

Slope Stabilization Using Soil Nails: Design Assumptions and Construction Realities

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ABSTRACT: Design and construction of slope remedial works pose high risk to both geotechnical designers and constructors, as the slope is susceptible to further failure during the implementation of the remedial works itself. Soil nailing is therefore, commonly adopted for slope remedial and stabilization works as it can be carried out on the slope surface with minimum earthworks and therefore lower the risk during construction. Soil nails, if properly designed, has proven to be an efficient and cost effective slope stabilization measure and various slopes stabilized using soil nails have been carried out in Malaysia. However, proper geotechnical design shall be carried out to prevent face failure, pullout failure, nail tendon failure and overall slope failure. In this paper, relevant design and construction issues concerning soil nailing will be presented with particular emphasis on the interrelationship between design and construction (implementation) to ensure safety of the slopes.

1 INTRODUCTION

Soil nailing essentially involves reinforcing and strengthening of existing grounds by installing closely-spaced steel bars, called 'nails', into a slope as construction proceeds from 'top-down'. This process creates a reinforced section that is in itself stable and able to retain the ground behind it. The reinforcements are passive and develop their reinforcing action through nail-ground interactions as the ground deforms during and following construction. In Malaysia, commonly referred codes of practice and design manuals for design of soil nailing are:

- a) British Standard BS8006: 1995, Code of Practice for Strengthened/Reinforced Soils and Other Fills.
- b) U.S. Department of Transportation, Federal Highway Administration (FHWA 1998), Manual for Design & Construction Monitoring of Soil Nail Walls.

A step by step approach to the design of soil nails as recommended by FHWA's manual has been discussed in Tan & Chow (2004). In this paper, a review of important design and construction issues will be presented especially on the importance of shotcrete face design for very high and steep slopes which is sometimes overlooked during design. The

responsibilities of the designer and constructor to ensure successful implementation of soil nailing works are also discussed. The division of responsibilities presented in this paper does not imply that each party is only responsible for certain aspects of the works. Both the designer and constructor are involved together during the works, e.g. QA/QC by designer during construction, etc. The division of responsibilities presented in this paper only highlights the responsibilities of each party for which they exert the greatest influence. The implication of top-down construction sequence and excavation of slope prior to installation of soil nails on the performance of the soil nails will also be discussed.

2 SOIL NAILING FAILURE MODES

The failure modes of soil nails can be categorized into the following:

- a) Pullout failure
- b) Nail tendon failure
- c) Face failure
- d) Overall failure (slope instability)

2.1 Pullout failure

Pullout failure as illustrated in Figure 1 results from insufficient embedded length into the resistant zone

to resist the destabilizing force. The pullout capacity of the soil nails is governed by the following factors:

- The location of the critical slip plane of the slope.
- The size (diameter) of the grouted hole for soil nail.
- The ground-grout bond stress (soil skin friction).

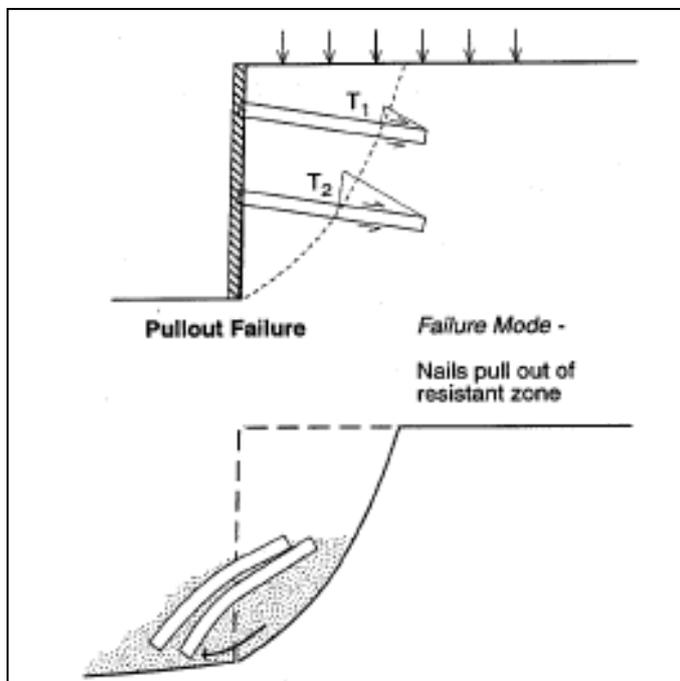


Figure 1. Pullout failure mode (from FHWA 1998).

The location of the critical slip plane for the slope could be readily assessed from manual calculations or various commercially available slope stability analysis software with capability to include internal reinforcements (e.g. geotextile, ground anchors and soil nails). Resisting force for the soil nails based on the available bond length from the critical slip plane shall then be input into the stability analysis in order to obtain appropriate factor of safety. Some software have the capabilities to automatically update the resisting force based on the computed critical slip plane. If not, iterative analysis need to be carried out to obtain the correct soil nail resisting force for slope stability analyses. The size (diameter) of the grouted hole for soil nail is usually in the range of 75mm to 150mm for commonly available drilling rigs. Therefore, for pullout failure, the responsibility between designers and constructors can generally be summarized as follow:

- Designer*: Determination of appropriate ground-grout bond stress and pull-out capacity based on critical slip plane. Some guidance on the determination of ground-grout bond stress is discussed in Tan & Chow (2004).
- Constructor*: To ensure diameter of grouted hole as specified by the designer is achieved at site and the hole is

properly grouted throughout the nail length. (Grouting using tremie method filling from bottom up and non-shrink grout shall be used).

