SOIL NAILING

CASE HISTORIES AND DEVELOPMENTS

A. D. BARLEY - Director of Engineering
Keller Ground Engineering

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SOIL NAILING CASE HISTORIES AND DEVELOPMENTS

A. D. BARLEY C.Eng., BSc (Eng), M.Sc., M.I.C.E., F.G.S. CONTRACTS DIRECTOR – KELLER CONCRETE

The paper reports on seven Soil Nailing Contracts involving stabilisation of existing walls and both new and existing slopes. Current tendon corrosion protection systems and costs are highlighted and development of new non-corrosive tendons is summarised.

INTRODUCTION:

1. The use of soil nails for the stabilisation of slopes has been common in France, Austria, Germany, Canada and the U.S.A. since the mid-1970's. This development followed extensive use of fully bonded rock bolts (passive anchors) for tunnel support during the 1950 and 1960's, which lead to the use of rock bolts in weaker rocks such as marls, and weck sandstones. The natural progression continued in the application of the same ground strengthening principles to weakly cemented sands, strong clays and subsequently to mid-strength soils. Soil nailing became an accepted practice for the stabilisation of existing slopes and walls and to allow slope cutting and steepening.

2. Despite the frequency of such applications of soil nailing techniques in other countries for over a decade, the number of contracts executed in the U.K. during recent years amounted to little more than a handful. Case histories of seven of the earliest soil nailing contracts carried out in the U.K. between 1985 and 1991 are summarised and some useful established design parameters are derived and compared with values previously utilised.

3. Available corrosion protection systems for steel tendons are assessed from technical, practicable and economic viewpoints. Current developments involving the use of glass fibre and polymeric materials as corrosion free tensile members are also discussed.

SOIL NAILING TO STABILISE EXISTING RETAINING WALLS

Denholme Clough, Bradford

4. The use of dry stone walling built more than a century ago to support sloping ground alongside roads through the Pennines is a common feature. At Denholme Clough the road crossed an open hillside with a side slope gradient in the range of 40%. The existing stone walls, between 2.5 and 3 metres in height, exhibited bulging and short areas of collapse over a total length of 140 metres. Prior to soil nailing, remedial construction works had been carried out in the areas of collapse, some vegetation removed, and a small footing trenching excavated at the base of the wall. Steel mesh (D49) had then been positioned on the face of the wall and a 50mm layer of gunite sprayed over the entire wall
length. The retained soil consisted of a mixture of wet sands, gravels and clays overlying a sloping sandstone bedrock. Some 200 No. 30 kN. load soil nails were installed, generally in two rows at either 1m or 1.5m horizontal spacing to depths of 4m to 5m at an inclination of 15°. Drainage holes were installed at base of the wall and at mid-height at 3m spacing (Fig. 1). During the work, three special trial nails were installed and tested satisfactorily to 80 kN. This proved a ground/grout bond capacity over a 2m bond length of 110 kN/m² without any indication of failure. After trial nail testing, and nominal loading of all the contract nails to 10kN, a new masonry facing was constructed by the local authority and gaps between the facing and the groutine were filled with sand/cement grout. No indication of movement or detection of cracks has been established during frequent observation throughout a six year period. This would suggest that stabilisation has to date been fully effective.

Cymseriog Primary School, Glamorgan

5. A 2.2m high masonry wall, almost 100m in length, retains a full range of wet granular materials with some clay, the surface of which slopes upward from the wall at a 35% gradient. This wall is located some 3 metres from a Victorian school building and protects the building and the school playground. The wall exhibited cracking and bulging, and movement of the order of 5mm had been monitored over a 6 month period. At the time of soil nail installation, temporary strutting was in place to provide additional support to the wall. Ninety soil nails were installed through the wall in two rows at a spacing of 2m horizontally and 0.75m vertically (Fig. 2). Working capacities of 30kN. were required of the 5 to 6m long nails and load was transferred from the nails to the 0.5m thick wall in direct bond via the cement grout. This load transfer over a short length without a bearing plate was aided by the use of deformed bar (T25) as soil nail tendon. Corrosion protection to the bar was provided by the use of a 50mm dia continuous corrugated plastic duct, identical to that used in anchor encapsulation systems but grouted in-situ. Three trial nails were installed and satisfactorily tested to 90kN., confirming that a factor of safety in the order of 3 was present at the bonded interfaces. Wall movement was monitored for 14 months after soil nail installation and no movement or further cracking was detected.

