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Model Tests for Validation of Analysis of Nailed Cuts

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Introduction

Soil nailing is a method of reinforcing the soil with steel bars or other materials. The nails suppress the tensile and shear stresses in soil and restrain lateral displacements in the soil. The nails are either placed in drilled bore holes and grouted along their total length to form 'grouted nails', or simply driven into the ground, called as 'driven nails'. The technique helps in stabilization of both natural slopes and vertical or inclined cuts. Many investigators (Gässler and Gudehus, 1981, 1983; Shen et al., 1981; Schlosser, 1982; Juran et al., 1988, 1990; Raju, 1996; Gupta, 2003; Gosavi, 2006) have proposed methods for investigating the stability of vertical/nearly vertical excavations. In each method, the assumed geometry of the slip surface is based on observations in either small scale model tests or full scale structures. The methods vary by the geometry of the assumed failure surface, the definition of the factor of safety and the forces assumed to act in the active zone.

In the present research work, a pseudo-static analysis for the stability of inclined nailed cut considering the log-spiral failure wedge (Figure 1) has been carried out. The formation of log-spiral rupture surface is supported by earlier investigators (Jewell, 1989; Plumelle and Schlosser, 1990; Juran and Elias, 1992) including the observations by Raju (1996) in his small scale model tests and trench tests. The forces acting on the sliding wedge are shown in Figure (1). Considering all these forces, the equation of Factor of Safety (FOS) can be written as,

$$\text{FOS} = \frac{\sum Resisting \quad moments}{\sum Driving \quad moments} = \frac{M_T + M_{Tc} + Mc}{M_{WV} + M_{WH} + M_{QV} + M_{QH}} \qquad (1)$$

where,

M_{WV} = Moment of weight of wedge a′bd along with vertical seismic coefficient $(1 \pm \alpha_v)$ about centre of log spiral 'o',

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M_{WH} = Moment of weight of wedge a′bd along with horizontal seismic coefficient α_h about center of log spiral 'o',

M_{QV} = Moment of surcharge q along with vertical seismic coefficient $(1 \pm \alpha_v)$ about center of log spiral 'o',

M_{QH} = Moment of surcharge q along with horizontal seismic coefficient α_h about center of log spiral 'o',

M_T = Moment of nail axial force T_i (for i = 0 to i = n, where n is the total number of nails in single column) about center of log spiral 'o',

M_{Tc} = Moment of maximum shearing resistance mobilized in i^{th} (i = 0 to i = n)nail i.e. T_{ci} about center of log spiral 'o',

Mc = Moment due to cohesion force 'c' action along the failure surface bd and about the center of log spiral 'o'.

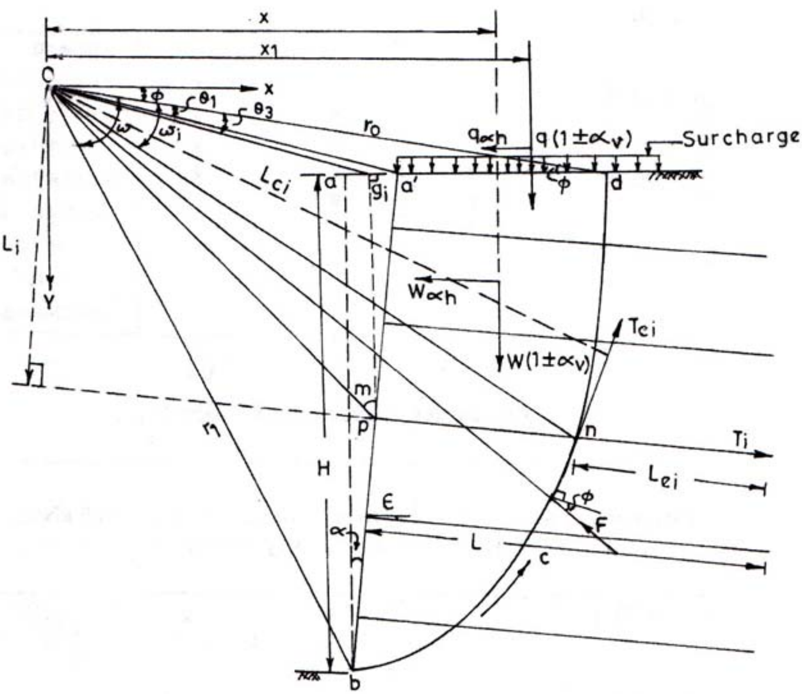


Fig.1 Forces Acting on Log-spiral Failure Wedge

The details of derivation of all the forces and their moments are given elsewhere (Saran et al., 2005; Gosavi, 2006; Gosavi et al., 2006,). The minimum FOS which was obtained by varying log spiral angle ω (Figure 1), is further dependent on the following factors: i) length and diameter of nails (L, d), ii) vertical and horizontal spacing between nails (S_v and S_h), iii) yield strength of nail (f_y), iv) coefficient of friction between soil and nail (f*), v) cohesion and frictional characteristics of soil (c, ϕ), vi) density of soil (γ),vii) inclination of cut with vertical, α, viii) inclination of nails with horizontal, ε ,ix) height of cut (H), x) seismic coefficients (α_h, α_v), and xi) surcharge intensity on the surface of cut, q.

For a given set of parameters, the minimum FOS of a nailed cut was obtained using a computer program developed in this study. The study has been made for different diameters of the nail, d (= 16 mm, 20 mm, 25 mm, 32 mm and 36mm); different heights of cuts, H (= 6m, 8m, 10m, 12m); different angles of friction, ϕ (=25°, 30° and 35°); different $\propto_h$ (= 0.0, 0.05, 0.10 and 0.15); different cohesion, c (= 0, 10 , 20 kN/m^2) and different surcharge intensity on ground, q, (= 0, 20 kPa and 40 kPa). Other parameters used in the study are $\alpha_v = \alpha_{h/2}$; γ, the unit weight of soil is 16.5 kN/m^3. Typical results for 10m high cut with L=8.0m, d= 25mm, ϕ =30°, $\varepsilon = 0°$, $\alpha_v = \alpha_h / 2$, f_y = 415 N/mm^2, f* = 0.50, ε = zero, α_η = 0.0,0.05,0.10 & 0.15, and α = 0, 5 and 10, c= 0 kpa, 10kpa & 20kpa and q = 0 & 20 kpa are presented in Table 1 and 2. The results for 40kpa surcharge are not reported in the tables. N is the number of nails and f_y is the tensile strength of steel nail. Parametric study has been made from the above analysis for non-dimensional parameters like the ratio between the length of nail and the height of cut, L/H (= 0.6, 0.7, 0.8, 0.9 and 1.0) and friction coefficient, f^* (= 0.4, 0.5, 0.6 and 0.7). Study showed linear increase in the value of FOS with the increase in the diameter of nail, L/H ratio and f^* for design of nailed open cuts. Therefore following correlations may be used to determine the factor of safety of nailed cuts considering any diameter of nail other than 25mm, f* other than 0.5 and L/H ratio other than 0.8.