2.2 Nail tendon failure

Nail tendon failure as illustrated in Figure 2 results from inadequate tensile strength of the nails to provide the resistant force to stabilize the slope. It is primarily governed by the grade of steel used and the diameter of the steel. Typically a minimum nail size of 25mm is used as nail sizes smaller than 25mm may cause installation problems for moderate to long nail lengths due to their low stiffness. Besides specifying the appropriate nail size corresponding to the required resistant force, it is important that proper detailings with regards to corrosion protection of the nails are specified and properly executed at site. Some of the important considerations include:

- Adequate cover for nails is provided by ensuring rigid spacers/centralizers at appropriate spacing. Figure 3 shows example of typical spacers used.
- Corrosion protection on the nails using galvanized steel bars or by encapsulation inside a corrugated plastic sheath.

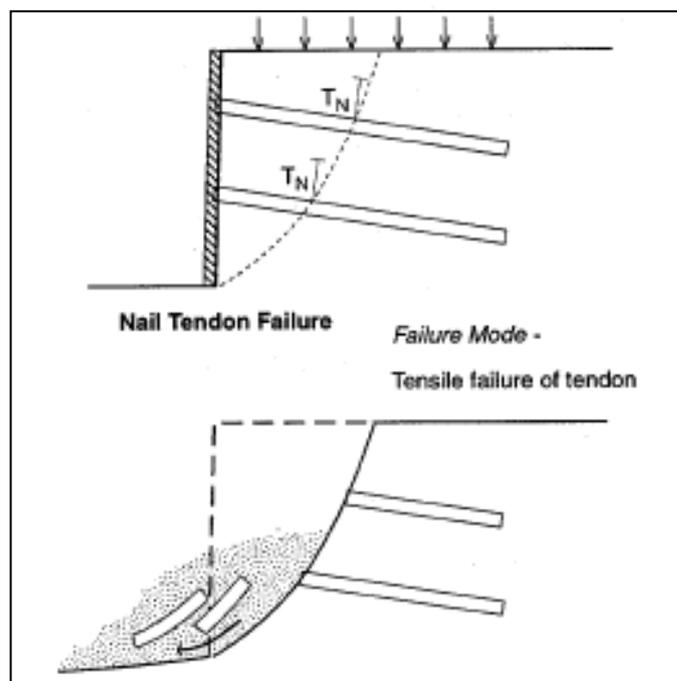


Figure 2. Nail tendon failure mode (from FHWA 1998).

Therefore, for nail tendon failure, the responsibility between designers and constructors are:

- Designer*: Determination of required nail diameter, spacing of spacers/centralizers and corrosion protection requirements.
- Constructor*: To ensure spacers/centralizers are rigidly secured to the nail and corrosion

protection carried out as per requirements.

Some of the common problems encountered at site include damage to the nails during transportation where the galvanized layers are being scraped off and also inadequate spacing between the nail and corrugated plastic sheath to form an effective grout protection layer. Figure 4 shows an example of such incidence where the very thin layer of grout crack and peeled off upon insertion of the nails into the drilled hole. Generally, it is not recommended to use pre-grouted corrugated plastic sheath for soil nails in Malaysia due to lack of good quality workmanship and control at site. For soil nails that need to use corrugated plastic sheath, then larger diameter hole with the diameter of the corrugated plastic sheath at least three times the diameter of the steel bar or minimum of 75mm, whichever is larger should be used. In addition, a minimum grout cover between the sheath and the borehole wall should not be less than 12mm (FHWA 1998) but commonly 25mm is recommended for practical purposes. Special care shall also be exercised during insertion of the pre-grouted corrugated soil nails to prevent bending and accidental knocking that could cause cracks to the grout and thus, loss of bonding between the grout and the steel bar (potential pullout failure).

Finally, the designer and constructor also have to ensure that the spacers/centralizers are rigidly fixed to the nails and do not deform during insertion and grouting (Figure 3).



Figure 4. Grout cracked and peeled off from nail – ineffective corrosion protection.

However, this assumption shall not be applied for all slopes and face failure is an important failure criterion that should not be overlooked. This is highlighted in the following clauses of BS8006 and FHWA's manual:

- a) BS8006: 1995, Clause 6.7.3:
“Facings should be designed to accommodate the loads resulting from horizontal soil pressures and the corresponding reinforcement tension reactions developed in the connections between the facing and the reinforcement.”
- b) FHWA's Manual for Design and Construction Monitoring of Soil Nail Walls (pg. 95):
“The facing structural design requires provision of adequate concrete thickness, reinforcement and moment capacity to resist the earth pressures applied to the facing span between adjacent nail heads, and provision of adequately sized bearing plates to provide adequate punching shear capacity.”

For example, for a slope of 10m high with global slope gradient of 45° (1V:1H) with soil properties of $\phi' = 33^\circ$ ($c' = 0$) and nail spacing of 1.5m (vertical and horizontal). The active force acting at the bottom of the soil nailed slope is only about 6kN taking into consideration that 50% of the force is transferred to the nails due to arching effect and flexible shotcrete facing as per FHWA (1998).

