Soil Nailing to Existing Slopes as Landslip Preventive Works

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Abstract: Soil nailing has become a well accepted technique for improving soil slope stability. This paper places particular emphasis on the use of the technique to provide improvements to marginally stable existing slopes in Hong Kong. A brief history of soil nailing is presented together with an outline of the design philosophy, standards and construction procedures which the Design Division of Geotechnical Control Office (GCO) are currently using in their work on landslip preventive measures contracts.

DEFINITION

Soil nailing can be defined as a technique for the improvement of behavioural properties of an insitu soil mass by the inclusion of slender unstressed reinforcement. The important feature is that it is slender unstressed reinforcement which is placed in insitu soil. This definition applies equally well to a number of other uses of reinforcement in soil. In the case of micropiling the reinforcement is primarily in compression, and for soil doweling primarily in shear. In soil nailing the predominant action of the reinforcement is in tension.

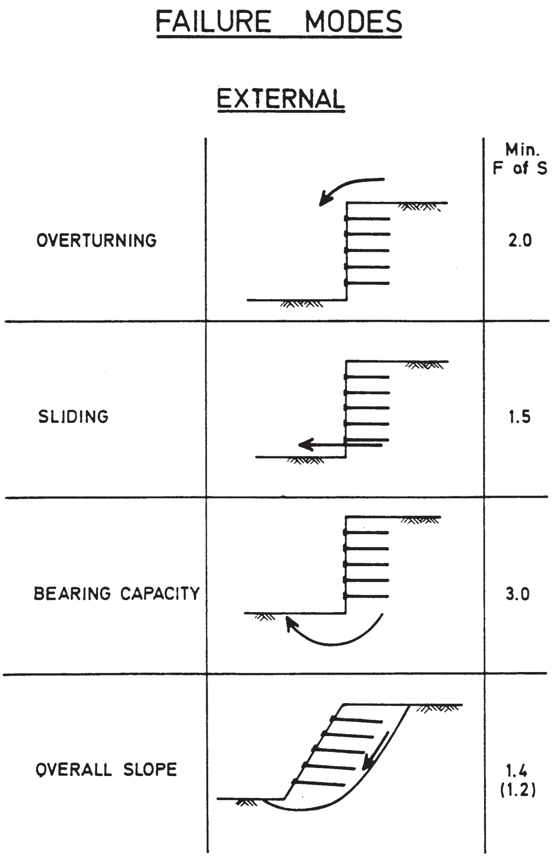

Figure 1(a)

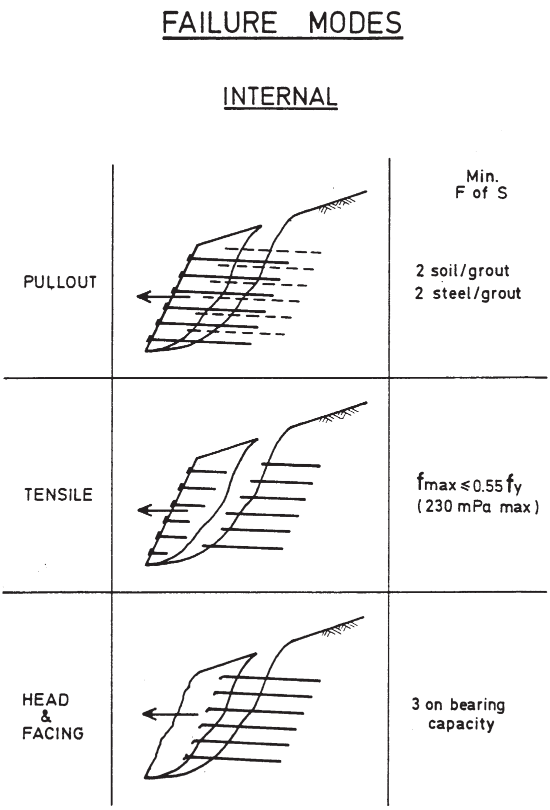

Figure 1(b)

BRIEF HISTORY

Soil nailing has its roots in rock bolting for tunnelling. With the introduction of the New Austrian Tunnelling method in the early 1960s bolting into less competent materials became more commonplace. In the early 1970's semi-empirical designs for nailing into soil began to be used and the first systematic approach, involving both model and full scale field tests were carried out in Germany in the mid-1970s. (Cartier & Gigan (1983), Juran et al (1983)). Germany, together with France and the US have continued to be the main practitioners, although others are now realizing the potential of this powerful method (Bruce & Jewell (1987)).