$$(\text{FOS})_{d=x} = \frac{x}{25}(\text{FOS})_{d=25} \tag{2}$$

$$(FOS)_{f^*=y} = \frac{y}{0.5}(FOS)_{f^*=0.5} \tag{3}$$

$$(FOS)_{\frac{L}{H}=z} = \frac{z}{0.8}(FOS)_{\frac{L}{H}=0.8} \tag{4}$$

Where,

$(\text{FOS})_{d=x}$ = FOS corresponding to any diameter (x mm) of the nail other than 25 mm.

$(\text{FOS})_{d=25}$ = FOS corresponding to 25 mm diameter nail calculated using Eq. 1.

$(FOS)_{f^*=y}$ = FOS corresponding to any f *= y, other than 0.5.

$(\text{FOS})_{f^*=0.5}$ = FOS corresponding to f *= 0.5 calculated using Eq.1

Table 1 Parametric Study For H = 10 m, γ = 16.5 kN/m^3, ϕ =30°, N=H/S$_v$, L/H = 0.8, d =25mm, $\varepsilon = 0°$, $\alpha_v = \alpha_h / 2$, f_y = 415 N/mm^2, α_η= 0 & 0.05

α_η	α	FOS											
		N	c=0 q=0	N	c=10, q=0	N	c=20, q =0	N	c=0, q=20	N	c=10, q=20	N	c=20, q=20
0	0	14	1.71	12	1.68	9	1.55	13	1.42	11	1.52	9	1.58
0	0	15	1.96	13	1.90	10	1.72	14	1.65	12	1.74	10	1.78
0	0	16	2.23	14	2.14	11	1.90	15	1.89	13	1.97	11	2.01
0	0	17	2.52	15	2.39	12	2.10	16	2.15	14	2.23	12	2.25
0	5	12	1.55	10	1.56	8	1.64	12	1.38	10	1.49	8	1.59
0	5	13	1.81	11	1.78	9	1.83	13	1.62	11	1.72	9	1.80
0	5	14	2.10	12	2.03	10	2.03	14	1.88	12	1.97	10	2.03
0	5	15	2.41	13	2.30	11	2.26	15	2.15	13	2.24	11	2.28
0	10	11	1.58	9	1.61	6	1.55	11	1.32	9	1.46	7	1.59
0	10	12	1.88	10	1.86	7	1.73	12	1.57	10	1.70	8	1.80
0	10	13	2.21	11	2.13	8	1.93	13	1.84	11	1.96	9	2.04
0	10	14	2.56	12	2.43	9	2.15	14	2.13	12	2.24	10	2.31
0	15	10	1.58	8	1.64	5	1.63	11	1.51	8	1.43	6	1.62
0	15	11	1.91	9	1.91	6	1.81	12	1.79	9	1.67	7	1.82
0	15	12	2.28	10	2.22	7	2.02	13	2.10	10	1.94	8	2.06
0	15	13	2.67	11	2.55	8	2.26	14	2.44	11	2.24	9	2.33
0.05	0	14	1.54	12	1.53	10	1.56	14	1.49	12	1.57	10	1.63
0.05	0	15	1.77	13	1.72	11	1.73	15	1.71	13	1.79	11	1.83
0.05	0	16	2.01	14	1.93	12	1.91	16	1.94	14	2.02	12	2.05
0.05	0	17	2.27	15	2.16	13	2.11	17	2.19	15	2.27	13	2.29
0.05	5	13	1.62	11	1.60	9	1.65	13	1.46	11	1.56	8	1.44
0.05	5	14	1.88	12	1.82	10	1.84	14	1.69	12	1.78	9	1.63
0.05	5	15	2.15	13	2.06	11	2.04	15	1.94	13	2.03	10	1.84
0.05	5	16	2.44	14	2.32	12	2.26	16	2.21	14	2.29	11	2.07
0.05	10	12	1.66	10	1.66	7	1.55	12	1.41	10	1.53	8	1.63
0.05	10	13	1.95	11	1.90	8	1.73	13	1.66	11	1.76	9	1.84
0.05	10	14	2.26	12	2.17	9	1.93	14	1.92	12	2.02	10	2.08
0.05	10	15	2.59	13	2.45	10	2.15	15	2.20	13	2.30	11	2.34
0.05	15	10	1.38	9	1.69	6	1.61	11	1.35	9	1.50	7	1.64
0.05	15	11	1.67	10	1.95	7	1.80	12	1.61	10	1.74	8	1.85
0.05	15	12	1.99	11	2.24	8	2.01	13	1.88	11	2.01	9	2.09
0.05	15	13	2.33	12	2.56	9	2.25	14	2.18	12	2.30	10	2.37

α_η is seismic coefficient, α is inclination of cut with vertical in°, c and q in kpa

Table 2 Parametric Study for H = 10 m, γ = 16.5 kN/m^3, ϕ = 30°, N=H/S_v, L/H = 0.8, d =25mm, $\varepsilon = 0°$, $\alpha_v = \alpha_h$ / 2, f_y = 415 N/mm^2, α_η=0.10 & 0.15

