharge intensity for various cohesion values.

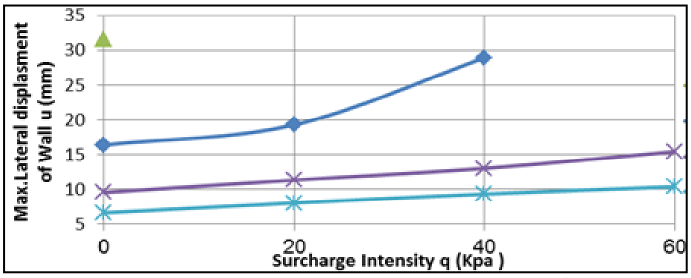

Fig. 18. Maximum lateral displacement vs. surcharge intensity for various cohesion values.

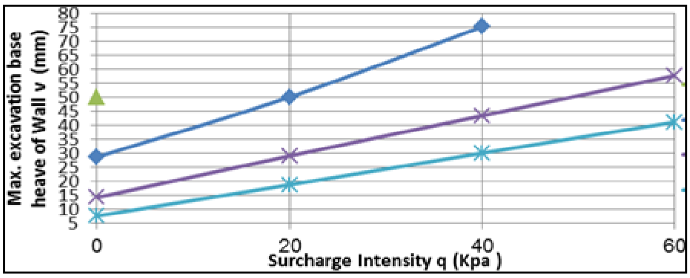

Fig.19. Maximum excavation base heave vs. surcharge intensity for various cohesion values.

TABLE 8 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS SURCHARGE VALUES (C-SOIL)

c (kPa)	q (kPa)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
37.5	0	113.97	4.32	14.09
	20	0	0	0
	40	0	0	0
	60	0	0	0
50	0	106.27	4.09	13.89
	20	123.28	4.34	15.91
	40	153.80	4.19	16.50
	60	0	0	0
62.5	0	102.23	3.23	13.20
	20	115.64	3.71	15.45
	40	132.68	3.81	16.17
	60	154.94	3.75	16.23
75	0	97.60	2.92	12.38
	20	110.71	3.23	14.23
	40	125.53	3.52	15.75
	60	142.36	3.50	16.11

X. GROUTED NAILS INTO COHESIONLESS SOILS

Grouted nails embedded into sand with different relative densities, are considered. The associated values of elastic parameters and soil unit weight (γ) are listed in Table 9.

TABLE 9 COHESIONLESS SOIL PROPERTIES FOR THE PARAMETRIC STUDY.

φ	ν	E_s (kN/m^2)	γ (kN/m^3)
25	0.2	15000	14
30	0.25	20000	16
35	0.30	40000	18
40	0.35	80000	20

XI. EFFECT OF HEIGHT OF EXCAVATION

This effect on the response, expressed by different parameters is shown in Fig. 20 through 22 and Table 10. The results revealed an increase in the global stability with the soil relative density increase and a decrease with the increase of height of excavation. For low values of friction angle, a maximum retained height of (6.0 m) is recorded. The lateral and bottom displacements are proportional with the height of excavation. The maximum nail axial force is proportional to the excavation height and is inversely proportional to the soil angle of internal friction. The maximum nail shear force and bending moment are insensitive to the excavated height.

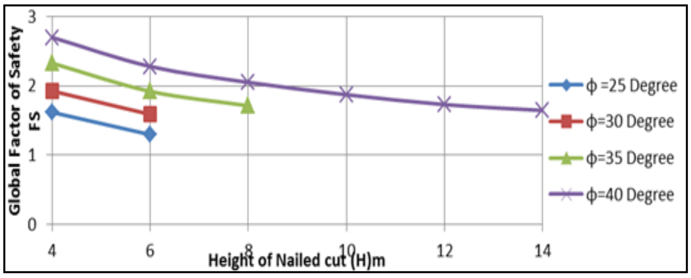

Fig. 20. Global factor of safety vs. height of nailed cut for various friction angles.