There is a substantial literature base and regular international symposia are held on this topic. This published knowledge, together with numerous case histories in a wide variety of ground conditions and applications give substantial confidence for its use here in Hong Kong.

Soil nailing was first used in Hong Kong as a prescriptive method to provide support to deeply weathered zones in otherwise sound material. These were followed by a few cases where passive anchors or tie-back systems were used. Some of the drive for these early cases came no doubt from the desire to avoid long-term monitoring of ground anchors. In the mid 1980s a small number of soil-nailed supports to temporary cuts were made.

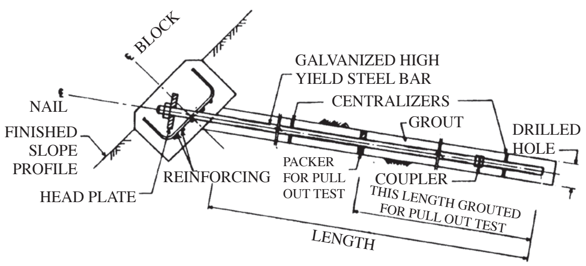

Figure 2. Typical details of soil nail

However it was not until 1987 that interest in soil nailing blossomed (Powell & Watkins (1990)). The vast majority of soil nailing is still for improvements to either existing or newly formed slopes, with disappointingly little use of them being made for temporary support. The majority of designs are by the engineers and not by contractors, again rather surprising considering the ease of construction and relatively low cost.

SOIL NAILING IN THE LANDSLIP PREVENTIVE MEASURES PROGRAMME

Government has an ongoing programme of preventive and remedial works to existing slopes called the Landslip Preventive Measures (LPM) Programme. A large number of existing cut slopes which, although they have stood for quite some time, do not have an adequate margin of safety and it is necessary to bring these up to an acceptable standard. The philosophy permitted by the Geotechnical Manual for Slopes (GCO 1984) is to assume that the existing slope has a minimum factor of safety of 1.0 for the worst experienced loading and groundwater conditions, and to make an improvement to the slope to bring it up to a factor of safety of 1.2. This approach is permitted where rigorous geological and geotechnical studies have been carried out, where the slope has been standing for a considerable time and when after improvement the loading conditions and groundwater conditions will remain substantially the same as those of the existing slope.

The preferred method of improving these slopes has been by cutting back, since it is relatively cheap, positive and allows the finished slope to be grassed. However it is often the case that there is insufficient space to cut back, and in the past structural solutions,

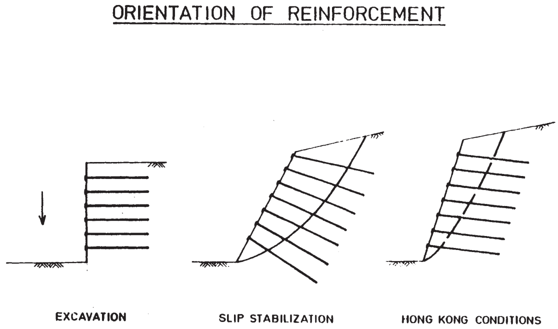

Figure 3.