However, for a slope of 40m high with global slope gradient of 76° (4V:1H) with similar soil properties and nail spacing, the active force acting at the bottom of the soil nailed slope is about 140kN which is more than 20 times larger than the earlier example. Such large active force acting on the shotcrete face should not be overlooked during design and the shotcrete thickness and reinforcement should be properly designed.



Figure 3. Typical spacers/centralizers for soil nails.

2.3 Face failure

This aspect of failure mode (Figure 5) for soil nailing is sometimes overlooked as it is generally wrongly “assumed” that the face does not resist any earth pressure. For soil nailing works which involve slopes of relatively low height and gentle gradient, the earth pressure acting on the shotcrete face is relatively small and nominal shotcrete thickness and reinforcement is adequate.

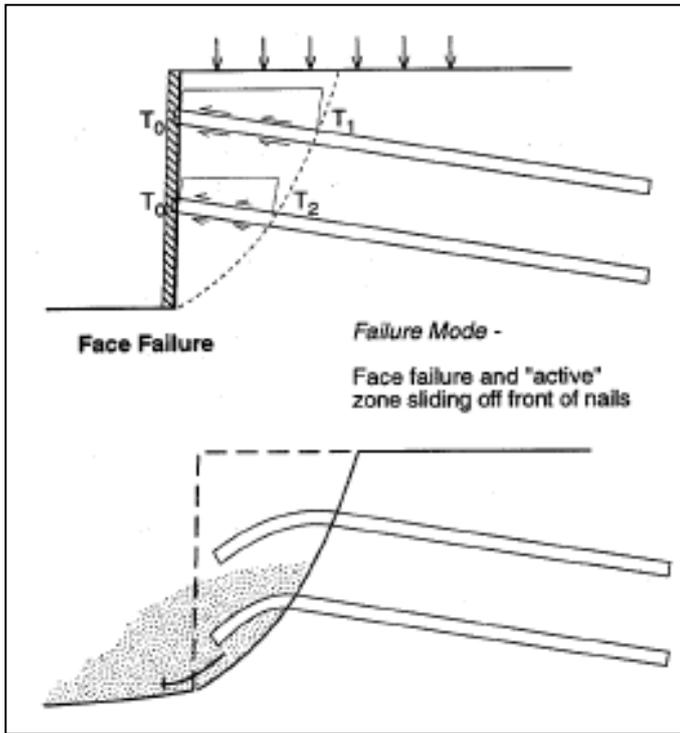


Figure 5. Face failure mode (from FHWA 1998).

Figures 6 and 7 show examples of failure due to face failure where nails ‘protruding’ out from the slope after failure can be observed.

It is interesting to note that FHWA (1998) recommendation of 50% of the active force transferred to the nails is based on results of field monitoring on typical nail spacing ranging from 0.75m to 1.8m. Therefore, for very high and steep slopes, large spacing of soil nails should be avoided unless reliable analyses on the stresses acting on the shotcrete surface is carried out and designed for it.

Similar to other modes of failure, the designer and constructor each have important roles to play to prevent face failure:

- a) *Designer*: Adequate shotcrete thickness and reinforcement provided with proper detailings. Figure 8 illustrates example of improper detailing which will trigger potential face failure.
- b) *Constructor*: To ensure shotcrete thickness and reinforcement as per requirements. A proper shooting technique by experience nozzleman and correct shotcrete mix are important to ensure shotcrete of good quality. Figures 9 and 10 show example of correct shooting positions and nozzling techniques for shotcrete face.



Figure 6. Example of face failure.



Figure 7. Example of face failure.

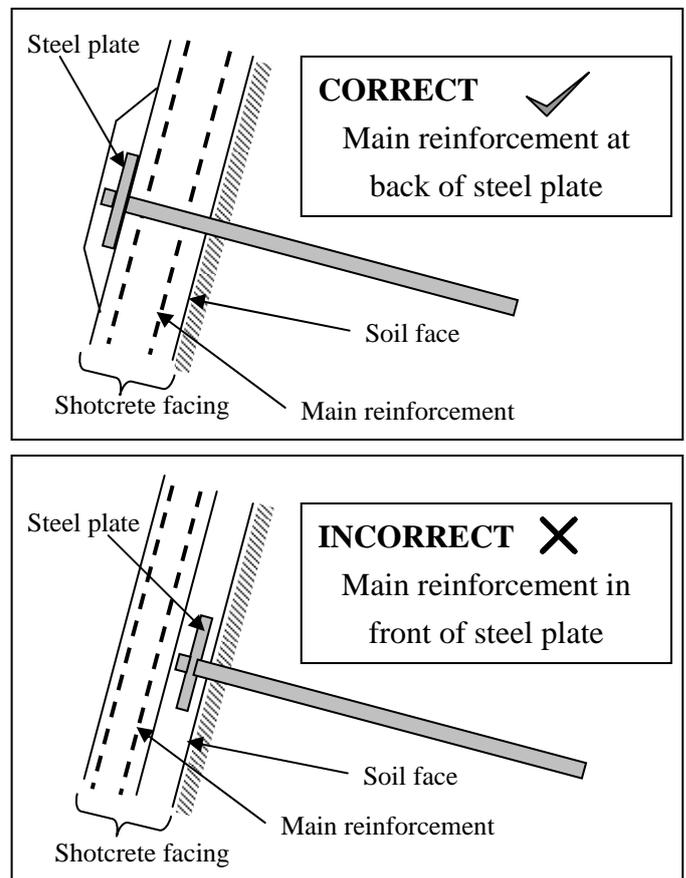


Figure 8. Example of proper and improper detailings.

