Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 833 9

Ballistic soil nailing

T.S. Ingold
Birmingham University, UK

B. Myles
Soil Nailing Limited, Cardiff, UK

ABSTRACT: Ballistic soil nails are fired directly into the ground using a compressed air launcher which can propel 38 mm diameter steel nails 6 m or more into the soil to be reinforced. Elements of design and construction of ballistically nailed works are considered and the versatility of the technique illustrated through four examples. The first relates to a steep cut to be retained by a reinforced soil modular block slope where temporary works construction gave rise to instability and the modular block slope was replaced by a ballistic nailed slope. The second details slope stabilisation works combining the use of bored piles, conventional reinforced soil walls and ballistic soil nailing. The third involves remedial works to a secondary road, supported by fill on sidelong ground, where the natural slope had been undercut by a stream at its toe. The final example recounts remedial work to a deep shaft, lined with concrete segments, which suffered a serviceability failure during construction.

1 INTRODUCTION

Ballistic soil nailing is well suited to reinforcing slopes formed in insitu soil, such as steep cut slopes formed in natural ground or fill, steep embankment slopes requiring strengthening or remedial works, and natural slopes requiring strengthening or remedial works. The same end objective can be achieved by use of reinforced fill but this requires the removal of soil, to make way for the reinforced mass, and thereby the additional cost, as well as the risks often associated with temporary works.

As the name implies, ballistic nails are fired from a compressed air launcher which propels the nail from its tip to which the force of the air pressure is transferred via a disposable plastic collet. Using this technique the nail is placed in tension in flight and this ensures that the nail does not buckle on impact. Once the nail enters the ground it is confined by the surrounding soil which maintains the straightness of the nail. The apparatus which fires the nail is known as an *air launcher* and this may be mounted on a wheeled or a tracked vehicle, as illustrated in Figure 1, with hydraulic attachments capable of precisely positioning the nail at the required inclination and location.

Figure 1 Track mounted launcher

2 STEEP CUT APPLICATION

A commercial development, started in 1994 and completed in 1995, required reduction of the existing ground level within the site boundary by up to 6.3 m. Since space within the site was at a premium, it was not economically viable for the cut slope to be formed as a conventional earthwork. Consequently it was planned to use of a reinforced soil modular block faced slope with a batter of $2\frac{1}{2}$:1, (68°). In the event, construction of the reinforced soil slope gave rise to stability problems and the modular block slope was replaced by a nailed slope.

2.1 *Soil parameters*

The site comprised an over-consolidated clay, with sand partings, overlying chalk at a depth of 4.5 m below the invert level of the cut. Effective stress design parameters were $c'=10$ kN/m², $\phi'=23°$ and $c'=5$ kN/m², $\phi'=35°$ for the clay and chalk respectively. The peak total stress shear strength for the clay was typically 100 kN/m² falling to around 30 kN/m² on remoulding. The phreatic surface in the natural slope was typically 2.5 m below ground level and on construction of the slope was drawn down one metre below the reduced site level at the toe of the slope.

2.2 *Analysis of modular block slope*

The required design life was 60 years and in addition to self weight loading the reinforced soil modular slope was required to support four 2.2 m square foundation pads for an electricity pylon. The pad nearest the slope was at a depth of approximately 2.5 m below original ground level and some 3 m back from the crest of the slope. Under normal conditions the vertical design load imposed by each pad was 200 kN combined with a horizontal load of 6 kN. For this loading condition the minimum required factor of safety on overall stability was 1.5. Analysis of the slope returned a minimum calculated factor of safety of 1.4 but this was not considered to be problematical since the required minimum value could have been readily obtained by lowering the ground water table slightly further. Under abnormal loading, once in 50 years, the vertical and horizontal loads increased to 570 and 19 kN respectively. For this case the minimum required factor of safety was relaxed to 1.3. This loading lead to a minimum calculated factor of safety of 1.1 which could not be improved by additional reinforcement or ground water lowering. In the event, others decided to found the modular block facing on a reinforced concrete ground beam supported by 750 mm diameter bored piles to obtain the required factors of safety.

2.3 *Modular block wall construction*

Reinforcement to the modular block facing extended up to 3 m back from the rear of the facing and to install the reinforcement required the formation of a temporary works slope a corresponding distance back from the final line of the face. Short term analysis indicates a minimum factor of safety in excess of 4 decreasing to less than unity in the long term, Figure 2. Intermediate term stability is difficult to predict in cohesive soils but, with the presence of frequent sand partings, it was probable that the long term condition would be attained in much a shorter time span than for a homogeneous clay. Shortly into construction, signs of failure were manifested and it seemed that the clay, over stressed by the temporary works, was reducing in shear strength from a peak to a residual value. Consequently a cantilever sheet pile wall was installed in the cut slope, to the rear of the reinforcement line, with a view to regaining stability in the area affected. In light of the instability associated with the temporary works it was decided, by others, that a permanent continuous sheet pile wall should be installed along the length of the modular block slope prior to slope construction.