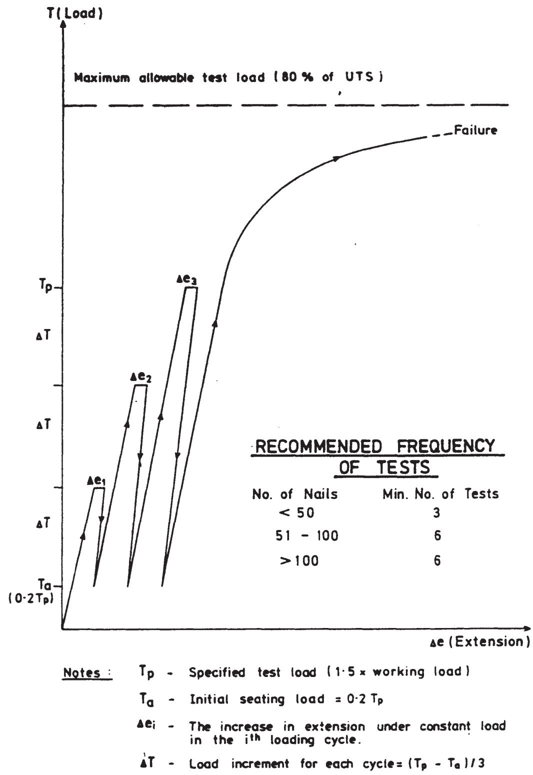

Figure 4. Pull out test loading sequence

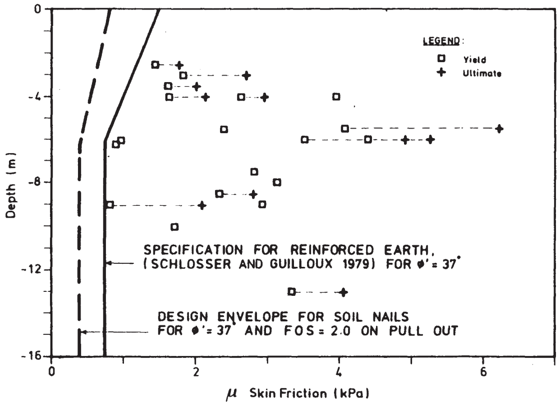

Figure 5. Skin friction derived from pull out tests

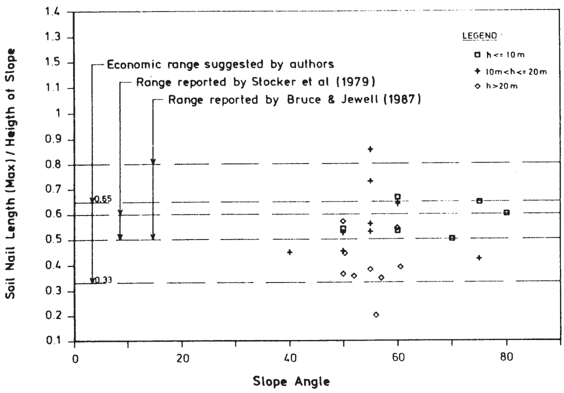

Figure 6. Soil nail length/height to slope angle relationships

such as cantilevered walls, soil dowels and retaining walls have been used (Koirala & Tang (1988), Powell et al (1990), Yim et al (1988)).

Soil nailing has a clear advantage over other structural solutions. The chance of failure through weak zones or along relict joints is significantly lessened, as the soil nails bind the soil together so that the mass strength is mobilized. In installing the nails there is minimal disturbance to the existing slope and hence the risk of failure from a temporary condition such as oversteepened temporary faces, is removed, and the confidence gained from the long-term performance of the slope is not reduced. The installation is robust in that failure of an individual element is not likely to lead to failure of the overall structure. In addition the costs are reasonable and certainly cheaper than other structural solutions. Finally, no matter what doubts there may be about analytical methods, the works are clearly an improvement over the existing condition.

DESIGN PHILOSOPHY

The design philosophy adopted for soil-nail installation has been to be conservative in the design and material specifications to allow for uncertainties in the method. In soil nailing to existing slopes it can be expected that the soil nails will be loaded very infrequently, only during periods of heavy rainfall or as a result of surcharging. It is therefore not practical to monitor for either stresses or deformation. With increased confidence and improvements in analytical methods and construction techniques an easing of standards can be expected.

BEHAVIOUR

Soil-nailed installation can range from individual nails through to closely spaced arrangements.

Individual or prescriptive nails are installed to either stabilize isolated areas or more commonly to provide additional confidence rather than because they are analytically necessary. A typical use would be to improve a narrow deeply weathered zone in otherwise sound rock.