2.3 Overall failure (slope stability)

This aspect of failure mode is commonly analyzed based on limit equilibrium methods. The analyses are carried out iteratively until the nail resistant force corresponds to the critical slip plane from the limit equilibrium analysis. To carry out such iterative analysis, it is important that the nail load diagram (Figure 11) is established. From Figure 11, it can be seen that the nail load diagram consists of three zones, A, B and C. Zone A is governed by the strength of the facing, T_F and also the ground-grout bond stress, Q . If the facing of soil nails is designed to take full tensile capacity of the nail, then the full tensile capacity of the nail can be mobilized even if the critical slip circle passes through Zone A. However, to design the facing with full tensile capacity of nails instead of lower T_F is not economical for high slope (e.g. more than 15m). Zone B is governed by the nail tendon tensile strength and Zone C is governed by the ground-grout bond stress, Q .

From the diagram, it is clear that the mobilized nail resistance should not exceed the nail load envelope developed from the three failure criteria discussed earlier. Therefore, the nail resistance to be input into slope stability analysis should refer to the nail load diagram (Figure 11) corresponding to the available bond length for the critical slip plane (Figure 12).

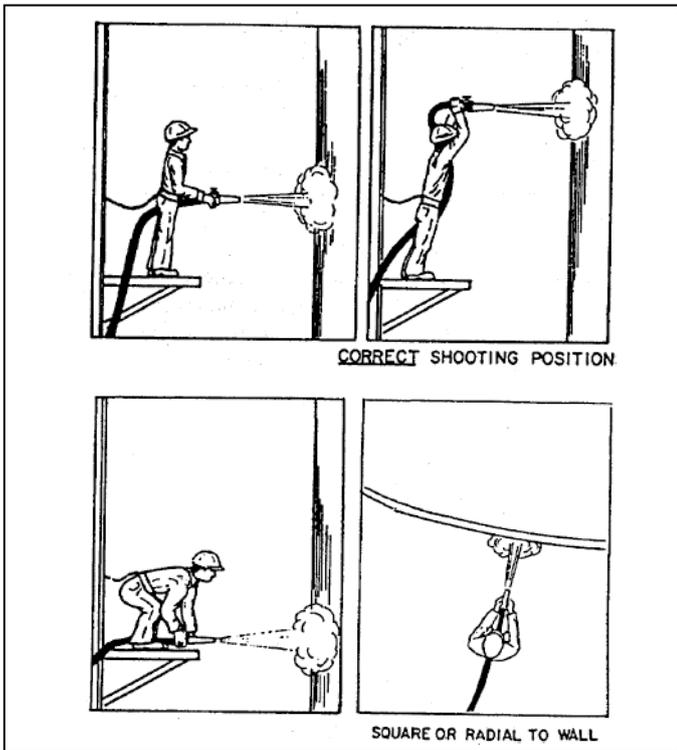


Figure 9. Correct shooting positions (from FHWA 1998).

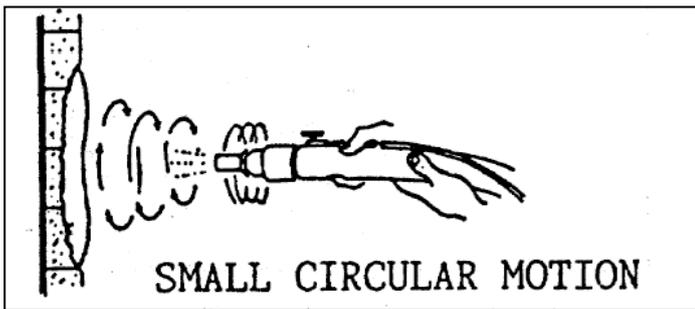


Figure 10. Nozzling techniques (from FHWA 1998).