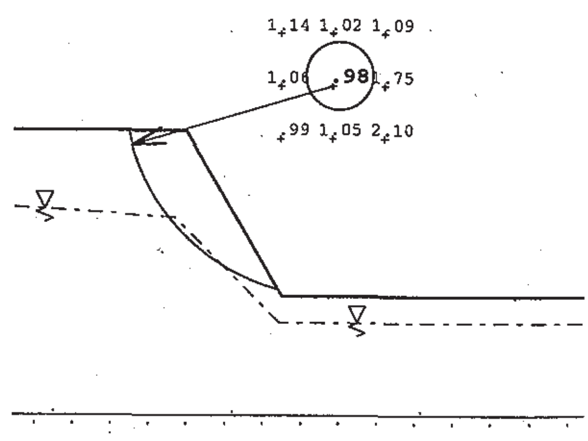

Figure 2 Stability of temporary works

2.4 *Analysis of nailed slope*

The installation of soil nails into natural ground is achieved from the face of the cut slope to be formed and nails may be installed from the top of the cut, downwards to the bottom of the cut, as construction proceeds. Consequently the cut slope may be permanently reinforced at all stages in the construction in which case no temporary works are necessary. In view of this, along with the resulting saving in time and cost, the client opted for soil nailed slopes rather than continuing with reinforced soil slopes.

The nailed slopes were designed at a batter of 1½:1, (56°), and at the design stage the 6.3 m high slope was assessed assuming use of 38 mm diameter steel nails with 5 nails, spaced evenly up the slope, at 1 m lateral spacings. Without the ground beam and bored pile foundation, as proposed for the modular block faced slope, the nailed slope returned only a minimum factor of safety of 1.18 under abnormal pylon loading.

However, rather than reverting to a piled foundation, it was decided to use mass concrete counterfort buttresses installed at the toe of the slope and extending downwards sufficiently into the clay foundation soil to raise factors of safety to the target values. A 1 m thick counterfort buttresses, installed to 2.7 m below the cut invert level, was calculated to raise the factors of safety to 1.51 for the normal pylon loading and 1.34 for the abnormal loading so attaining the target values, Figure 3.

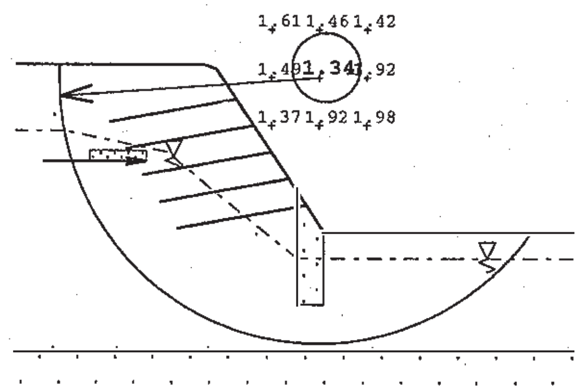

Figure 3. Stability of final nailed slope

2.5 *Construction of nailed slope*

Insitu pull out tests confirmed the magnitude of the ultimate pull out stress and that, using a launcher firing pressure of 17 MPa, the average achievable penetration was 3.2 m as opposed to the 5.0 m used in the preliminary design. Consequently the number of rows of nails was increased from 5 at 5 m long to 8 at an average length of 3.2 m. Analysis of this revised nail configuration returned minimum factors of safety of 1.51 and 1.29 for the normal and abnormal pylon loadings respectively. The slope was constructed by excavating and then nailing incrementally down the slope to the required invert level where the mass concrete counterfort buttresses were installed. Prior to installing the nails the currently exposed face of the slope was covered with a lightweight biaxially oriented geogrid, with a 20 mm square mesh size, and overlain by a 150 mm by 100 mm steel mesh. These meshes were secured to the face by cruciform locking plates, attached to the protruding nail heads by collets, and the excess lengths of nail heads cut flush with an angle grinder. Some 261 nails were installed at a rate of typically 5 minutes per nail. As can be seen from Figure 4, careful excavation and nailing produced a neat, planar slope ready for taking the final face finish which in this case was hydroseeding. For this particular project the soil nailing solution cost less than 50% of the originally proposed solution.