α_η	α	FOS											
		N	c=0 q=0	N	c=10, q=0	N	c=20, q =0	N	c=0, q=20	N	c=10, q=20	N	c=20, q=20
0.1	0	15	1.60	13	1.57	11	1.58	15	1.54	12	1.43	10	1.49
0.1	0	16	1.82	14	1.76	12	1.75	16	1.76	13	1.63	11	1.67
0.1	0	17	2.05	15	1.96	13	1.93	17	1.98	14	1.84	12	1.87
0.1	0	18	2.29	16	2.18	14	2.12	18	2.22	15	2.06	13	2.09
0.1	5	14	1.68	12	1.65	9	1.50	14	1.54	11	1.42	9	1.49
0.1	5	15	1.93	13	1.86	10	1.67	15	1.76	12	1.62	10	1.68
0.1	5	16	2.19	14	2.09	11	1.85	16	2.00	13	1.84	11	1.88
0.1	5	17	2.47	15	2.34	12	2.05	17	2.26	14	2.08	12	2.11
0.1	10	12	1.47	11	1.70	8	1.56	13	1.50	11	1.60	8	1.48
0.1	10	13	1.73	12	1.94	9	1.74	14	1.74	12	1.83	9	1.67
0.1	10	14	2.00	13	2.19	10	1.94	15	1.99	13	2.08	10	1.89
0.1	10	15	2.30	14	2.47	11	2.15	16	2.27	14	2.35	11	2.13
0.1	15	11	1.47	9	1.50	7	1.61	12	1.45	10	1.57	8	1.67
0.1	15	12	1.75	10	1.74	8	1.80	13	1.70	11	1.81	9	1.89
0.1	15	13	2.05	11	1.99	9	2.01	14	1.97	12	2.07	10	2.14
0.1	15	14	2.37	12	2.27	10	2.24	15	2.26	13	2.36	11	2.40
0.15	0	16	1.64	14	1.60	12	1.60	15	1.40	13	1.49	11	1.53
0.15	0	17	1.85	15	1.79	13	1.76	16	1.59	14	1.68	12	1.72
0.15	0	18	2.07	16	1.99	14	1.94	17	1.80	15	1.88	13	1.91
0.15	0	19	2.31	17	2.20	15	2.13	18	2.01	16	2.09	14	2.12
0.15	5	14	1.51	13	1.69	10	1.52	14	1.40	12	1.48	10	1.54
0.15	5	15	1.73	14	1.90	11	1.69	15	1.61	13	1.69	11	1.73
0.15	5	16	1.97	15	2.12	12	1.87	16	1.83	14	1.90	12	1.93
0.15	5	17	2.22	16	2.36	13	2.06	17	2.06	15	2.14	13	2.16
0.15	10	13	1.54	11	1.53	9	1.58	14	1.59	11	1.46	9	1.53
0.15	10	14	1.78	12	1.74	10	1.75	15	1.82	12	1.67	10	1.73
0.15	10	15	2.05	13	1.97	11	1.95	16	2.07	13	1.90	11	1.94
0.15	10	16	2.33	14	2.22	12	2.16	17	2.33	14	2.15	12	2.18
0.15	15	12	1.54	10	1.55	8	1.62	13	1.55	10	1.43	8	1.53
0.15	15	13	1.81	11	1.78	9	1.81	14	1.80	11	1.65	9	1.72
0.15	15	14	2.09	12	2.02	10	2.02	15	2.06	12	1.89	10	1.95
0.15	15	15	2.40	13	2.29	11	2.24	16	2.34	13	2.15	11	2.19

α_η is seismic coefficient, α is inclination of cut with vertical in°, c and q in kpa

$(FOS)_{\frac{L}{H}=z}$ = FOS corresponding to any L/H ratio = z, other than 0.8.

$(\mathrm{FOS})_{\frac{\mathrm{L}}{\mathrm{H}}=0.8}$ = FOS corresponding to L/H=0.8 calculated using Eq.1

The basic aim of this study is to validate the analysis developed during this research. To validate the analysis developed for the nailed open cuts, model tests were performed. Studies have been performed on two model nailed cuts, i.e. 1.0 m high and another 2.0 m high. Apparent coefficient of friction between nail and soil (f*) plays an important role in determining the stability of nailed cuts. For determination of this factor, pull out test on each actual nail of the nailed cuts had been performed.

Soil Used

The soil used in the study was dry sand collected locally from river Solani bed. According to the Indian Standard (IS: 1498-1970) classification, the soil is classified as poorly graded sand (SP). The maximum and minimum void ratios were determined in accordance with the procedures laid down in Indian Standard IS: 2720 (Part XIV, 1968). Table 3 provides the relevant properties of the soil.

Table 3: Properties of Soil used in Experimental Programme

S. No.	Property	Value
1	Effective size (D_{10})	0.16 mm
2	uniformity coefficient (C_u)	5
3	specific gravity	2.54
4	minimum void ratio (e_{min})	0.45
5	maximum void ratio (e_{max})	0.79
6	unit weight of sand (γ)	16.5 kN/m^3
7	relative density	70%
8	angle of internal friction of soil (ϕ)	38^o

Nail Material and Dimensions

In model tests, tor steel bars of 10 mm and 12 mm diameter with lengths equal to 0.75 H and 0.8 H were used as nails, H being the height of model nailed wall.

Tests on 1.0 Meter High Nailed Cut

In a 1.1 m high tank, two nailed vertical excavations of 1.0 m height were made with configurations of nails as shown in Figure 2 (a and b). Tor steel bars of 10 mm diameter and length 750 mm were used as nails. The pseudo-static analysis developed by the authors (Saran et. al, 2005; Gosavi, 2006) gives the factor of safety for these configurations (Figure 2 a and b) as 1.86 and.1.47 respectively with no surcharge on the top surface of nailed cut. The details are summarised in Table 4.