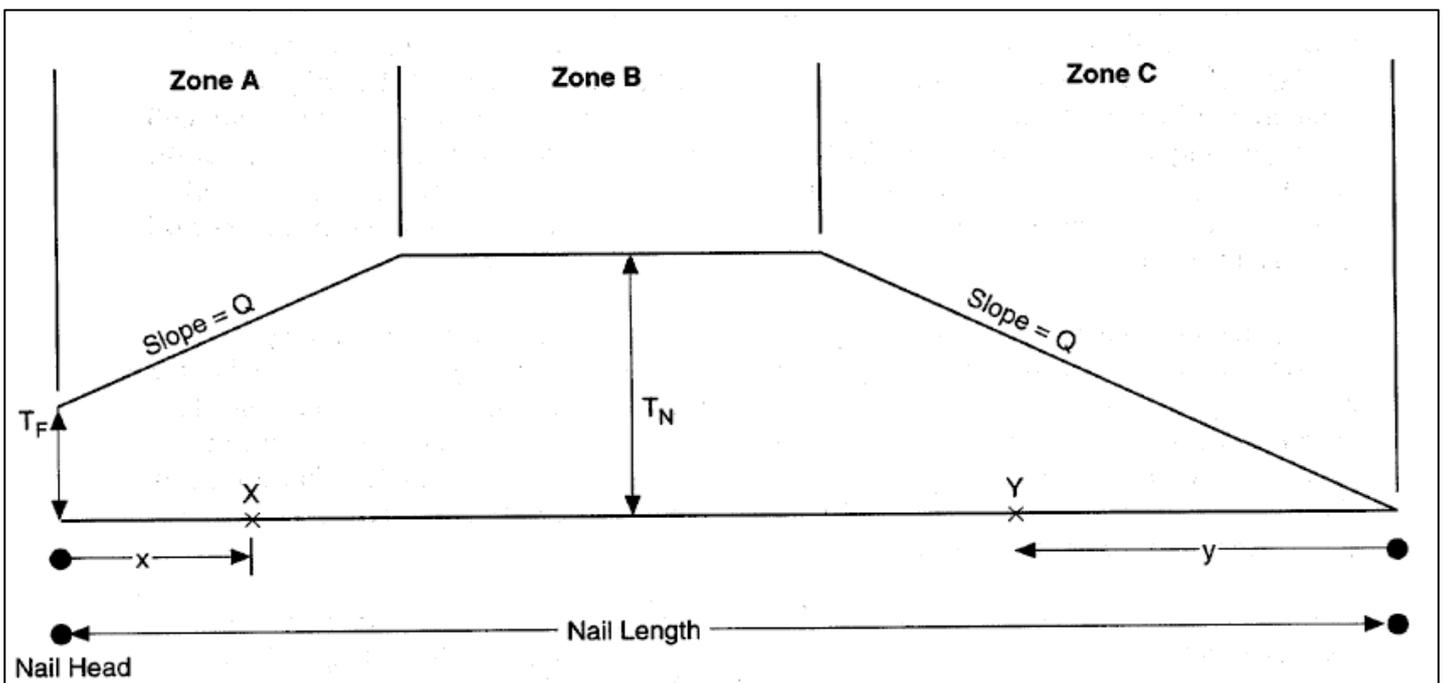


Figure 11. Nail load diagram (from FHWA 1998).

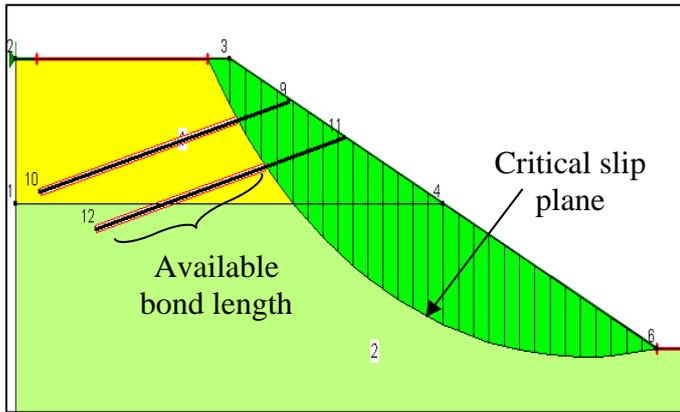


Figure 12. Available bond length from slope stability analysis.

Some slope stability analysis software have the capabilities to automatically adjust the nail resistance based on the ground-grout bond stress and nail tendon tensile strength. However, extra caution needs to be exercised as some of the software does not cater for the reduction of nail load at Zone A and assumes strength of T_N . As illustrated in Figure 13, failure to cater for the reduction of soil nail resistance in Zone A may lead to overestimation of the available nail resistance in slope stability analysis for critical slip circle that passes through this zone.

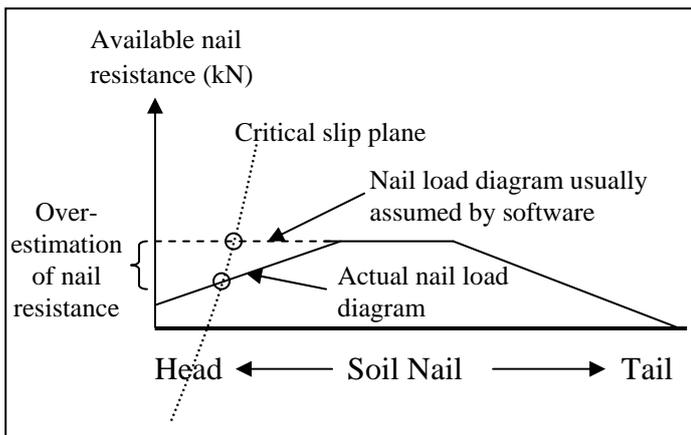


Figure 13. Overestimation of nail resistance if shotcrete facing strength not taken into consideration.

3 CONSTRUCTION SEQUENCE

Soil nailing works is usually carried out 'top-down' as shown in Figure 14. For soil nailing works, construction sequence and associated temporary works are also important to ensure the stability of the slope. Ensuring every stage of works is safe and stable is very important in soil nailing works. For this purpose, it must be highlighted that soil nailing works which involve cutting of slopes should be carried out in stages where the next stage of works (cutting to final level) can only be carried out when the preceding level of soil nail has been installed and shotcreted. Case histories of failure due to indiscriminate cutting of slopes and delayed installation of soil nails are not uncommon.

Therefore, the stability of the slopes prior to installation of soil nails shall be assessed to determine the allowable height of slope that can be cut at every stage of the works. A site trial can also be carried out to assess the standup time of a cut slope. Typically, each stage of works should not exceed more than 3.0m or two levels of soil nail at one time. Therefore, the designer should clearly indicate this constraint in the relevant documentations and the constructor should follow strictly the designer's instructions. It is recommended that the stages of works for soil nailing to be included in construction drawings and relevant work specifications. A typical example of drawing illustrating this aspect is shown in Figure 15.

