Case Studies on Soil Nailed Retaining Systems for Deep Excavations

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ABSTRACT
The urban infrastructure requirement has resulted in deep excavations for construction of multiple basements. The advent of reinforced soil structures and related construction technology in recent past has facilitated handling deep excavation problems with ease. If the basement excavations are taken close to the property boundary the above techniques are to be modified. The soil nailing together with touch piles or micro piles are extensively used for solving such and related problems. By judiciously planning and designing the nailing system the earth pressure on the permanent retaining wall can be reduced. A few case studies of protection systems are discussed in this paper.

1. INTRODUCTION
Vidal (1969) proposed a very innovative technology of soil reinforcement with which high embankments and deep excavations could be handled with much ease. The technique is very simple and cost effective. In embankment construction the process is incremental with bottom-up principle with pre-cast or in-situ cast RCC facing elements as in RE Panel wall construction. In deep excavation it is incremental top down principle with nails positioned in to the virgin excavated face and MS weld mesh fastened to the nails and the surface either shot-creted or RCC cast in-situ with only front shuttering. In soil nailing two options are possible with driven nails (re-bars) for less resistant soils with moderate depths and grouted nails with re-bars introduced into the predrilled holes and grouted with cement slurry and whaler beams connecting the nails, for hard and high resistant ground conditions and greater depths. In both the cases the dewatering need to be addressed completely. The design methods involving both internal and external stability analyses are well established (Bruce & Jewell 1986, 1987, Elias & Juran 1991, Thompson & Miller 1990). Failure cases are essentially due to non-adherence of sequence of construction and poor assessment of ground conditions.

2. THEORETICAL BACKGROUND
Soil nailed structures rely on the transfer of tensile forces generated in the nails in an active zone to a resistant zone through friction or adhesion mobilized at the soil-nail interface. For a top down incremental excavation and stabilization case in granular soils with horizontal back surface, the failure surface could be a logarithmic spiral which starts from the final grade line at an inclination of $(45 + \phi/2)$ with the horizontal and emerges perpendicular to the back surface at a distance of 0.3H. It can also be described as shear stresses in the soil mass generated due to excavation or loading are countered by the interfacial shear stresses mobilized between the nail and soil mass. The reinforcement and its interaction with soil mass will translate the soil mass into a coherent mass with net shear stress at every point being less than the shear strength of the soil. Behavior of soil-nailed wall can be divided into internal behavior and external behavior. The internal behavior, more often referred to as the internal stability, relates the internal mechanisms of behavior like in-situ properties of soil and their variation, stresses within the structure and characteristics of the nails and facing. The facing element will be generally non structural or nominal in driven nails where the reinforcement density will be generally higher. In the case of grouted nails where the nails spacing will be very large, the whaler beam together with either the shot-creted surface or the cast in situ concrete facing will be the structural member to transfer the earth pressure to the grouted nails. The whaler beam together with the concrete facing can be modeled as a beam on elastic foundation with the ground stiffness known. Further
depending on the temporary nature or otherwise of the protection system the factor of safety and also the type of materials to be adopted would vary.

3. DESIGN METHODOLOGY

As common to retaining structures the external stability can be checked for the conditions of Overtopping, Sliding and Bearing Capacity failures in addition to the failure slip surface beyond the reinforced soil mass. However from the experience of several failed and un-failed structures it has been well established that the first two conditions can be satisfied with by providing the reinforcement (nails) length of 0.7 to 0.8H (Bruce and Jewell, 1987). Though the third condition of bearing capacity failure is generally specific to rigid structures it is being followed discretely for RE walls and nailed walls also. In the nailed walls constructed by driving nails into the natural ground with residual soil and the ground water table is well below the excavation depths this need not be strictly followed. The overall stability determination of deep excavation protection system in heavily built up locality by passing slip circle beyond the reinforcement zone and considering all the superimposed loads there on is also in practice. This seems to be critical in urban areas of sedimentary deposits where N value may be fluctuating extremely with depth.

The internal stability requirements define the spacing and diameter of the nails. Generally the two criteria to be satisfied are:

1. Friction or bond failure between the soil and the reinforcement in the case of driven nails and both bond failure between grout and reinforcement and grout and soil in the case of grouted nails. The bond between the grout and the reinforcement is not normally critical. The governing equations for satisfying the failure criterion between nail and soil or grout and soil as the case may be are:

   Bond ratio = (dL/S) = 0.5 to 0.6 for grouted nails in granular soils and 0.6 to 1.1 for driven nails in granular soils. In this equation, d is the diameter of the bar in driven nails and is the diameter of the grouted nail hole in grouted nails, L is the length of nail and S is the influence area of each nail (S_x S_y) with S_x and S_y being the horizontal and vertical spacing of the nails.