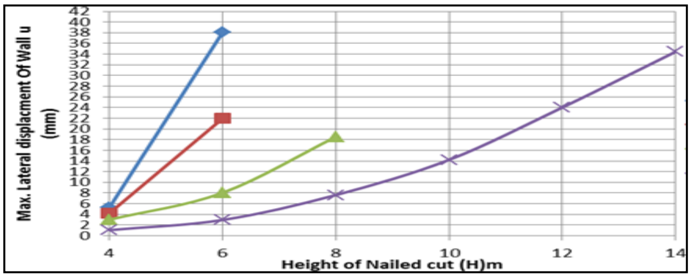

Fig. 21. Maximum lateral displacement vs. height of nailed cut for various friction angles.

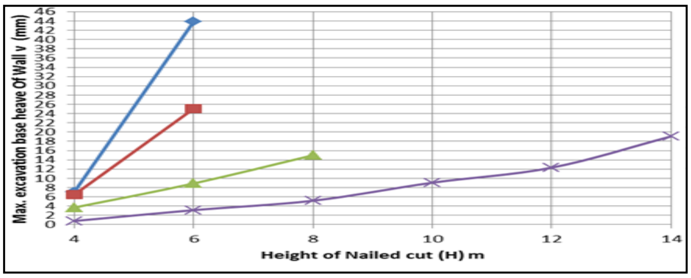

Fig. 22. Maximum excavation base heave vs. height ofnailed for various friction angles.

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TABLE 10 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS HEIGHT VALUE (Φ-SOIL).

φ°	H (m)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	4	44.99	3.88	11.68
	6	79.02	3.67	12.38
	8	0	0	0
	10	0	0	0
	12	0	0	0
	14	0	0	0
30	4	40.04	3.70	12.00
	6	63.01	3.62	12.10
	8	0	0	0
	10	0	0	0
	12	0	0	0
	14	0	0	0
35	4	34.05	2.64	11.62
	6	53.16	2.43	11.62
	8	89.12	3.58	14.18
	10	0	0	0
	12	0	0	0
	14	0	0	0
40	4	29.54	1.81	10.18
	6	47.01	1.92	10.18
	8	72.96	2.36	12.27
	10	103.45	3.00	15.44
	12	147.62	4.67	23.28
	14	167.89	5.55	27.46

XII. EFFECT OF LENGTH OF NAILS

Fig. 23 shows slight increase in global stability as nails get longer. The maximum lateral displacement and base heave decrease with the increase of nails length for low values of soil friction angle. This behavior is apparent from Fig. 24 and 25. Table 11 indicate minor effects on maximum nail axial force, bending moment, and shear force.

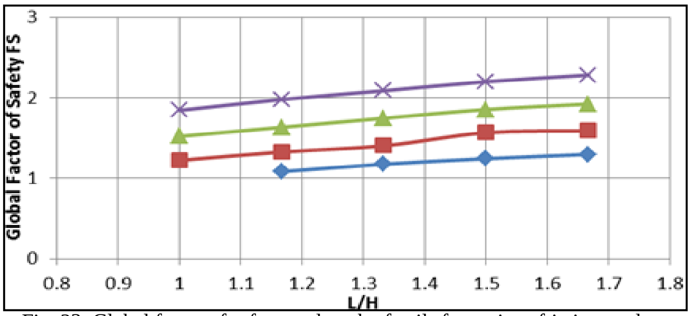

Fig. 23. Global factor of safety vs. length of nails for various friction angles.

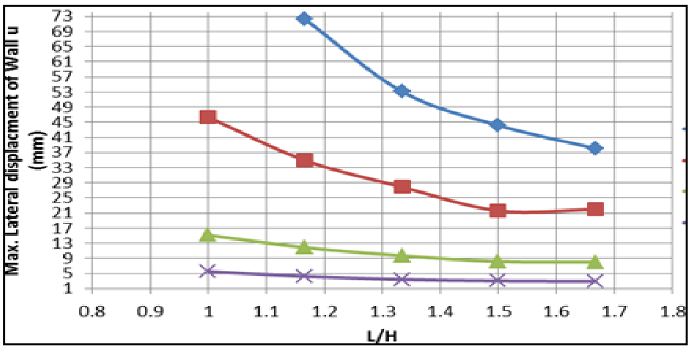

Fig. 24. Maximum lateral displacement vs. length of nails for various friction angles.