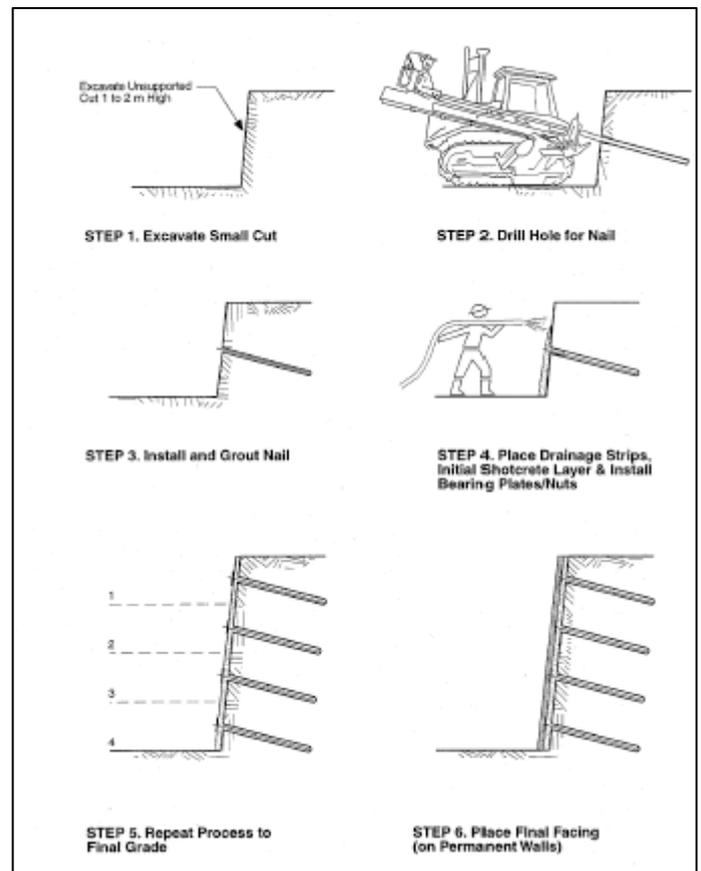


Figure 14. Typical soil nailing construction sequence (from FHWA 1998).