   Also the mechanistic equation of the bond criteria for each bar can be written based on a defined potential failure surface which divides the soil mass into active and passive zone. The bond criterion is given by the following Eq. (1):

   \[ k_\gamma h S_x S_y (FS) = 2dhL \tan (\phi') \]  

   Where \( k_\gamma \) is the active earth pressure coefficient, \( \gamma \) is the unit weight of the soil, \( h \) is the height of the free surface from nail level, \( S_x S_y \) is the influence area of the nail, FS is the factor of safety which normally is about 1.25 to 1.5, \( L_e \) is the effective length of the nail in the passive zone, \( \phi' \) is the angle interfacial friction between soil and the nail.

   The Eq. (1) can be written in a general way to cover all the nails or a group of nails in a stratum. It is interesting to note that ‘\( \gamma h \)’ term exists on both sides indicating that the length of reinforcement would be constant with depth. Also it implies that the acting force itself mobilizes the resisting force. This will have special advantage while designing for seismic conditions.

2. The criterion for tensile failure of the reinforcement due to the pull out force has been described as strength ratio and is in the form:

   \[ (d^2/S) = 0.0004 \text{ to } 0.0008 \]  

   for drilled and grouted nails in granular soils, 0.0013 to 0.0019 for driven nails in granular soils, where, d is the diameter of the bar and S is the influence area of the nail.

   The mechanistic equation for the above criterion can be written as (Eq. 2):

   \[ k_\gamma H_{max} S_x S_y (FS) = \sigma_y A_x \]  

   Where, \( H_{max} \) is the maximum height of the excavation at a section for which the design is being made, \( \sigma_y \) is the permissible yield stress of the reinforcement material and \( A_x \) is the area of cross section of the reinforcement bar.

   Quite often the critical condition of driven nails will be only bond failure since from drivability condition, higher diameter bars, say minimum 20mm will be used. The corrosion allowance needs to be provided for only the case of critical tensile failure criterion. For bond failure being critical the non uniform corrosion will increase the interfacial frictional resistance and hence it will increase the factor of safety.

   A few case studies covering both the driven nail walls and grouted nail walls will be presented in the following paragraphs.

4. CASE1: 9M DEEP EXCAVATION IN MARINE SOIL VERY CLOSE TO THE EXISTING BUILDING

The soil investigation report (Fig. 1) indicated alternating layers of sandy silt and soft marine clay. The N value for sandy silt layers was in the range of 18 to 22 while the same for soft clay was ranging from 1 to 4. The water table
was reported to be at about 3 to 4M below the ground level. The existing foundation of the adjoining building was at about 2M below the ground level and within 3M from excavation line. It was required to excavate a depth of 9M below the existing ground level.

**Design**

The following design scheme was proposed and successfully implemented. The cost of this scheme against the originally proposed sheet piling scheme was less than 50%. The angle of internal friction value was not available. Based on N value and weighted average of the same with depth, $\phi = 25^\circ$ was estimated using available correlations. This value $\phi$ was used for estimating the active earth pressure coefficient which is equal to 0.40. The interfacial frictional coefficient, $f_s$ was estimated directly from N values of the sandy silt layer which is equal to 2N in kN/M$^2$. The water table was assumed to always be below the excavation line by at least 2M. The basic design inputs are:

$H = 9M, L = 0.7$ to $0.8H = 7M, L_e = (L - 0.3H) = (7 - 2.7) = 4.3M, \gamma = 17kN/M^3$.

The governing equations are:

$K_a \gamma h S_x S_y (FS) = f_s n d L_e$ and Bond ratio, $(dL/S) = 0.6$ to 1.1

For the bottom most layer $H = 9M, f_s = 40kN/M^2, \gamma = 17kN/M^3, L_e = 4.3M$ and FS of 1.25, from the above governing equation $S_x S_y = 0.141M^2$ and $S_x = S_y = 375mm$ c/c. For this case the bond ratio is 1.07 and hence OK.

The maximum tension in the bottom most layer is 8.6 kN and even 10 TOR bar has more tensile capacity than this value. From drivability consideration 20TOR bars have been used. The $(d/S)$ is equal to 0.0028 which more than satisfies the tensile failure criterion and hence is OK.

For the clay layer portion the nails 20TOR and of length 7.5M were introduced at an inclination of about $20^\circ$ upward for first 3 layers and downwards for the next 3 layers such that the effective length of 4.3M will be within the top and bottom sandy silt layers. The recommended scheme and sequence of construction were as follows.

1. Excavate a depth of 2M vertically in the top sandy silt layer in two increments of 1M each and install short nails of 1M long and fasten 50x50x2.8mm MS weld mesh to the nails close to the surface and shotcrete the surface to a thickness of 50mm with 1:2:1 cement concrete grout using 8mm down aggregates (IS 9012).