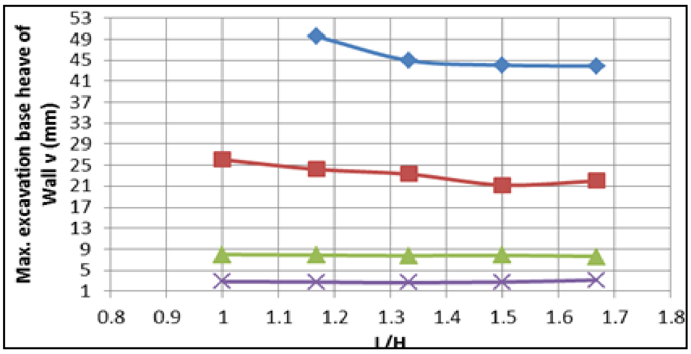

Fig. 25. Maximum excavation base heave vs. length of nails various friction angles.

TABLE 11 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL LENGTH (Φ-SOIL).

φ°	L (m)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	6	0	0	0
	7	80.88	3.99	12.35
	8	80.93	3.71	12.32
	9	80.75	3.71	12.32
	10	79.02	3.67	12.38
30	6	73.20	4.17	13.54
	7	69.24	3.92	12.56
	8	66.96	3.77	12.32
	9	66.90	3.70	11.90
	10	63.01	3.62	12.10
35	6	61.29	2.63	10.94
	7	58.14	2.53	11.05
	8	57.38	2.51	11.32
	9	55.77	2.53	11.32
	10	53.16	2.43	11.62
40	6	50.17	1.74	9.81
	7	48.51	1.79	9.79
	8	47.19	1.80	9.79
	9	47.73	1.89	9.79
	10	47.01	1.92	10.18

XIII. EFFECT OF THE INTERFACE FRICTION FACTOR

It can be realized from Fig. 26 that, the friction factor has a minor effect on the global safety factor. Fig. 27, 28 and Table 12 show decreasing trends of deformations and maximum nail internal reactions, with the increase in friction factor. This behavior is pronounced for low (φ-values).

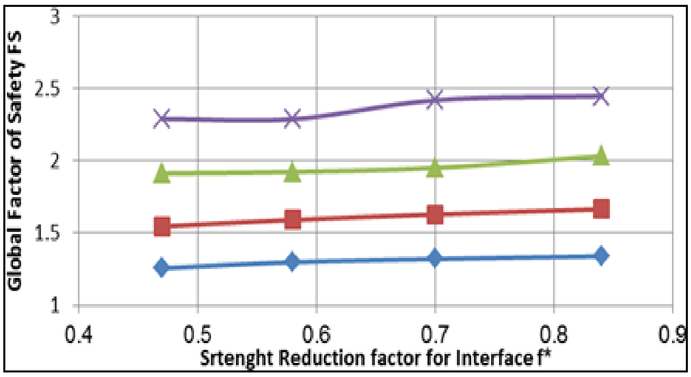

Fig. 26. Global factor of safety vs. interface friction factor for variousfriction angles.

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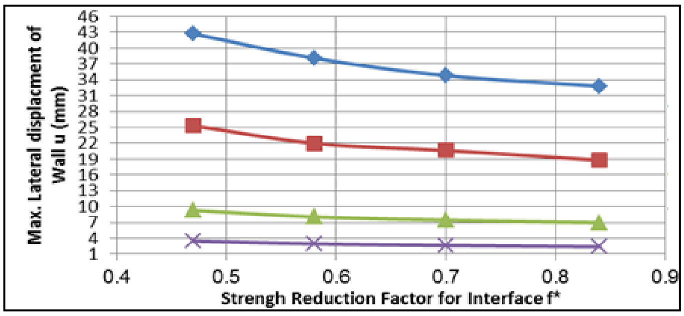

Fig. 27. Maximum lateral displacement vs. interfacefriction for various friction angles.