For the improvement of potential slip surfaces to achieve specified factors of safety, nails are designed to cross potential failure surfaces. These provide additional shear capacity over the potential failure surfaces and reduce the risk of surficial failure along relict joints or other geologic anomalies.

Where nails are sufficiently closely spaced, they form a monolithic block which acts in a similar manner to a retaining structure. Earth pressure theories are appropriate to determine loadings for such structures.

MODES OF FAILURE

Both internal and external modes of failure need to be considered (Figure 1). For the external modes of failure, the first three modes, sliding, bearing capacity and overturning are normally only applicable to a monolithic structures, but overall stability must be checked for all cases. The recommended minimum factors of safety for each mode are also given in Figure 1 (a).

Internal stability must be checked in all cases. Three possible modes of failure are shown in Figure 1(b) together with the recommended minimum factors of safety for each mode.

The major components of a soil nail are the steel bar, the surrounding grout column and a nail head. Figure 2 shows a typical soil nail arrangement.

The material specification and allowable design stresses for these components as used in GCO contracts are :

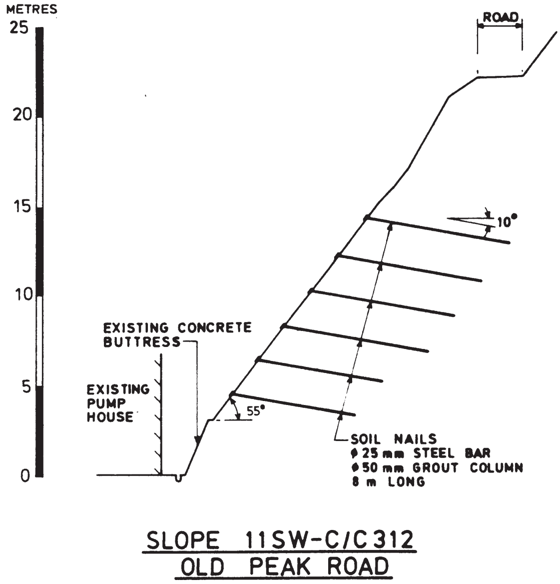

Figure 7(a)

Steel Bar: High yield bars to BS 4449. Max design tensile stress 0.55 yield stress or 230 MPa whichever is less.

Grout: 30 MPa cement grout with a water cement ratio not exceeding 0.45. Design bond stress (grout to steel) is taken as 0.5 ultimate bond stress determined in accordance with BS 8110.

Steel bars used in permanent installation are also provided with corrosion protection which is provided in three ways:

(1) All soil nails are hot-dip galvanized to BS 729;
(2) A sacrificial layer of 2 mm on the radius is allowed to account for steel loss with time; and
(3) A minimum grout cover of 10 mm all round is provided.

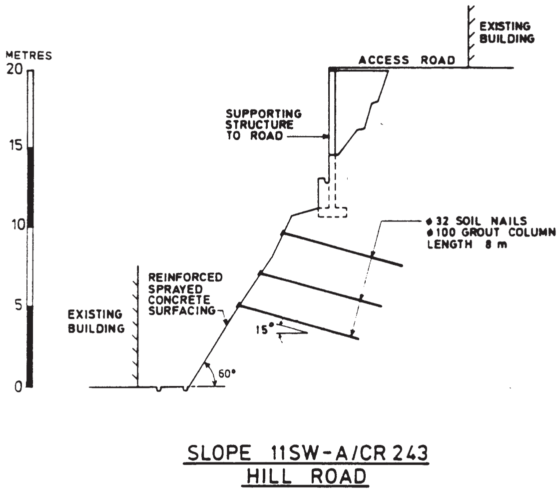

Figure 7(b)

The major risk of corrosion arises from the possibility of hole collapse prior to grouting of the steel bar, which may result in soil and ground water being in direct contact with the nail. To minimize this risk drill holes are blown clean immediately before installing the nail and once the steel bar has been installed the grouting is carried out as soon as possible thereafter. Occasionally there will be hole collapse in isolated areas but it is considered that these corrosion protection measures are sufficient to ensure that the required capacity will be retained for normal soil and groundwater aggressivity. For more corrosive environments, additional protection may be required.