2. Excavate further 2M vertically and commission the suitable dewatering system (either open well and drain system or the multiple well point and multi stage system) to maintain the water table at least 2M below the level of the proposed present stage of excavation.

3. Install 7M long 20 TOR nails horizontally in the sandy silt layer @ 375c/c (5rows) both ways and fasten the weld mesh of 50x50x2.8 and shotcrete as above to a thickness of 50mm. Below the water table level install 2M long 400mm dia. PVC porous drain tubes clad with non-woven geo-textile filter fabric @ 2M c/c in both the directions to act as weep holes.

4. In soft clay layer lower the water table by 2M and excavate a depth of 1M and install 7.5M long 20TOR bars @ 330c/c, inclined 20 degrees up ward with the horizontal (3rows) such that the effective length is embedded in the sandy silt layer above the clay layer and drive 4M long 16 tor horizontal bars @ 500 c/c (2 rows) and repeat the steps including installation of drain pipes and shot-creting.

5. Repeat the step 4 with down ward inclination of $20^\circ$ of the 20 TOR bars @ 330 c/c while lowering the water table further by 1M.

6. In the lower sandy silt layer, further lower the water table by 3M and excavate in 2 increments of 1.5M each and repeat the step 3 for both the increments. The following two photographs (Figs 2a, b) show the actual implementation at site.

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![Photographs of Implementation of Case Study 1](image-url)
5. CASE2: 14.5M DEEP EXCAVATION WITH GROUTED NAILS

The site measuring more than 1.5 Hectares is situated close to an earlier lake in the central business district of Bangalore. The proposed building had three basements requiring a nearly vertical excavation of 14.5M. The top horizontal ground surface need to have access to construction vehicles like RMC transit mixers and trucks. The soil investigation report indicated the presence of reddish lateritic sandy silt soil up to about 3M followed by disintegrated rock to highly weathered rock for the rest of the depth of excavation. The N value for the top layer was about 15 to 20 and for the rest of the depth varied from 30 to more than 50. The water table was at about 3M from the ground level. The surroundings had a few buildings within the close proximity of 20M. From the geotechnical and drivability considerations, protection system with driven nails was considered to be not feasible and hence protection system with grouted nails was the option.

Design

The design scheme was to install 135mm dia. passive grouted nails at suitable spacing with different dia. reinforcement bars varying with depth. Between the nails shot-creted surface with whaler beam is designed to transfer the earth pressure to the nails which in turn will dissipate through interfacial friction to the soil in passive zone. From design considerations the interfacial resistance between the grout and the soil could be taken as 2N in kPa. Assume the excavation face inclined at 80° with the horizontal. By installing the first grouted nail at 1M below the ground level and at an inclination of 35° with the horizontal the free length will be 7M. At this depth the N value is about 35. Assuming $f_s = 70kN/M^2$ the fixed length of the grouted nail was calculated as follows.

$$K_a = 0.35, \gamma = 18kN/M^3, S_y = S_z = 3M^2 (S_y = 1.5M and S_z = 2M) and h = 0 to 2M, the horizontal active earth force on the nail will be 63kN and normal force on the nail will be 77kN and with FS of 1.25 the design nail force will be 95kN. The anchor length beyond the failure plane of 45° will be 4M making the total length of grouted nail as 11.5M. The bond criterion (dL/S) = 0.515 and hence satisfied. Use 25 TOR nails with tension capacity of more than 95kN. The tension criterion (dL/S) = 0.006 and hence satisfied.

Similarly nails were designed for other depths of 3M, 5M, 7M, 9M, 11M and 13M. The appropriate values of N and the interfacial shearing resistance have been considered. The reinforcement bar diameter of the grouted nail has been varied with depth. Top 2 rows have 25TOR, 3rd and 4th rows have 32TOR and last three rows have 36TOR bars. The surface is fastened with MS weld mesh of 50x50x2.8mm and shot-creted in two layers to 75mm. The whaler beam used to connect all the nails in pairs is 2 of ISMC 100 back to back and welded to the nails.

Fig. 3: Details of the scheme

The above photos (Figs 4a, b, c and d) indicate the field condition before completion of the work. The recommended scheme and sequence of construction were as follows.

1. Excavate a depth of 2M nearly vertical. Drill 135mm dia. 11.5M long holes inclined at an angle of 35° with the horizontal at 1.5M c/c. Clean and flush the hole. Insert a spacer and the 25TOR re-bar and grouting tube.
2. Grout the hole with cement slurry by gravity and as the hole is filled with grout withdraw the grouting pipe. Allow it to set for few days.
3. Fasten to the excavated surface MS weld mesh of 50x50x2.8mm MS weld mesh using U hooks or short driven nails. Shot-crete the surface with 1:2:1 CC grout to a thickness of 75mm may be in two layers.
After completion of one row of nails and surface shot-creting, connect each pair of nails to the whaler beams of 2x100ISMC and grout the space between the whaler and the shot-creted surface.