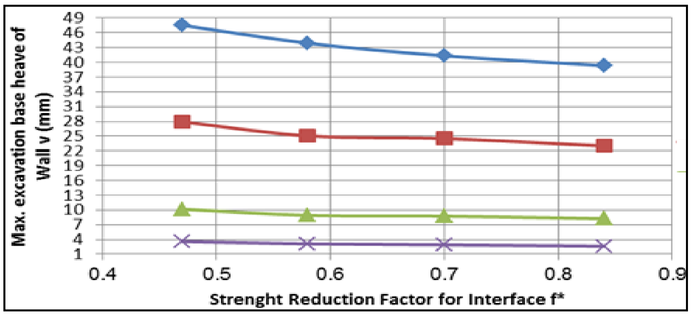

Fig. 28. Maximum excavation base heave vs. interface friction factor for various friction angles.

TABLE 12 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS INTERFACE STRENGTH REDUCTION FACTORS (Φ-SOIL).

φ°	f*	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	0.47	81.70	4.15	12.48
	0.58	79.02	3.67	12.38
	0.70	75.97	3.49	11.40
	0.84	74.54	3.23	10.87
30	0.47	65.52	4.00	12.12
	0.58	63.01	3.62	12.10
	0.70	62.24	3.40	11.17
	0.84	59.54	3.25	10.89
35	0.47	55.46	2.67	10.83
	0.58	53.16	2.43	11.62
	0.70	52.86	2.31	10.80
	0.84	51.43	2.20	10.53
40	0.47	47.86	2.00	9.94
	0.58	47.01	1.92	10.18
	0.70	46.65	1.84	10.00
	0.84	45.15	1.73	9.89

XIV. EFFECT OF NAIL DIAMETER

The responses of the wall due to changing the nail diameter are illustrated in Fig. 29 to 31 and Table 13. There are no significant effects of nail diameter on the global stability and deformation characteristics. Slight increase in the maximum axial force is detected with the increase in nail diameter. Increasing the nail diameter attracts more shear force and bending moment but, still the values are small.

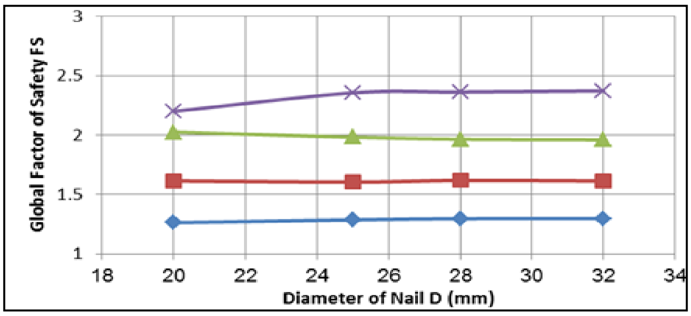

Fig. 29. Global factor of safety vs. diameter of nail for various friction angles.

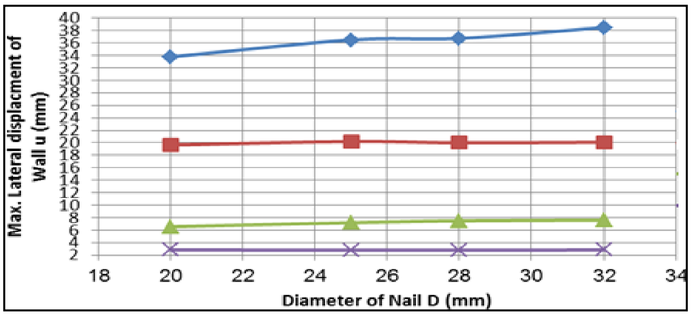

Fig. 30. Maximum lateral displacement vs. diameter of nail for various friction angles.