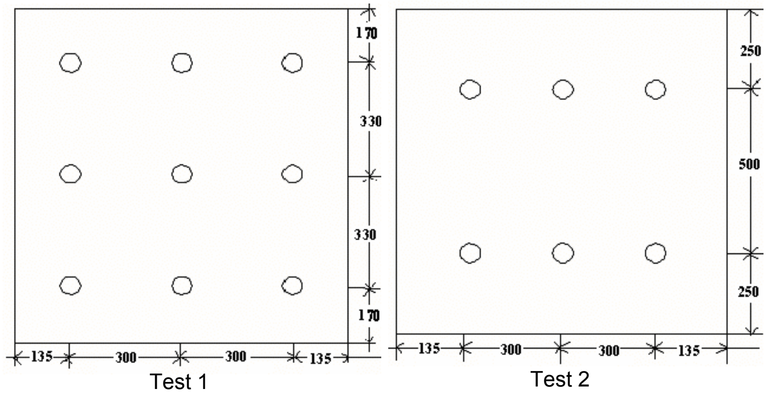


Fig. 2 Horizontal and Vertical Spacing of Nails in 1.0 m High Nailed Cut Tests

Table 4: Tests on 1.0 m High Nailed Cut

Test No.	Nail Diameter (mm)	Nail spacing		Length of nail (m)	FOS obtained by analysis
		S_v (m)	S_h (m)		
1.	10	0.33	0.3	0.75	1.86
2	10	0.5	0.3	0.75	1.47

Test Tank

Experiments on model wall were conducted in a rigid steel tank directly resting on base frame of steel channels which in turn rested on cement concrete floor. One side wall and one end wall of tank were completely made of 6 mm thick mild steel sheet welded to the vertical frame work of steel channels. The other side wall was built by 6 mm thick mild steel sheet in a length of 0.8 m and balance by 12 mm thick Perspex sheet (1.2 m long). The Perspex sheet was held in position by nuts and bolts both at its top and bottom. The remaining fourth side of the tank was the facing of the model nailed cut which was hinged at its bottom to the tank so that the deflection of vertical facing can be read at respective heights. It was ensured before doing the filling in the tank that the facing rotated freely to and fro, without touching the two sides of the tank. The total inside length of the tank behind the facing was 1.55 m and its width and height were 0.87 m and 1.1 m respectively (Figure 3).

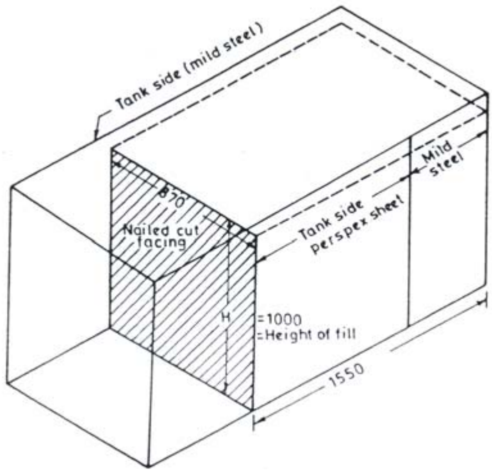


Fig 3 Set Up of 1.0 m High Nailed Cut Test

Model Wall Facing

In actual soil nailed cuts, where the soil can stand unsupported for excavation depth of about 0.5 m to 1.0 m, a shotcrete or precast panel facing is commonly used. Since dry sand was used in these tests, a vertical excavation face could only be maintained using a rigid facing. A 19 mm thick ply board (1.0 m high and 0.865 m wide) was used as a pre-placed continuous facing.

Circular holes of diameter 12 mm were made on pre-placed continuous facing at the horizontal and vertical spacing as illustrated in Figures 2 (a) and (b). The inner periphery of these holes was made smooth by grinding to avoid any friction of the wall material with nail. To avoid the leakage of sand through these holes, flaps of size 25 mm x 25 mm made of 2 mm thick aluminium sheets were fitted on these holes with single rivet to cover these holes. The advantage of these flaps was that it could be turned up and down along the rivet.

Test Procedure

The following procedure was adopted for construction of nailed cut for test 1:

- Ply board facing was placed vertically across the tank at a distance of 1.55 m from rear end of tank. The facing was brought to absolute vertical position with the help of a tri-square and it was clamped at the top of its both ends to restrict the lateral movement of facing during filling of tank.
- The narrow gaps between the facing and the tank sides were closed by a polyethylene sheet strip bent into an angle along the length.
- Two dial gauges were fixed in position to measure the deflection of the facing at the top and at mid height and their initial readings were taken when the tank was empty.
- The filling of the sand was done by rainfall technique to achieve the unit weight of sand as 16.5 kN/m^3. It corresponds to relative density of sand

equal to 70%. To check the density achieved by rainfall technique, a container of known volume (i.e. 0.001 m^3) was placed at different depths in tank. By measuring the actual weight of the sand filled in the containers, unit weight of fill at the respective points was calculated. Average unit weight achieved was observed to be 16.5 kN/m^3, variation in the density found by rainfall technique at the different depths in the two small scale model tests was only 5%. While filling the tank, aluminium flaps fixed on holes on front side of the facing were turned down to cover all the holes. The sand was filled in tank upto the centre of holes of respective row of nails (upto 165 mm from the bottom of the tank for 1st row of nails in small model test 1).

> The top surface of sand was leveled properly and the predetermined numbers of nails were placed in the holes at specified horizontal spacing. Total length of the nail was kept as 800 mm (length of nail inside the tank was 750 mm, extra 50 mm length was provided for the nail head connections). One end of the nail was threaded for a length of 60 mm while the other end was made sharpened and pointed by grinding.

> Again sand was filled over these nails in the tank, till the next location of nails (i.e. at 495 mm and 835 mm from bottom of the tank in small model test 1). The sand pouring was continued until reaching the desire height of wall.

Similar procedure was adopted for construction of nailed cut for Test 2.

Surcharge Application on Backfill

After the backfill had been brought to the height of 1.0 m, the two side clamps holding the wall, were removed and lateral movement of the nailed wall was recorded with the help of dial gauges. Uniform surcharge was applied on the backfill till the failure of nailed wall occurred. The surcharge loading was applied by placing gunny bags filled with known weight of sand and also with cast iron weights placed on the 8 mm thick mild steel plate directly resting on the top surface of the sand fill. For the observed failure load, the factor of safety of the model nailed cuts for test 1 and test 2 were calculated taking into account the side wall friction of tank (Gosavi, 2006). The details of this are given in Appendix 1.

Measurement of Lateral Movement of Wall and Failure Surface

The lateral movement of wall was recorded at zero surcharge and at each increment in the surcharge loading till the failure of the nailed wall occurred. The lateral deformation recorded by the dial gauge fixed near the top edge of wall was used for computing wall rotations. The inclination of failure surface, which developed at active condition, was observed and recorded through the perspex sheet. The approximate shape and size of the failure wedge were recorded by the breaks in bands of coloured sand observed through the Perspex sheet.