Beaufort Road, Bristol

6. This masonry wall was also about 100 years old and retained 2.5 to 3.8m height of ground plus a rear upward slope at a 50% gradient. However, at this location vegetation was abundant and the upper slope contained shrubs and trees. Retained soil consisted of made ground over fissured silty clay and grey siltstone bedrock. Stabilisation was required prior to building work at the
top of the slope. Fifty three nails were installed in 3 rows over the higher section which reduced to 2 rows where the wall height fell below 3m and where the slope height behind was reduced. Nails were installed on a grid pattern at an inclination of 20° with a 2m horizontal and 1.5m vertical spacing, with lengths of 9, 7.5 and 6m working from top to bottom (Fig. 3). On completion of soil nailing operations, a steel mesh was fitted to the face and a gunite surface applied in a thickness of 50mm. Detailed observation some two years after completion indicates a stable wall with a crack free surface.

Ampthill Road, Bedford

7. Movement of the 1.5 to 2m high gravity brick wall supporting the A6 trunk road in the approach to a road over a rail bridge had been causing concern. Although the height of the wall was low, the earth slope behind rose at a 30° to 55° gradient to the road pavement, resulting in a total wall and slope height of approximately 5m. The retained earth and the embankment generally consisted of firm to stiff silty clay which increased in sand and gravel content with depth. The eighty eight soil nails required for temporary wall stabilisation possessed characteristics of both anchors and nails. Although the specification called for an unbonded 'free length' equivalent to about one third of the nail length, the nails were unstressed and left in a passive state. Nail lengths ranged from 8.5 to 12.5m at inclinations of 10° to 20°. Four preliminary trial nails attained 150% design load without failure, and all nails were finally bonded into the 0.5 to 0.6m thick brick with cement grout without any utilisation of bearing plates. The stabilised wall has been observed at monthly intervals and although accurate monitoring has not been carried out, visual observations over the 2½ year interim period confirm that movement and crack widening has ceased.

SOIL NAILING TO STABILISE SLOPES
Temporary Soil Nail Support in Birmingham

8. Building construction and site limits demanded the excavation and the accompanying stabilisation of a 150m wide steep face up to 8m in height. Soils consisted of firm to stiff clay overlying weakly cemented sandstone (Keuper Marl). The upper 2m in the firm clays could be battered back at a 100% gradient. Some 300 soil nails, in up to 5 rows, at 1.5 m spacing both vertically and horizontally, were required to support the shotcreted face. Construction was in a downward progression with the 100mm thick shotcrete facing, containing 100 x 100 steel mesh, proceeding immediately after face exposure. The nail installation and 50mm slotted PVC drainage hole construction followed, generally with the unsupported face height not exceeding 2m. Length ratio of the nailed slope generally equated to 1.0, with 8m nails in a slope
Fig 1 Soil Nailed Wall at Denholm Clough, Bradford

Fig 2 Soil Nailed Wall at Cymytrig, Glamorgan

Fig 3 Soil Nailed Wall at Beaufort Road

Fig 4 Temporary Soil Nailed Slope in Birmingham

Fig 5 Soil Nailed Slope at Dolywern, Clywd

Fig 6 Rock Bolted and Soil Nailed Slopes at Lakeside, Thurrock
of that height and 5m nails where the slope height reduced to 5m (Fig 4). The T25 bars were installed in lengths up to 6m with the use of couplers being required for the longer nails. The bond capacity over the full length of grouted bar and borehole was supplemented by the positioning of 200 x 200mm dia plates on the shotcrete surface.

9. It was unfortunate that after heavy rain, a collapse at one end of the face took place. It was suggested that this failure could be attributed to insufficient control of the numerous operations being carried out by different working parties.
   a) Excavation proceeding below the 2m limit of unsupported face;
   b) The omission of a number of soil nails due to over-excavation;
   c) The blockage of a number of drainage ducts with shotcrete;

Subsequent to this collapse, controls were tightened and satisfactory face support to the full height was provided.