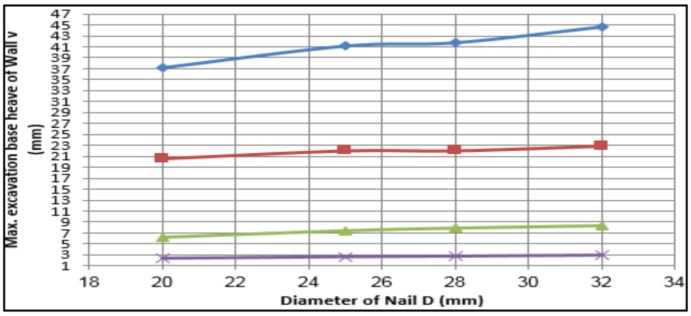

Fig. 31. Maximum excavation base heave vs. diameter of nail for various friction angles.

TABLE 13 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL DIAMETER VALUES (Φ- SOIL).

φ°	D (mm)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	20	70.84	1.76	9.26
	25	76.69	3.07	11.33
	28	77.42	3.43	11.83
	32	80.41	4.14	12.95
30	20	58.85	1.67	9.00
	25	63.82	3.07	11.02
	28	65.99	3.40	11.39
	32	68.40	4.39	12.93
35	20	47.31	1.06	8.59
	25	52.99	1.99	10.45
	28	54.98	2.21	11.22
	32	57.52	2.83	12.38
40	20	42.39	0.84	7.13
	25	47.04	1.58	9.47
	28	48.17	1.75	9.86
	32	50.19	2.22	10.85

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XV. EFFECT OF ANGLE OF NAIL INCLINATION

Fig. 32 shows an increase in global stability with the nail inclination increase, up to an inclination angle of about (10^0). Beyond this value, a decrease in safety factor is commenced. It is clear from Fig. 33 and 34 that, the lateral and basal displacements are proportional to the nail inclination angle beyond a value of (10^0). The maximum axial force drops beyond inclination angle of (10^0) to a minimum value at ($\theta=20^0$). After this value, the increase is obvious from Table 14. Proportional trends of the maximum shear force and maximum bending moment in soil nails are observed in Table 14.

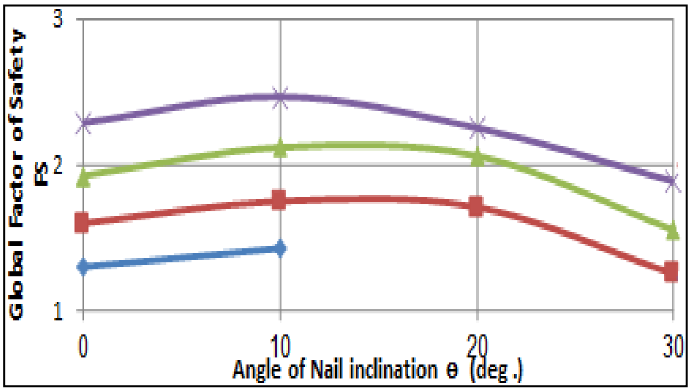

Fig. 32. Global factor of safety vs. angle of nail inclination for various friction angles.

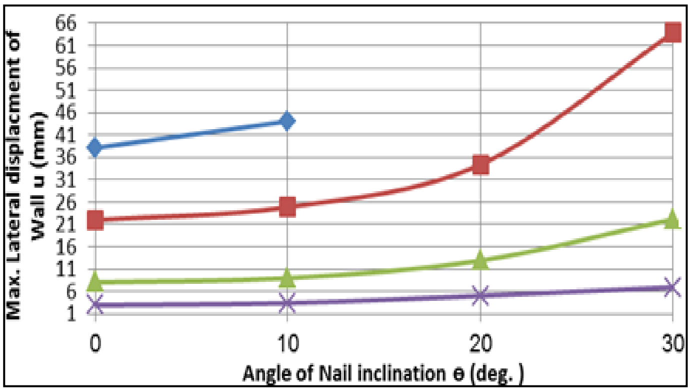

Fig. 33. Maximum lateral displacement vs. angle of nail inclination for various friction angles.