Test Results

It was observed that when surcharge intensity exceeds 9.7 kPa (Test No. 1) and 5.2 kPa (Test No. 2), the deflection of the nail wall increases suddenly (Figure 4). These surcharge intensities are designated as failure surcharge intensities. Since the value of apparent coefficient of friction f* between nail and soil affects the stability of nail wall significantly, it was decided to determine the actual value of f* for the nail used in both of the tests at their respective positions. For this, at the end of construction pull-out tests were performed on these actual nails after applying surcharge. Values of f* were worked out as given in Table 5.

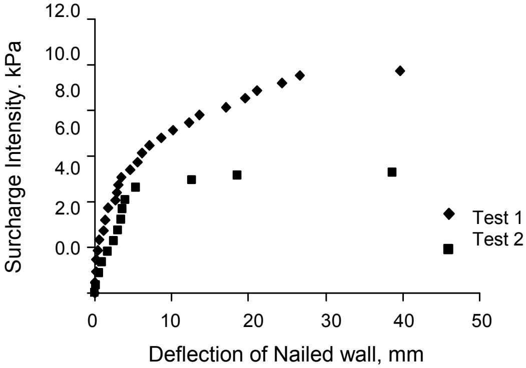


Fig. 4 Normal Stress Versus Deflection of Nail Wall for 1.0 m High Model Test 1 & 2

Table 5 : Small Model Test Results

Test No.	Nails Placed at depth (m) from top	γ kN/m^3	FOS	$\gamma.z + q$ kN/m^2	f^*	FOS
	0.165			12.47	0.61	
1	0.495	16.5	1.86	17.915	0.53	1.12
	0.825			23.36	0.49	
2	0.25	16.5	1.47	9.398	0.61	1.10
	0.75			17.648	0.54	

Using these values of f * (Table 5) the factor of safety for nailed cut for test No. 1 and test No. 2 with failure surcharge intensity of 9.7 kPa and 5.2 kPa worked out as 1.12 and 1.10 respectively. Actually the FOS with respect to surcharge intensities (i.e. 9.7 kPa and 5.2 kPa) in the two tests should be 1.0, therefore the proposed analysis predicts about 10 to 12 % higher values of FOS, which may be considered within acceptable limits from point of view of design of nailed cuts. It was observed that, in both test 1 and 2, at failure loads the wall fails by rotation about its toe. The failure surface was observed by breakage in black colour sand lines placed at 100 mm centre to centre along height of tank for both small model tests. By measuring the distance of the breakage in the colour sand line from the "at rest" condition of nailed cut and plotting the same with its height from toe of the wall, a failure wedge is drawn and the same is presented in Figure 5 along with the failure wedge obtained by analysis presented by authors (Saran et.al, 2005) for both small model tests. It was observed that the failure wedge obtained by analysis and actually observed through perspex sheet are of similar nature showing the log-spiral failure wedge.

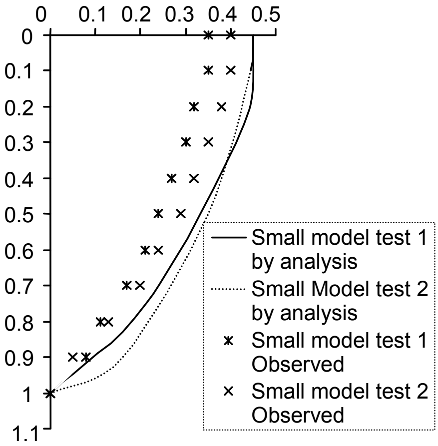
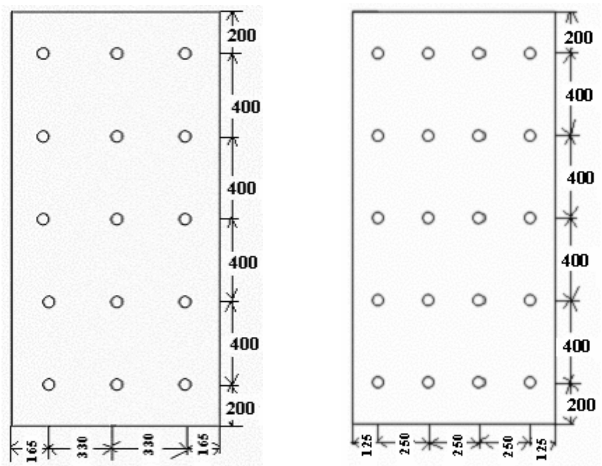


Fig. 5 Failure Surface Observed for 1.0 m High Nailed Model Test 1 and 2

Tests at 2.0 Meter High Nailed Cuts

Nailed vertical excavations of 2.0 m height were made in a concrete tank, 2.5 m high with two configurations of nails as shown in Figure 6 (a) and (b). Tor steel bars of 10 mm and 12 mm diameter and 1500 mm and 1600 mm length were used as nails respectively. The sand used in these model tests was the same as used for small model tests. Properties of the sand used in these tests is described in Table 1.



All dimensions in mm

Fig. 6 Horizontal and Vertical Spacing of Nails in 2.0 m High Nailed Cut Tests

Factor of safety of the nailed cuts with configuration of nails presented in Figure 6 (a) and (b) was obtained as 1.97 and 1.89 by the analysis developed by authors. The details of the large model tests are summarised in Table 6.

Table 6: Details of Large Scale Model Tests

Test No.	Nail Diameter (mm)	Nail Spacing		Length of Nail (m)	FOS
		S_v (m)	S_h (m)		
1.	12	0.4	0.33	1.6	1.97
2.	10	0.4	0.25	1.5	1.89

Tests were conducted on a specially fabricated concrete tank of size 2.5m x 1.0m x 2.5m (L x B x H) (Figure 6). The side walls of the tank were made with 150 mm thick RCC wall so as to provide sufficient stiffness to nailed excavation during application of surcharge. The bottom of tank was made with 200 mm thick RCC slab. The tank was made 1 m underground and 1.5 m above the ground so as to make workable conditions. Inner sides of the tank were plastered by 1:6 cement mortar with smooth finish.