Permanent Support, Dolywern, Clwyd

10. A steep embankment alongside the B5400 between Chirg and Glyn Ceirig in North Wales had been providing the County Council with reasons for concern over a number of years due to observations of settlement and cracking of the upper road surface. The vegetated slope between a minor road at the top and the main road below has a gradient in the order of 100% and a maximum height of approximately 10 metres. The soils consist of silty clays with some gravel and cobbles. The slope has now been stabilised by the use of some 180 soil nails in two stages of contract work. Nails were generally required at 1.5m spacing both vertically and horizontally and at an inclination of 15°. (Fig 5). Nail locations in up to 7 rows were staggered in adjacent rows. The nail steel consisted of galvanised 25mm dia high yield thread bar, 5m long complete with 250 x 250 x 10mm galvanised plates and nuts at the head. All major bonding within the soil nail in order to stabilise the soil and the slope was achieved by the sand/cement grout, whilst the plate positioned on the protruding nails provided a mode of retention of the galvanised steel mesh (A142) which was finally spread over the entire embankment (Fig. 6). This mesh prevented spalling and erosion, and supported the growth of fresh vegetation. On completion of nailing operations, the surface of the minor road was patched up, and from observation of the patching condition there is every indication that further slope movement has to date been prevented.

Lakeside - Thurrock

11. Recent development of a modern shopping complex within an extensive disused chalk quarry required the trimming and stabilisation of a 500m long 15m high face.
Initially the exposed chalk face was trimmed to a 70 to 75 degree slope. Above the chalk level was a 4 to 6m wide berm behind which was, for most of its length, a rock armour covered 40 degree clayey, sandy chalk slope. Intermittent within the chalk face were large solution features with a face area as much as 7m vertical by 5m wide, where chalk had been washed away and naturally replaced with overlying materials of chalky sands, gravels and flints. Stabilisation was carried out by the installation of some 1500 bolts in up to 8 rows in the chalk. The 6m long steeply inclined bolts at the back of the berm were threaded with cables to support the suspended galvanised mesh. The intermediate 6 rows ranging from 3 to 4m long, stabilised the chalk face and held the mesh in place and bolt contact by the use of galvanised plates and nuts (Fig 6). The lower row, complete with threaded cables, retained the lower extremity of the mesh approximately 1m above the base of the steep face.

The granular material content of the exposed solution features was removed and replaced by wet concrete filled bags built into the cavity in a brickwork type formation with a finish flush with the chalk face. 3 to 4m long bolts in a grid of about 1m spacing were installed through the filled cavity to tie the bagged facing to the intact chalk behind. At the western end of the face the chalk level and berm level reduced over an 100m length. This resulted in the presence of a 40° clayey, sandy chalk slope, attaining up to 6m in height above the berm. The soil nail stabilisation of this slope was only considered necessary where the slope height exceeded 3m. The 150 nails ranging in length from 3 to 6m, consisted of galvanised high yield 25mm diameter steel bars the same as that employed for the bolts. The nails also executed a dual purpose of slope stabilisation and support and constraint of galvanised mesh and tensar mat. Some dozen bolts/nails installed early in the works were satisfactorily tested to 120 kN, without failure. On completion, about 7500 m² of mesh was installed on the chalk face and 3400 m² on the berm and on the overburden slope behind.

SOIL NAIL PARAMETERS FROM SLOPE AND WALL STABILISATION

12. When summarising the state-of-the-art of soil nailing and reporting on continental practice in 1986, Bruce and Jewell derived four basic parameters each of which provides a useful measure of the characteristics which contribute to the stabilisation or record the slope movement:-

a) Length Ratio = maximum nail length/excavation height;

b) Bond Ratio = hole diameter x nail length/vertical face area supported by nail;

c) Strength Ratio = (nail diameter)²/vertical face area supported by nail;
Fig 7 Mode of Dimension Analysis for Deriving Soil Nail Parameters

<table>
<thead>
<tr>
<th>BRIMNAGHAM</th>
<th>COLCHESTER</th>
<th>THURROCK</th>
<th>GRANULAR SOILS</th>
<th>NORMAIN AND MARL</th>
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<tr>
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<td>0.09</td>
<td>0.1 to 0.8</td>
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<td>15° slope of Silty Clay</td>
<td>43° upper slope of Clayey Chalk</td>
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Fig 8 Soil Nail Stabilisation Parameters for Slopes