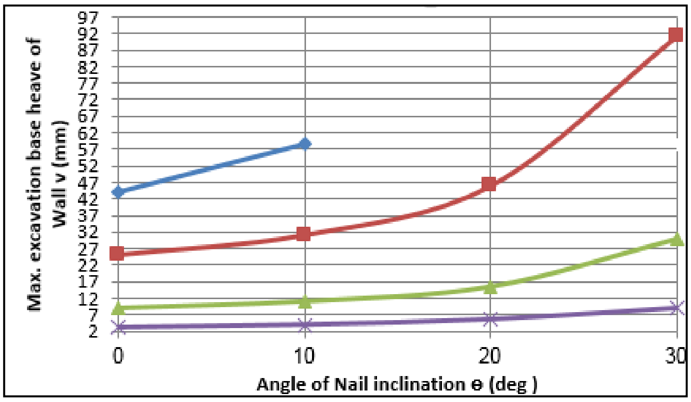

Fig. 34. Maximum excavation base heave vs. angle of nail inclination for various friction angles.

TABLE 14 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS NAIL INCLINATION ANGLES (Φ-SOIL).

φ°	θ°	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	0	79.02	3.67	12.38
	10	74.63	7.98	23.00
	20	0	0	0
	30	0	0	0
30	0	63.01	3.62	12.10
	10	63.20	6.83	22.93
	20	58.11	14.73	39.78
	30	63.16	38.82	83.19
35	0	53.16	2.43	11.62
	10	51.54	4.75	19.80
	20	48.69	8.29	29.99
	30	58.70	23.92	71.34
40	0	47.01	1.92	10.18
	10	45.52	3.26	17.80
	20	43.74	5.04	22.10
	30	45.24	12.90	47.50

XVI. EFFECT OF SURCHARGE INTENSITY

Fig. 35 reveals slight decrease in global stability due to the increase in backfill surcharge. Fig 36, 37 and Table 15 show proportional trends of the deformation characteristics and the maximum nail internal reactions with the surcharge intensity.

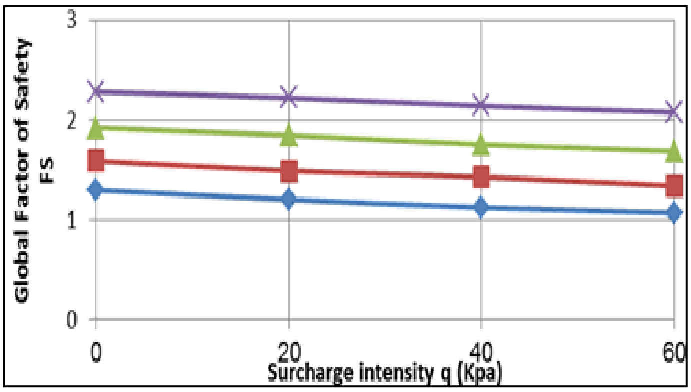

Fig. 35. Global factor of safety vs. surcharge intensity for various friction angles.

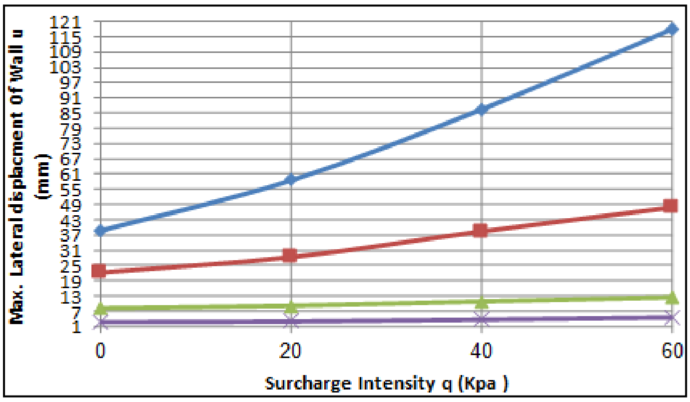

Fig. 36. Maximum lateral displacement vs. surcharge intensity for various friction angles.