Excavate further 2M at an inclination of 80° with the horizontal and repeat the steps 1 to 4 and repeat this step itself to reach the desired level of excavation.

When the water table is met the dewatering system should be activated to lower the water table to a level 2M below the excavation level of the present stage. Insert 2M long 50mm dia. porous pipe clad with 250gsm geo-textile filter fabric into a pre-drilled hole @ 2M c/c below the water table level to act as weep holes.

**CASE 3: 13M DEEP EXCAVATION FOR THREE BASEMENT CONSTRUCTION WITH TOUCH PILES AND GROUTED NAILS**

The Site in Bangalore had multi-storey buildings in all the three sides. The soil investigation report had indicated the reddish lateritic soil for a depth of 4 to 5M and below is the highly weathered soft rock and large boulders of original hard granitic gneisses. The weathering conditions were so varying that the reported N value varied from 20 to more than 100. There was no core recovery. The water table was at about 3M from the ground level (Fig. 5). Since the presence of weathered rock and large boulders of hard rock with high water table was present and presence of neighboring tall buildings very close to the excavation, it was neither possible to adopt driven nails as in Case 1 nor only the grouted nail scheme as in Case 2.

A modified scheme with RCC cast in-situ near touch piles of 300 dia. @ 450 c/c, installed using rotary drilling with grouted nails/anchors was designed. The piles had been designed to withstand 4M depth of excavation as free standing cantilever. As a large boulder intervened which needed blasting, additional grouted nails were introduced within that depth. The grouted nails were 135mm dia. and were 10M long and as specified in Case 2 above. The spacing was 1.35M c/c in horizontal direction and 2M c/c in vertical direction. Since piles have good stiffness the deformation for initial lifts of excavation will be negligible and this shifts the passive anchor zone close to the excavation line. The Passive anchor zone was assumed beyond 60° inclined line with horizontal behind the touch piles. The grouted anchor fixed lengths were decided iteratively based on the drilling output at site. The f values of 40kN/M² in soil, 150kN/M² in soft rock and 500kN/M² in hard rock were adopted. The whaler beams for connecting the nails in the same row were 2x100 ISMC.

The total dewatering system was adopted to keep the water below the excavation level.

**CASE 4: ADDITIONAL BASEMENT AFTER COMPLETION OF 2 BASEMENTS**

In the same site of Case 3, one half of the site had two basements with columns and retaining walls. It was required to excavate a depth of 4.5M for 3rd basement construction below the second basement already constructed. The rear side retaining wall along with the columns as shown in the Photo (Fig. 6) had to be retained to protect the multi-storey building in the adjacent property.
minimal displacement is permitted the interfacial friction between the soil and nail was assumed to be equal to N in kN/M². It was proposed to install 4 rows of grouted nails. The length required was estimated to be between 9 and 11M for different layers for a horizontal spacing of 1.5M c/c. 20 TOR bars were used for the first and second row and 25 TOR bars were used for the other rows. The following scheme was proposed and implemented successfully.

1. Cut the core of size 75mm at an inclination of 20° with the horizontal at four levels in the stem of the RCC retaining wall.
2. Install grouted nails of 65mm dia. with 20 and 25 TOR bars, as the case may be, through the core cut hole of the retaining wall, designed to hold the wall in position. Provide the whaler beam of 2x100 ISMC and weld the re-bars of the grouted nails to the beams.
3. Cut and remove the toe slab along the edge of the stem of the retaining wall.
4. Install 200mm dia. 6M (1.5M more than the final excavation depth) long MS casing pipes in the pre-drilled bore hole as micropiles at 500c/c along a line close to the stem of the retaining wall. Grout the annulus space and fill M20 concrete in the pipe.
5. Excavate in increments of 1.5M depth close to the face of the micro piles. Fasten MS weld mesh to the pipe face and shotcrete the surface.
6. Install 135mm dia 12M long grouted nails at 2M c/c in each row. Total three rows of grouted nails are required.
7. Fasten 2X100 ISMC whaler beams between the nails and micro piles.
8. Construct the permanent retaining wall as per structural design with out rear shuttering and providing water proofing on the shotcreted surface.

The project is successfully completed.

6. CONCLUSIONS
The driven nailed and grouted nailed protection schemes and anchored touch piles for deep excavation form viable and economical options in urban areas with restricted space all round. They provide a very safe, flexible and easy implementable options.

REFERENCES