<table>
<thead>
<tr>
<th>STABILISATION OF EXISTING RETAINING WALLS</th>
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<tbody>
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<td>BRADFORD</td>
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<tr>
<td>LENGTH RATIO</td>
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<tr>
<td>BOND RATIO</td>
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<td>STRENGTH RATIO X 10^-1</td>
</tr>
<tr>
<td>PREDOMINANT SOIL BOND MATERIAL</td>
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</table>

* Effective height and area per nail determined from ground section at mid-length of the longest nail

Fig 9 Soil Nail Stabilisation Parameters for Existing Walls
d) Performance Ratio = Outward movement/excavation height.

Fig. 8 tabulates stabilisation parameters from the three stabilised slopes described, in addition to general parameters produced by Bruce and Jewell. It should be noted that the latter were derived from sites involving steep slopes (80° or steeper) and thus only allow direct comparison with data from the Birmingham slope. In the case of slopes at Dolywern and Thurrock, lower values of length ratio and higher values of bond and strength ratios may be expected, since the shallower slopes would be partly self-supporting and nailing was carried out to increase the factor of safety against slope collapse and to retain a surface mesh to control surface erosion. No data has been published with regard to the application of the three stabilisation parameters to the stabilisation of existing walls. In such an application it is recommended that the effective supported height, and the vertical face area supported by a nail, are taken at a cross section at the mid-length of the longest nail (Fig 7). On the basis of this consideration, Fig. 9 tabulates values derived from the four stabilised walls.

Owing to the initial conservative approach to wall nailing, length ratios are relatively high. Bond and strength ratios are low due to the self-support of the slopes and walls for many years. Again, the recent nailing has been carried out to supplement the stability and not to provide the major component of the resisting force. Although the parameters established from the stabilisation of newly formed steep slopes and those analyzed from early wall stabilisation contracts take the same format, it is important that they are considered separately. The input data for height and nail area is necessarily in each case defined in a different mode as shown on Fig. 7. However, the parameter can be seen to serve a useful purpose for comparing like with like and, furthermore, by contrasting unlike schemes.

CORROSION PROTECTION SYSTEMS FOR STEEL TENDONS

13. An awareness of the vulnerability of steel tendons due to corrosive action may lead to any of the following considerations in order to establish an optimum balance between cost and risk of loss of steel section in a soil nail:

a) assessment of loss of steel section in either a homogeneous or a non-homogeneous soil;

b) the effectiveness of the alkaline environment of cement grout in resisting/reducing corrosion in either a crack controlled or random cracked grout column;

c) the provision of a sacrificial coating on the steel (i.e. galvanising) the protection of the coating during handling and the estimation of lifespan when in situ;

d) the provision of an epoxy coating on the steel and the protection during handling and any possible
degradation of the protection layer;

e) the provision of corrugated plastic ducting around the steel tendon, all grouted in situ;

f) the use of stainless steel and estimation of lifespan when in situ;

g) the provision of two concentric corrugated ducts around the steel tendon generally prefabricated prior to installation; There are currently two British Standards documents which may be considered appropriate to the design of soil nails: the Code of Practice for Ground Anchorages (BS 8081) is published, whilst the Code of Practice for Strengthened/Reinforced Soils and Other Fills (B.S. 8085) is drafted for comment.

In soil reinforcement systems where the surrounding soil can be carefully selected and controlled, option (a) may be considered appropriate, whereas in Ground Anchorage practice protection systems at the other end of the range, as highlighted in (g), are recommended for permanent works.