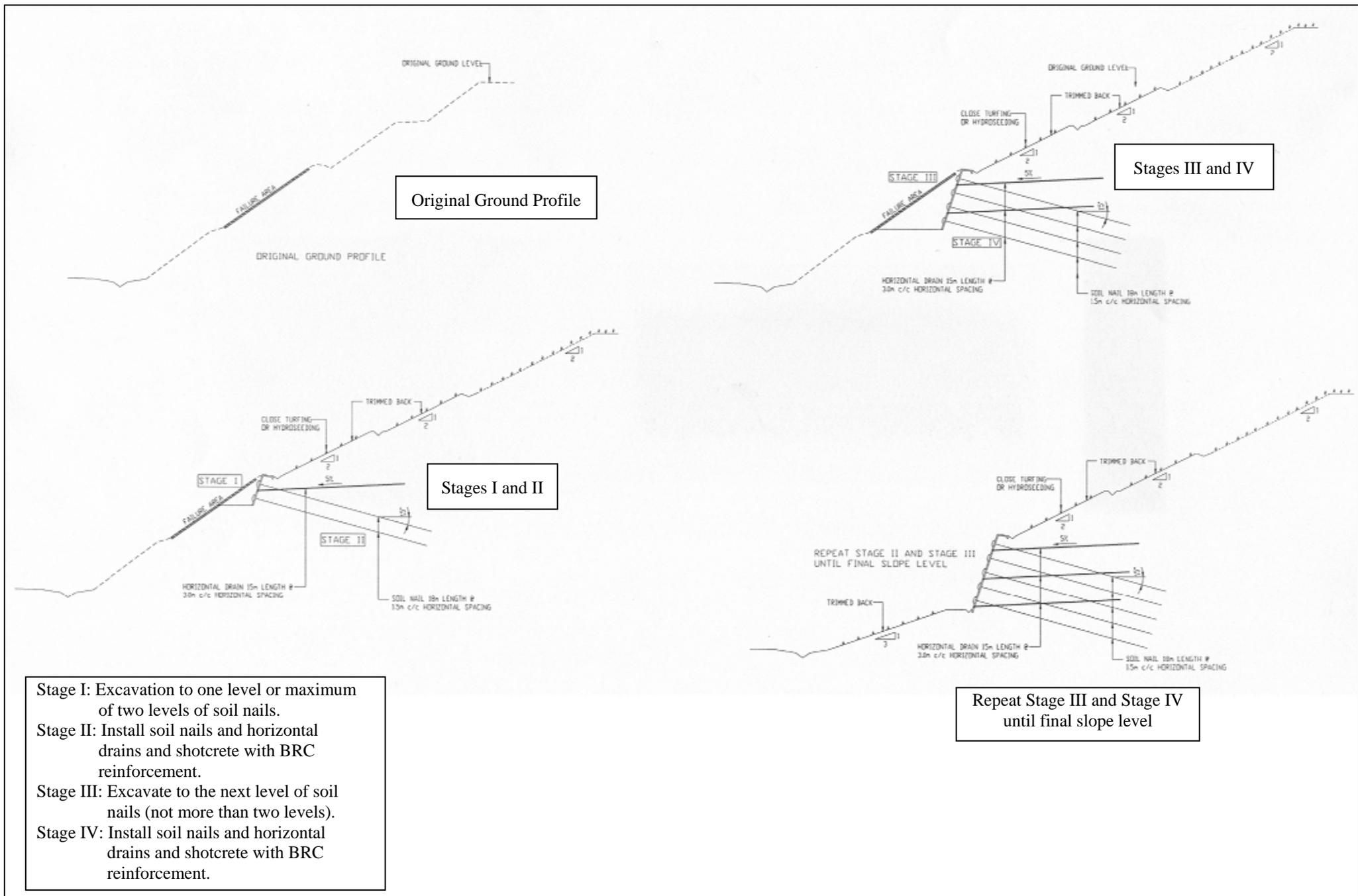


Figure 15. Typical drawing showing construction sequence.

4 CONCLUSION

Soil nailing is an effective slope stabilization method especially for remedial works involving failed slopes. However, a properly designed and constructed soil nailing works are essential for optimum performance. The following failure criteria should be clearly understood and proper design provisions made to ensure optimum performance of the soil nailing works:

- a) Pullout failure
- b) Nail tendon failure
- c) Face failure
- d) Overall failure (slope instability)

An understanding on the roles played by the designer and constructor is also important to ensure design intentions are communicated to the site and similarly, site constraints are made known to the designer. Construction sequence on soil nailing works also influences the degree of success of the works especially for slope remedial works. It is therefore recommended that the designer clearly indicate the required stages of works in relevant drawings and work specifications.

Finally, proper supervision of soil nailing works to ensure conformance to design requirements and specifications is important and checklist, a sample of which is enclosed in the Appendix, will be useful.

REFERENCES

- British Standard Institution, *BS8006: 1995: Code of Practice for Strengthened/Reinforced Soils and Other Fills*.
- FHWA. (1998). *Manual for Design & Construction Monitoring of Soil Nail Walls*, Federal Highway Administration, US Department of Transportation, USA.
- Tan, Yean-Chin & Chow, Chee-Meng. (2004). *Slope stability and stabilization, Tropical residual soils engineering*. Taylor & Francis Group, London.

APPENDIX: Sample checklist for construction supervision of soil nailing works.

No.	CHECKLIST ITEMS	ACKNOWLEDGED BY	CHECKED BY	
		CONTRACTOR	GUE & PARTNERS SDN BHD (G&P)	
1.0	EARTHWORK FOR SOIL NAIL SLOPE	SIGNATURE	YES	NO
1.1	The construction sequences (stages of construction) shall be referred to the construction drawing.			
1.2	The soil excavation shall not exceed 3m height per stage before soil nails, horizontal drains and shotcrete surface are completed.			
1.3	The next stage of excavation (after Item 1.2) shall only be allowed after the soil nails, horizontal drains and shotcrete surface are completed.			
1.4	The 4V:1H slope surface shall be covered with shotcrete after the installation of soil nails. No portion of the slope should be left exposed at 4V:1H gradient for more than 3 days .			
1.5	Temporary slope protection using canvas shall be carried out to prevent slope erosion.			
1.6	Contractor that refuse to follow or not following the above construction sequences shall be WARNED and BLACKLISTED from G&P registration. The Project Engineer and Project Director shall be informed IMMEDIATELY .			
1.7	<u>REMARKS:</u>			
2.0	SOIL NAIL	SIGNATURE	YES	NO
2.1	Soil Nailing Material <ul style="list-style-type: none"> Steel Nail reinforcement shall comply with BS 4449 or equivalent standard. (Only nails greater than 12m in length can be spliced using mechanical splicer approved by Engineer.) Galvanizing: galvanize steel bar/ steel plate/ washer/ hexagon nut (All threading process on the steel elements shall be completed before galvanized or else the epoxy paint shall be applied on the threaded portion) Centralizer: Provide only plastic centralizer or equivalent of a minimum diameter 25mm smaller than the nominal diameter of the drilled hole. 			

2.2	<p>Steel Welded Wire Fabric</p> <ul style="list-style-type: none"> • Shall comply to BS 4483 or equivalent • Lap mesh shall be at least 200mm or one mesh grid standard in both directions which ever is larger. • Tie wires shall be bent flat in the plane of the mesh and not forming large knot. • Spacer: Provide sufficient spacer (eg: at least 1m interval) and ensure the spacer is solid. 			
2.3	<p>Horizontal Drain</p> <ul style="list-style-type: none"> • Provide as required and shown on drawings (slotted and unslotted PVC) with end cap. • Provision shall be made to ensure that the hole does not collapse prior to the insertion of the slotted drain 			
2.4	<p>Grout for Nails</p> <ul style="list-style-type: none"> • Provide non-shrink neat cement or non-shrink sand cement grout with pumpable mixture capable of reaching minimum 28 days cube strength of 30 MPa in accordance with BS 1881. • To achieve non-shrink effect, additives shall be added (e.g. Intraplast Z). • Please record name and percentage of the additives that have been used as follows: <ul style="list-style-type: none"> ➤ _____ (name) ➤ _____ (percentage) • Have the additives been approved by the Engineer? <ul style="list-style-type: none"> ➤ Yes / No • Cube test to be carried out after every batching of grout. 			
2.5	<p>Permanent Structural Shotcrete Facing</p> <ul style="list-style-type: none"> • Materials: <ul style="list-style-type: none"> - Cement: Ordinary Portland Cement complying with BS12 or MS 522 and Portland Pulverized Fuel Ash Cement complying with MS 1227. - Aggregate: shall comply with BS 882 - Accelerating additives shall be compatible with the cement used, be non-corrosive to steel and not promote other detrimental effects (cracking and excessive shrinkage) and shall not contain calcium chloride. - Water used in the shotcrete mix shall be potable, clean and free from substances or element, which may be injurious to concrete and steel or cause staining. 			