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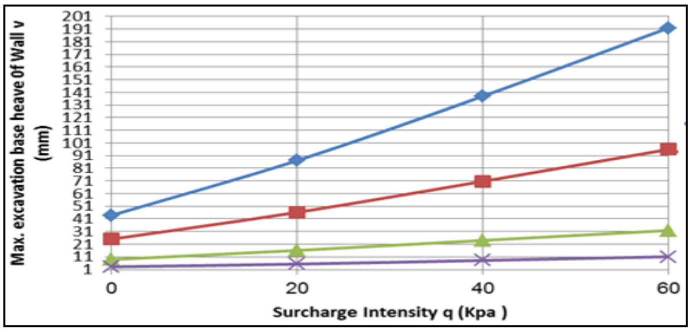

Fig. 37. Maximum excavation base heave vs. surcharge intensity for various friction angles.

TABLE 15 RESULTS OF THE PARAMETRIC STUDY FOR VARIOUS SURCHARGE VALUES (Φ- SOIL).

φ°	q (kPa)	T (kN)	B.M. (kN.m/m)	S.F. (kN/m)
25	0	79.02	3.67	12.38
	20	102.34	4.23	14.23
	40	124.48	4.82	16.33
	60	146.32	5.23	17.71
30	0	63.01	3.62	12.10
	20	86.24	4.09	13.50
	40	105.99	4.53	16.00
	60	122.74	4.94	17.23
35	0	53.16	2.43	11.62
	20	69.16	3.26	13.33
	40	81.76	3.77	15.37
	60	92.90	4.19	17.18
40	0	47.01	1.92	10.18
	20	57.11	2.41	13.02
	40	68.01	2.74	14.70
	60	80.66	3.14	16.80

XVII. CONCLUSIONS

For the adopted practical ranges of soil properties and nailed wall characteristics, the following conclusions can be drawn.

Cohesive Soils

1. Increasing soil cohesion will increase the global stability and decreases the maximum values of wall lateral displacement, base heave, nail axial force, shear force and bending moment.
2. Reversed effects are detected regarding the excavated height. Ultimate heights associated with soil cohesion values are reported. The effect of retained height on the nails' maximum axial force is more pronounced than soil cohesion.
3. Increasing nails' length results in slight increase in global stability and maximum base heave whereas, the maximum lateral displacement is reduced, (only) for low value of cohesion. The maximum nails' axial force is proportional to their length.
4. The interface strength reduction factor has minor effects on the response, especially for large cohesion values. The maximum nails' axial force is inversely proportional to that factor.
5. A slight decrease in the global safety factor is observed when the nails' diameter is increased. Other responses are proportional to the nails' diameter.
6. The maximum stability is attained at a nails' inclination angle of around (10^0). The maximum values of displacements, nails shear force and bending moment are increased considerably beyond this value whereas, the maximum nails axial force is reduced.
7. The surcharge intensity on backfill side of the wall reduces the stability and increases the maximum displacements and nails' maximum axial force. It has negligible effect on both of the maximum shear force and bending moment in the nails.
8. The nails' maximum bending moment and shear force are small compared to the maximum axial force.

Cohesionless Soils

1. The global stability is increased as the soil angle of internal friction gets bigger values. The maximum values of displacements and nails' internal reactions are reduced.
2. The excavated height has invers effects on the response. Ultimate heights for various friction angles are observed.
3. Slight increase in stability and reduced maximum displacements are reported for an increased nails' length. Minor effects on the nails' maximum internal reactions are indicated.
4. The interface friction factor has a minor effect on stability. Other responses show decreasing trends with the factor increase, especially for low (φ- values).
5. Increasing nails' diameter has insignificant effects on stability and maximum deformation characteristics. The nails maximum internal reactions are proportional to the nails diameter.
6. The maximum safety factor is obtained at a nails' inclination angle of about (10^0). The maximum values of displacements, nails shear force and bending moment are increased considerably beyond this value. The maximum nails axial force is reduced beyond the same angle to a minimum value at ($\theta=20^0$).
7. The global stability decreases with the increase of surcharge intensity. Other responses are proportional to this factor.
8. The maximum axial force in nails is the dominated internal reaction.

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