14. In-situ soils into which nails are installed can rarely be considered adequately homogeneous to prevent current differential, or of low enough permeability to eliminate the presence of moisture and a replenishment of a supply of oxygen. Furthermore, due to the general straining of the soil of the nail tendon, and of the grout, the maintenance of crack free or even crack controlled grout cover is improbable. Thus, in the current climate approaches (a) and (b) are generally considered unsuitable for long term permanent stabilisation work. Options (c) (d) and (e) are generally available in a similar price range. Costs increase is in the order of 60 to 100% over and above the cost of the uncoated steel bar. Since the protected steel tendon costs generally range from only 6 to 10% of the total soil nails costs, a variation in preference for any of the three systems would not make a major cost change to the contract value. The Author has no direct experience with the use of epoxy coating system, but with excellent characteristics of adhesion to steel, of impact resistance and of elastic properties compatible with the steel, it clearly deserves due consideration. However, the frequency, the size and the effect of the presence of "holidays" (pin-holes in the coating of a few microns in diameter) should be assessed. The use of a single plastic duct is well tried in both nailing and anchoring systems, and the exposure of test samples and the exhumation of a number of ground anchorages, all confirm that the plastic layers are well preserved and remained un-perforated even after being subjected to severe loading conditions. In the Author's experience, galvanising has its limitations. Firstly, the zinc coating is sacrificial and will deteriorate in the long term leaving parts of the steel exposed. Secondly, chipping of the zinc coating during bar loading, unloading, handling and installation appears to occur despite extensive precautionary measures and
careful operation controls. Thirdly, within the thread length (if required), the zinc coating will be either of minimal or zero thickness at some point in the male or the female thread. Although stainless steel (f) is available in a number of base forms, it is not invulnerable to long term corrosion. Furthermore, it has a large cost differential over and above that of normal uncoated steel (800 to 900%) and this would lead to a considerable increase in the cost of the works (35 to 50%). The use of a prefabricated double corrosion protection system, consistent with those generally specified for permanent ground anchorage works, would provide the most efficient corrosion resistance steel tendons currently available. The additional cost of such tendons, of the additional haulage, and of handling considerably heavier units must be offset against the protection benefits available. Additional costs increase a nail tendon cost by some 500% which in turn may lead to an increase in cost of the works of 25 to 30%. In terms of the use of prefabricated double plastic ducting as compared to single in-situ grouted ducting, the additional cost would be in the order of 20%.

DEVELOPMENT OF NON-CORROSIVE SOIL NAIL TENDON SYSTEMS
15. Continental practice has already generated and proven the use of glass reinforced plastics both in rock bolting and ground anchorages, the latter system being first used in prestressed bridge decks. Bonding with resinous grouts has been favoured in rock bolting technology, although published data has also confirmed the adequacy of bond capacity between G.R.P. and cementitious grouts. Research work is currently being undertaken by Keller Colcrete to further investigate bond capacity at this interface when utilising a variety of G.R.P sections. Considerable investigation work has been completed by Keller Colcrete on the use of folded geotextiles as the main tensile member within of a grouted soil nail borehole. Bond capacities have been well proven, and modes of installation of such flexible members have been established.

16. Both G.R.P and geotextiles, when incorporated as tensile members, exhibit a considerable increase in elastic extension over that of steel bars. However, the resulting problems have already been overcome in the rock bolting application, and investigation work is currently underway to assess the effect of increased tendon elasticity on the stability of soil nailed slopes. The alternative system of prestressing of soil nails to mobilise tensile capacity and thereby reduce soil strain is also being assessed. This operation would require a two phase grouting operation which may prove to be cost prohibitive.

SUMMARY
17. Soil nailing has been used extensively on a worldwide basis and has now been satisfactorily proven in
a number of slope and wall stabilisation works in the United Kingdom. When utilised for temporary support of steep excavated slopes the necessity for tight control of all phases of operations has been highlighted. In addition to soil nailing works reported in this paper, slopes have been stabilised using soil nails at a number of other locations in the U.K. New techniques involving the firing of soil nails are also being investigated but these clearly demand a different approach to corrosion protection systems and modes of load transfer. The soil nail parameters originally derived by Bruce and Jewell have provided a useful yardstick for assessment of stabilisation characteristics of both soil nailed slopes and nail stabilised walls. A number of options are available to provide varying modes and degrees of corrosion protection to steel tendons. The paper has provided guidelines to cost and efficiency of a number of systems available. The use of non-corrotable man-made fibres in the form of glass reinforced plastic or polymeric materials are currently in use in rock bolting, anchoring and soil reinforcement. Research and development is approaching a stage where their introduction into soil nailing should be carried out within the near future.

REFERENCES:
5. B.S. Code of Practice for Ground Anchorages BS8081