Wall Facing

Same as that of a small model tests, pre-placed facing of ply board was used in the large model tests also. The height (2.0 m) of facing was achieved by placing four panels of 1.2 m width and 19 mm thick ply board panels one over the other. Out of these four panels two were made of 0.5 m height which were fixed at the lower most and top most levels, while other two panels placed in the centre were of 0.6 m and 0.4 m heights respectively as shown in Figure 6. The different heights of wooden panels were chosen to ascertain specified vertical spacing of nail as per Figure 6 (a) and (b). In this facing also, the round holes were made to place the nails at the designed spacing as described for small model tests. To keep the facing in a vertical position during filling of the tank, facing was supported temporarily form outside with the help of wooden logs.

Test Procedure

Same procedure as discussed for nailed cuts of 1.0 m height was adopted for construction of nailed cuts of 2.0 m height. Only the difference was that instead of a single plyboard panel used as a facing in case of 1.0 m high nailed cut here, the wall facing was replaced by 4 plyboard panels (Figure 7) placed simply one above the other were used as a facing. The filling of the tank was also done in this case by rain fall technique same as that of small model tests. Nails of design lengths were placed at designated vertical and horizontal spacing as per Figure 7 after leveling the top surface of the sand. Again the sand filling was done above the nails till next location of nails. In this way the total depth of nailed backfill was attained behind the nailed facing.

Measurement of Lateral Movement of Wall

After the tank was filled for 2.0 m height, the backfill soil was properly leveled. Before any surcharge was applied, it was decided to check the vertical alignment of nail wall. To check the alignment, a plumb bob was tied at the central position of the nail wall from a rigid beam tied to the loading frame 1.5 m above the backfill. Plumb bob was kept 200 mm away form the nail wall. The temporary supports provided to the facing of nailed cut from outside were removed one by one and the lateral movement of the nailed wall at each nail level was noted with respect to the position of plumb bob.

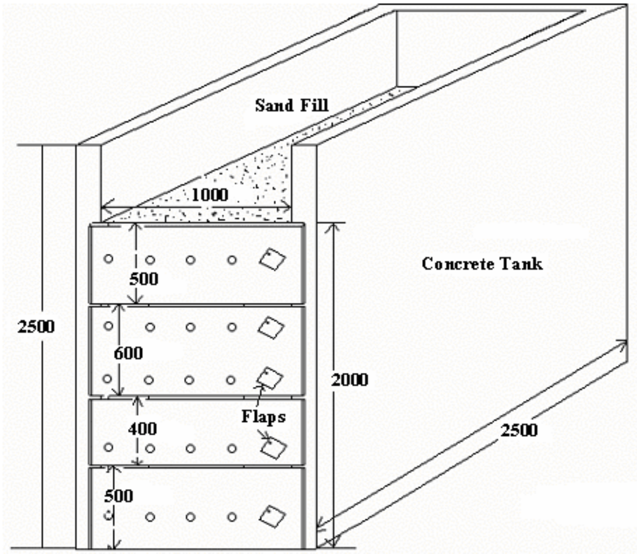


Fig. 7 Details of Large Scale Model Tests Set Up

Surcharge Application on Nailed Backfill

A rigid steel plate of size 0.8 m width, 2.4 m length and 25 mm in thickness (unit weight = 100 kN/m^3) was placed centrally on the nailed backfill. Above this steel plate, other steel plates of sizes 1.5 m x 0.8 m x 25 mm thick, 0.75 m x 0.75 m x 25 mm thick and 0.3 m x 0.3 x 25 mm thick were placed one above the other. These steel plates were kept on the sand fill to ensure uniform application of surcharge. At the centre of the top most steel plate, a proving ring of 300 kN capacity was placed to measure the surcharge applied by hydraulic jack of 500 kN capacity. The jack was reacted against a loading frame made with heavy steel sections of ISMB 200 (200 mm x 100 mm x 249.2 N/m) spaced at 1.25 m centre to centre along the length of the tank. Surcharge load was applied in increments of 10 kN and the readings of the lateral movement of the facing were taken with respect to the position of the plumb bob till the failure of nailed cut occurred. For the observed failure load, the factor of safety of the model nailed cut was calculated for the designed length, diameter and spacing of nails considering the side wall friction of the model tank into account (Gosavi, 2006). The details of this are given in Appendix 1.

Test Results

Surcharge intensity versus deflection of nailed wall plots for 2.0 m high nailed model tests 1 and 2 are presented in Figure 8. From these plots, it was observed that when the surcharge intensity increased, deflection of the nailed wall increased. At surcharge intensities 112.7 kN /m^2 (test No. 1) and 101.7 kN /m^2 (test No. 2), sand from the model tank started flowing outward from the sides of the nailed facing and further increase in the surcharge intensity was not possible. These surcharge intensities are designated as failure surcharge intensities. An exercise was done to determine the value of f* between nail and soil for the nail used in both of the large scale model tests at their respective positions with surcharge intensity as 86.3 kPa, 75.3 kPa, 92.9 kPa, 81.9 kPa, 99.5 kPa, 88.5 kPa, 106.1 kPa, 95.1 kPa, 112.7 kPa and 101.7 kPa respectively. For this, pull-out tests were performed on these actual nails in the same set up of nailed cut and found that the f^* obtained is same as 0.5 irrespective of the varying position and surcharge intensity on backfill.