ANALYSIS

There is as yet no generally accepted method of analysis for soil nailed installations. (Bruce & Jewell (1987)).

To analyse the modes of failure illustrated in Figure 1, a number of limit states can be considered. External stability will not be discussed as it is straightforward. For internal stability, failure modes which pass through some or all the nails must be considered and the worst case designed against. A number of analytical methods have been published, and computer programs are available for some of these.

The critical design condition for the improvement of existing slopes is the determination of the necessary resistance across the particular potential critical surface being examined. GCO Design Division commonly use the JANBU analysis (Janbu, 1972) to determine the total horizontal force required to maintain the required factor of safety. The distribution of this force along the sliding plane is a matter of some debate. When the nails are evenly distributed along the plane, then the total force is assumed as distributed equally between the nails. Other nailing arrangements may require different assumed distributions. There is little guidance in the literature on this, and subjective judgement backed by sensitivity analyses are necessary.

In analysis bending moments and shear forces are ignored. This is satisfactory provided the nails are oriented correctly. Excavations orientation should normally be horizontal and slope improvements slightly inclined downwards as shown in Figure 3. In Hong Kong the potential failure surfaces are often as shown in this figure and so uniformly oriented nails at 5 - 10°downwards for ease of grouting are used.

SKIN FRICTION

Once the total required force per nail is determined the length beyond the critical slip surface is calculated from an assumed skin friction. Currently the formulae by Schlosser and Guilloux (1981) is used:

$T_1 = Pc^1 + 2D\, v\mu^*$, where

T_1 is the pull-out force per linear metre
P is the perimeter of the reinforced grout column
c^1 is the effective cohesion of the soil
D is the width of an equivalent flat reinforcing strip (i.e. the hole diameter)
v is the theoretical vertical stress in the soil calculated at mid depth of the reinforcing bar
μ^* is the coefficient of apparent friction of the soil

The coefficient μ^* takes into account dilatory effects and the values for high adhesion reinforcement, as suggested by Schlosser & Guilloux (1981). μ^* is greater than unity for shallow depths, and reduces to Tan ø' at depth, where ø' is the effective angle of internal friction of the soil. The calculated ultimate pull-out force is factored by a safety factor of 2.0 to give the allowable pull-out force.

The design pull-out capacity is checked on site by conducting pull-out tests in advance of the installation of permanent nails. The sequence of loading and the minimum frequency of testing is given in Figure 4. The bonded length of a bar for pull-out tests is typically 2.0 m.

Some results from loading tests are shown in Figure 5. The tests are mostly in completely decomposed granite. It can be seen that the loads measured are well in excess of the design values, by between 4 and 14 times.

SOIL NAIL HEADS

The typical soil nail head currently used is shown in Figure 2. Soil nail heads are usually concrete pads, either isolated or integral with shotcrete used to surface the slope. Beams or grillages are also occasionally used.

CORRELATIONS FOR PRELIMINARY DESIGN

Data on soil-nailed installations in Hong Kong has been plotted in a number of ways to see if useful correlations can be established. Unfortunately, there is considerable scatter in the results so empirical design guidance is difficult to give. However, Figure 6 shows a plot of nail length/height vs slope angle. It can be seen that nail length to height ratios in the range 0.33 to 0.65 are appropriate for improvement to existing slopes in Hong Kong.

CONSTRUCTION

In 1985 the first soil nail works were carried out on a GCO construction site were in 1985 at a site in King's Road where they were used to provide temporary support to a steep soil cut face during the construction of a retaining wall. These temporary works were to the contractor's design.

The next soil-nail construction was not till 1987-88 and was for permanent soil nails to improve the stability of a masonry skin wall at a site in Kam Shan, Tai Po where nails were to the engineer's design. Since 1988 more than 30 sites using soil nailing have been included into LPM contracts. Figure 7 shows cross-sections of some sites. All of these works were to the engineer's design with no risk to the Contractor for failure of pull-out tests. However, no nails have yet failed for lack of bond.