	<ul style="list-style-type: none"> Quality: Shall be produced by dry or wet mix process achieving a minimum compressive strength of 18MPa in 7 days and 30MPa in 28 days. Construction Testing: carry out a test panel and send cores for testing in accordance to BS 1881. 			
2.6	<u>REMARKS:</u>			
3.0	NAIL INSTALLATION	SIGNATURE	YES	NO
3.1	<p>General procedures:</p> <ul style="list-style-type: none"> Check the size (diameter) of drill bit and compare with the required diameter of soil nail as specified in the drawings. Any anomalies shall be reported immediately to the Engineer. <ul style="list-style-type: none"> ➤ _____mm (diameter of drill bit) ➤ _____mm (required soil nail diameter) Check the diameter of hole being formed. <ul style="list-style-type: none"> ➤ _____mm Mark clearly and accurately the point of the soil nail location. The drilled hole shall be located within 150mm of the location shown on drawing. Supervisor and driller to ensure the drilling methods is suitable for maintaining open drill holes and do not promote mining and loosening of the soil at the perimeter of the drill hole or fracture soils with weak stratification planes by control the flush volumes and pressure. Provide nail length and nail diameter necessarily as required but not less than lengths and diameter as shown in the construction drawing. At the point entry, the nail angle shall be within ± 3 degrees of the inclination as shown in the construction drawing. Centralizers shall be provided at 2m intervals for the whole length of nail with the last centralizer located at 300mm from the end of each nail and ensure that not less than 30mm of grout cover is achieved along the nail. Record the depth where the seepage of groundwater was observed (if any). Inject grout at the lowest point of the drill hole. (Pump grout through tubes, casing, hollow stem auger or drill rods such that the hole is filled from the bottom to the top to prevent air voids until clean grout is seen to run from the top of the hole). Remark: Grout pipe must be used or else the particular soil nail will be rejected 			

	<ul style="list-style-type: none"> Grouting equipment shall have capability of continuous mixing and producing grout free of lumps. 			
3.2	<u>REMARKS:</u>			
4.0	SHOTCRETING	SIGNATURE	YES	NO
4.1	<p>General procedures:</p> <ul style="list-style-type: none"> Slope surface to receive shotcrete shall be cleaned with air blast to remove loose material, mud, rebound from previously placed shotcrete and other foreign matter that will prevent bonding of shotcrete. Dampen the surface before shotcreting. During placement of shotcrete, the horizontal drains and weep holes shall be protected against contamination or clogging of shotcrete to ensure proper functioning. Thickness measuring pins (non-corrosive) shall be installed on 1.5m grids in each direction. Check the thickness of measuring pins using normal ruler or measuring tape. <ul style="list-style-type: none"> ➤ _____ mm Thickness, method of support, air pressure and water content of the shotcrete shall be controlled in such a manner as to preclude sagging of sloughing off. The shotcrete shall be applied from the bottom up to prevent accumulation of rebound shotcrete on the surface, which is to be covered. Horizontal and vertical corners, and hollow areas shall be filled first. Checking for hollow areas on the completed shotcrete surface shall be carried out with a hammer. All shotcrete which lacks uniformity, exhibits segregation, honeycombing or lamination, or which contains any dry patches, slugs, voids or sand pockets shall be removed and replace with fresh shotcrete. In situ core test shall be carried out for verification. Immediately after the completion of shotcreting works, keep shotcrete surface continuously moist for at least 24 hours for curing purpose. The opened cut area shall be protected with canvas or suitable material to avoid erosion. 			

	<ul style="list-style-type: none"> As built drawing showing the location, dimensions, photos and details of the soil nail wall shall be produced by the contractor. 			
4.2	REMARKS:			
5.0	PULL OUT TEST	SIGNATURE	YES	NO
5.1	<p>List of Equipment</p> <ul style="list-style-type: none"> A single acting hollow hydraulic jack connected to hydraulic pump and pressure gauge with minimum capacity of 20MT A pull out steel fabricated cage A steel bracket At least 4 displacement gauges A pressure meter Nut and washers Stopwatch to measure the period of observation. 			
5.2	<p>General Procedures</p> <ul style="list-style-type: none"> Pull out test should be carried out in ground types and in environmental conditions similar to those existing at the proposed site. The stressing equipment, pressure gauge and load cells should be calibrated by the manufacturer and in accordance with clause 10.6 BS 8081:1989. The load cycle, load increments and minimum periods of observation shall be as instructed by the Engineer. As built drawing showing the location of pull out test, dimensions, photos and details of the test shall be produced by the contractor. 			
5.3	REMARKS:			