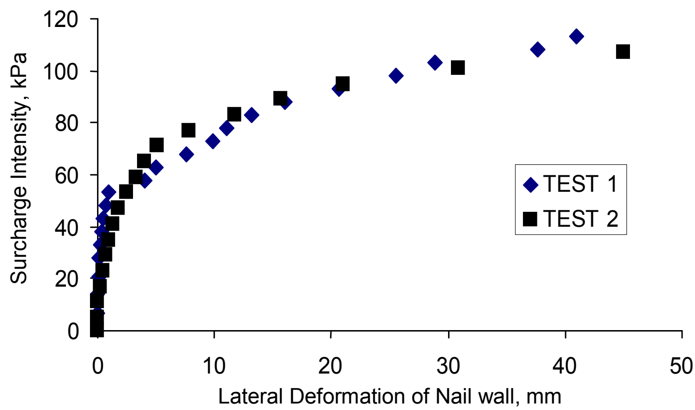


Fig. 8 Normal Stress versus Lateral Deformation at Height of 2.0 m of Nailed Wall

Using this value of f*=0.5 the factor of safety for nailed cuts for test No. 1 and test No. 2 with failure surcharge intensity 112.7 kN/m^2 and 101.7 kN/m^2 is worked out as 1.01 and 0.95 respectively. For these two tests, the differences in these FOS are 1% and 5% respectively with respect to FOS as 1. Therefore it can be concluded that the proposed analysis predicts the model tests results satisfactorily.

Conclusions

Nailed cuts have FOS equal to unity at the verge of failure. Tests on nailed cuts of 1.0 m and 2.0 m height enabled the determination of surcharge intensities which bring the cuts at the verge of failure. The proposed analysis for these surcharge intensities predicts the FOS with a maximum difference of 12%. Further the test data confirmed that rupture surface is approximately a log spiral. Hence the test data validate the proposed analysis.

Acknowledgements

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List of Notations

c	=	cohesion acting along the surface of sliding wedge bd
d	=	Diameter of the driven nail ,
ε	=	Inclination of nail with horizontal plane,
α	=	Inclination of nailed cut with vertical,
f*	=	Apparent coefficient of friction between nail and soil.
i	=	Number of nail, It varies from i = 1 to i = N,
N	=	Total number of nails in a single column of nails,
q	=	Applied surcharge intensity on the ground surface,
Tc_i	=	Mobilised shear in the i^{th} nail which acts normal to the axis of nail at its intersection with slip surface, Jewell & Pedley (1990),
T_p	=	Fully plastic axial force = $f_y \times A_s$,
ω	=	Log spiral angle.

Appendix A
Determination of Side Wall Friction Force and its Moment

General

Model tests were carried out on nailed cuts in a steel tank of dimensions 1.55 m x 0.88 m x 1.1 m (L x B x H) and a RCC tank of dimensions 2.5 m x 1.0 m x 2.5 m. In steel tank, length of nailed facing was kept as 0.87 m and in concrete tank it was kept as 1.0 m and backfill height in steel and concrete tanks was kept as 1.0 m and 2.0 m respectively as shown in Figures 3 and 7. Uniform surcharge was applied on nailed backfill and the nailed cut was brought to failure. At the surcharge loads, factor of safety of the nailed cut for each configuration of nails (Figures. 2(a), 2(b), 6(a) and 6(b)) was calculated using computer program developed for the design of nailed cuts during this research work. It was noticed that in all the tests, the factor of safety calculated at failure loads was found to be greater than 1. Tests with same configuration of nails were repeated 6 times and all the repetitions gave almost same value of failure load and factor of safety for corresponding failure load. Analysis was thoroughly checked for each nail configuration. It was decided to evaluate the force of friction, which was developed on the two sides of test tank during the test.

The tendency of this force and its moment would be to increase the magnitude of the actual resisting moments acting on the nailed cut. This might be playing an important role in getting higher factor of safety values at failure loads. During large model tests, it was also observed that in the initial increment in surcharge loading, there was a negligible lateral movement of facing of nailed cut. This also prompted the investigator to estimate theoretically the magnitude of this force and its moment about the plane passing though the bottom of wall.

Derivation of Expressions

The expression was derived for the condition of loading as shown in Figure A–1 in which ab represents wall height H, bd represents log-spiral failure surface and q represents intensity of uniformly distributed surcharge load. In case of small model tests, δ_1 and δ_2 were the angles of wall friction for sand and steel and sand and perspex sheet respectively. In case of large model tests both the tank sides were of concrete. For this tank, δ is taken as the angle of wall friction for sand and concrete.

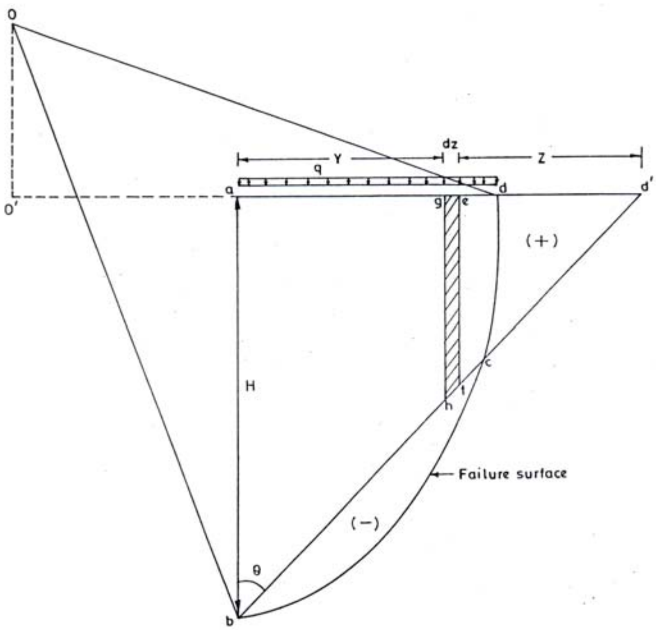

Fig. A-1 Log-spiral Failure Wedge for the Calculation of Side Wall Friction

In case of small model tests δ_1 was considered as 2/3 ϕ and δ_2 as 1/3ϕ, where ϕ is angle of internal friction of sand. For large scale model tests δ was taken as 2/3ϕ.

The derivation was based on the concept that there exists 'at rest' condition in the sand mass which was bounded by the log-spiral portion abd. For simplifying the calculations for side wall friction, a triangular wedge abd′ having same area as that of log-spiral failure wedge abd was considered as a failure wedge. Now, it was the triangular failure wedge within which soil mass was supposed to move. The resisting forces, which would develop within the triangular area (abd′) on each side of tank were considered effective. The critical failure wedge angle θ was calculated by equating the area of critical log-spiral failure wedge abd (failure wedge providing minimum factor of safety) to the area of Δ abd′.