Construction of soil nails is a simple task requiring only the drilling of a fairly short hole, with a reasonable latitude in tolerance, and the insertion and grouting of a steel bar. Little in the way of specialist skill is required, and the technique lends itself to sites where access is difficult or where working space is limited.

DRILLING AND INSTALLATION

Drilling is usually carried out from bamboo scaffold. Holes of up to 55 mm and 6 m in length can be drilled using hand-held pneumatic equipment. Larger diameter, usually 75 mm or 100 mm, or longer holes require more powerful equipment and a pneumatic percussion rig is commonly used. (A typical rig is shown in Plate 1.) The rig is around 4m long and so the proximity of buildings or other constraints at the toe of the slope need to be considered. Air flush is used in all cases and the holes are drilled without casing. Hole collapse is very rare unless the soil material is either very loose fill or significant water inflow is occurring.

When drilling takes place from bamboo scaffolding, vibratory movement of the equipment is common and ovelling or oversizing in holes may occur. This is not a problem as it helps to provide the roughened hole assumed in design. Drilling in firm soil and corestones is straightforward although some difficulty has been encountered in drilling through masonry walls and bouldery fill/colluvium. In these cases the rock may be displaced by the drill head and then fall back against the drilling rods, thereby making it very difficult to pull the equipment out.

Bars and all the associated couplers, head plates and nuts should be hot-dip galvanized. In practice, contractors have found it difficult to successfully galvanize the threaded end of the bar as the long lengths preclude the use of a centrifuge. Consequently, on-site threading after the bar has been galvanized has been permitted and the exposed ungalvanized portion of the thread has been painted. Hadley and Yeomans (1990) provide useful commentary on galvanising threads and nuts, and on the use of paints to restore corrosion resistance. Once the hole is drilled the bar is installed by hand and grouted in place. Spacers are used to centralize the bar in the hole and where necessary couplers are used to facilitate handling of the bar particularly in areas of restricted working space.

SLOPE SURFACE FINISH

The early approach to finishing slope surfaces after soil nailing was to apply sprayed concrete reinforced with mesh. Whilst sprayed concrete provides a good engineering answer to slope surfacing, environmentally it can be very visually obtrusive. More recently slopes have been hydroseeded after soil nailing. Where superficial failures or erosion between nail heads could be a problem, wire mesh may be laid on the surface interconnected with the nail heads and the slope then hydroseeded.

QUALITY CONTROL MEASURES

For any construction, quality control measures begin by having adequate and sufficiently experienced supervisory staff on site. They are supplemented with good clear specification and procedures for checking compliance. In addition other information such as the drilling penetration rate and the grout take should be obtained and a check made to confirm that holes have not collapsed and that they are clear and free of water prior to installing the steel bars.

There remain areas where quality control measures can be improved. For instance, deformation criteria for pull-out tests would be useful. Designing engineers have suggested that deformation over and above the elastic extension of the free length should not exceed 0.2 - 0.3% of the grouted length and some more positive guidance on this is desirable. Possibly some means of acceptance test would also be useful. In the course of time it should be possible to provide a performance specification and ask contractors to submit details to their own design.

COSTS

Soil nailing costs around \$1,000 per m^2 of slope face (at 1990 prices) which is similar to the cost of cutting back a slope. However, cutting back is often not possible and soil-nail costs should be compared with much more expensive structural options like caisson stitching. Over four fairly recent or current LPM contracts the cost per individual nail varies from \$2,000 to \$3,300 for a 6 m long nail. The cost of each pull-out test varies from \$1,500 to \$4,000.

CONCLUSION

Soil-nailing design and construction is in its infancy in Hong Kong and improvements can be expected to be seen particularly in methods of analysis and design parameters, particularly the assumed soil/grout bond, construction techniques and range of applications. Nevertheless soil nailing in its current state is economic, flexible, provides a robust design solution for both slope improvement or for the support of cuttings for temporary works, and should be used more often for these purposes.

ACKNOWLEDGMENTS

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