Thus, A (∆abd′) = A (log spiral wedge abd)

Or, $\frac{1}{2} H^2 \tan\theta$ = A (log spiral wedge abd)

$$\theta = \tan^{-1}\left[\frac{2A(\text{log spiral wedge abd})}{H^2}\right] \quad \text{(A-1)}$$

Expression for Total Side Wall Frictional Force

The following procedure was adopted for the calculation of side wall friction force developed in small model test tank.

Consider an elemental strip bounded by ef and gh of thickness ‘dz’ at a distance z from d′.

The lateral force due to backfill alone acting on this elemental strip of steel side wall, acting perpendicular to it is given as,

$$\sigma_h = K_0.\gamma.z.\frac{\cot\theta}{2}.dz.z\cot\theta \quad \text{(A-2)}$$

Frictional force, acting along mild steel plate side of the tank, due to lateral force (σ_h) is expressed as,

$$P_{F\gamma}^{S} = K_0.\gamma.z.\frac{\cot\theta}{2}.dz.z\cot\theta.\tan\delta_1 \quad \text{(A-3)}$$

Similarly, frictional force $P_{F\gamma}^{P}$, acting on the perspex sheet side of tank is calculated as,

$$P_{F\gamma}^{P} = K_0.\gamma.z.\frac{\cot\theta}{2}.dz.z\cot\theta.\tan\delta_2 \quad \text{(A-4)}$$

Integrating Equations (A-3) and (A-4) over the range ‘zero’ to ‘H tan θ’ and on adding them, the total frictional force due to backfill $P_{F\gamma}$, acting on the two sides of tank was obtained as,

$$P_{F\gamma} = \int_0^{H\tan\theta} K_0.\gamma.z^2.\frac{\cot^2\theta}{2}\tan\delta_1 dz + \int_0^{H\tan\theta} K_0.\gamma.z^2.\frac{\cot^2\theta}{2}\tan\delta_2 dz \quad \text{(A-5)}$$

$$= \frac{K_0.\gamma.H^3.\tan\theta}{6}\left[\tan\delta_1 + \tan\delta_2\right] \quad \text{(A-6)}$$

Frictional force acting on the two sides of tank due to uniform surcharge loading (q) is given as,

$$P_{Fq} = K_0.q.z\cot\theta.\tan\delta_1 dz + q.K_0.z\cot\theta.\tan\delta_2 dz \quad \text{(A-7)}$$

Integrating the Eq. (A-7) over the range 'zero' to 'H tanθ' we get,

$$P_{Fq} = \left(\frac{1}{2}\right) K_0.q.H^2 \tan\theta.(\tan\delta_1 + \tan\delta_2) \quad \text{(A-8)}$$

Therefore, $P_{F\gamma}$ (Eq. A-6) and P_{Fq} (Eq. A-8) provide the total frictional forces developed on the two sides of small model test tank due to backfill and surcharge load respectively.

The resisting moments $M_{F\gamma}$ and M_{Fq} about point 'a' due to force $P_{F\gamma}$ and P_{Fq} are worked out as,

$$M_{F\gamma} = \int_0^{H\tan\theta} P_{F\gamma}^S (H\tan\theta - z)dz \quad \text{(A-9)}$$

or,

$$M_{F\gamma} = \frac{K_0.\gamma.H^4.\tan^2\theta}{24}\left[\tan\delta_1 + \tan\delta_2\right] \quad \text{(A-10)}$$

$$M_{Fq} = \int_0^{H\tan\theta} P_{Fq}^S (H\tan\theta - z)dz \quad \text{(A-11)}$$

or,

$$M_{Fq} = \frac{K_0.q.H^3\tan^2\theta}{6}\left[\tan\delta_1 + \tan\delta_2\right] \quad \text{(A-12)}$$

In case of log-spiral failure wedge, resisting moments were worked out about the centre of the log-spiral 'o'. Therefore resisting moments $M'_{F\gamma}$ and M'_{Fq} due to force $P_{F\gamma}$ and P_{Fq} about point 'o' are worked out as,

$M'_{F\gamma} = M_{F\gamma}\,(o'a + x)$

where, $x = \dfrac{M_{F\gamma}}{P_{F\gamma}}$

or,

$$X = \frac{H.\tan\theta}{4} \quad \text{(A-13)}$$

Therefore,

$$M'_{F\gamma} = \frac{K_0.\gamma.H^4.\tan^2\theta}{24}\left[\tan\delta_1 + \tan\delta_2\right] \times \left[o'a + \frac{H\tan\theta}{4}\right] \quad \text{(A-14)}$$

and $M'_{Fq} = M_{Fq} \times (o'a + x')$

where, $x' = \frac{M_{Fq}}{P_{Fq}}$

or,

$$x' = \frac{H.\tan\theta}{2} \tag{A-15}$$

Therefore,

$$M'_{Fq} = \frac{K_0.q.H^3 \tan^2\theta}{6}\left[\tan\delta_1 + \tan\delta_2\right] \times \left[o'a + \frac{H\tan\theta}{2}\right] \tag{A-16}$$

Similar procedure was adopted for calculation of frictional forces acting of the side walls of the large scale model test tank. In case of large scale model test tank, all the tank sides were made of concrete and δ was considered as angle of wall friction for sand and concrete. Therefore for large scale model test tank, Eq. A-15 and Eq. A-16 are modified as,

$$M'_{F\gamma} = \frac{K_0.\gamma.H^4.\tan^2\theta}{12}.\tan\delta \times \left[o'a + \frac{H\tan\theta}{4}\right] \tag{A-17}$$

$$M'_{Fq} = \frac{K_0.q.H^3 \tan^2\theta}{3}.\tan\delta \times \left[o'a + \frac{H\tan\theta}{2}\right] \tag{A-18}$$

With the help of Equations A-15, A-16, A-17 and A-18 the resisting moments were evaluated for the side wall frictional force for each configuration of nails given in Figures 2(a), 2(b), 6(a) and 6(b) for small and large model tests separately.

This resisting moment due to side wall friction was then added with the equation of resisting moment in the equation of factor of safety of nailed cut, and factor of safety was calculated for each configuration of nail. It was observed that the FOS calculated considering failure surcharge intensities of nailed cuts in small and large model test tank, considering the side wall friction force was approximately equal to unity.

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