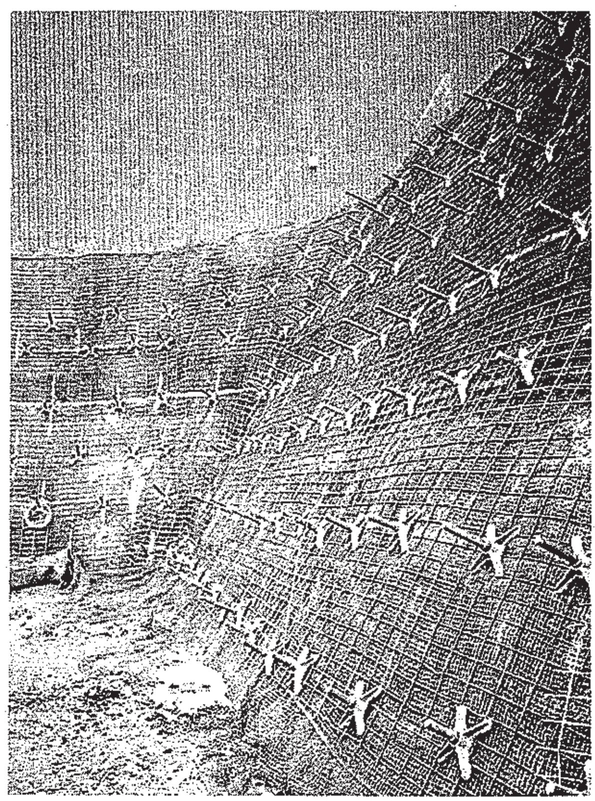

Figure 4 Nailed slope ready for hydroseeding

3 SLOPE STABILISATION APPLICATION

In 1994 a football stadium was constructed with part of the structure being built into a natural mudstone slope. This section of the structure was supported by contiguous bored piles and the temporary works associated with the piling required a high level bench to be cut into the slope to allow access for the piling rig. The bench, with a side slope inclined at 85° to the horizontal, was subsequently abandoned on the assumption it would remain stable. To create access to the stadium the toe of the natural slope was cut back to a nearly vertical slope, Figure 5. Both cut slopes, and the natural slope, were stable in the short term but had begun to weather and so required stabilisation to ensure long term stability.

The initially proposed stabilisation works involved the use of a gabion wall solution at high level and a reinforced concrete king post wall immediately in front of the lower slope. Using the king post wall would have entailed the installation of 37 bored king posts, at 2 m spacings, and horizontally spanning reinforced concrete planking to form the wall. To weight the toe of the natural slope, and so improve long term stability, it was planned to import a substantial quantity of granular fill to be placed behind the wall.

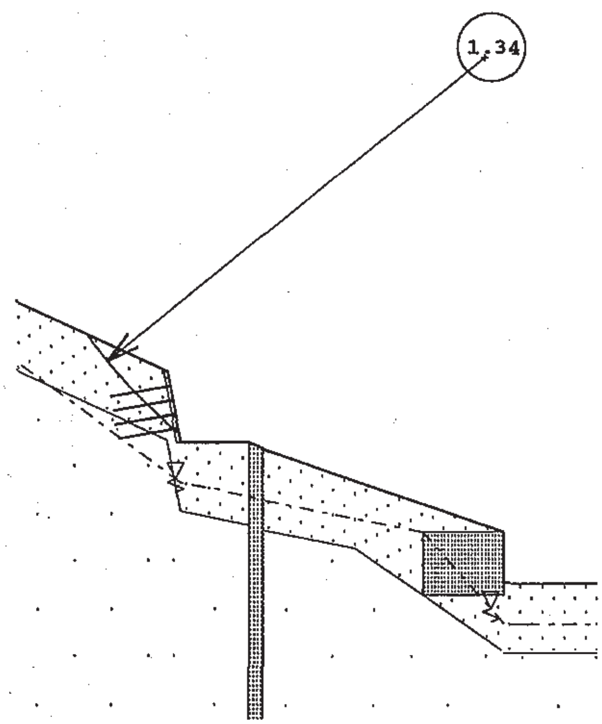

Figure 5 Typical slope cross section

3.1 *Reinforced soil alternative*

Study of the logistics of the initially proposed solution indicated this would not be viable due to the constraints on time and site access. The stadium was in use and therefore all works had to be phased around football fixtures so leaving a period of only nine weeks for both design and construction. Extensive block paving had been laid in the area of the lower works which would only support light construction plant. Access to the lower area was also limited by turnstiles with access to the upper area being limited by raking columns supporting the stadium roof.

It became apparent that a ballistic soil nailing solution, in combination with some reinforced fill, would overcome the vast majority of the construction difficulties and so a reinforced soil alternative was suggested. The overall height of the slope to be stabilised was some 15 m and it was proposed that the upper slope, with a bench slope height of typically 3.5 m, be formed as a 5:1 (79°) nailed slope with the lower slope, typically 2.5 m high, formed as a 4:1 (76°) reinforced fill or a soil nailed slope. The slope facings needed to be permanent and so it was suggested that a 200 mm square, 10 mm bar diameter, galvanised steel structural grid be used. To give an aesthetically pleasing finish, the facing was to be backfilled with clean rock, so giving the appearance of a gabion, and to prevent loss of finer rockfill the 200 mm grid was to be backed by a 50 mm square grid. Additionally it was proposed that the face of the mudstone slope be covered with a heavyweight nonwoven geotextile to serve as both filter and drain. This alternative was accepted based on a 43 day programme for design and construction.

3.2 *Design and construction*

The root cause of the stability problem was that the mudstone slope had weathered, to a depth of around 3.5 m, and was subject to a high ground water table issuing at the slope toe. Based on $c'=0$, $\phi'=33°$ and $c'=20$ kN/m², $\phi'=33°$ for the weathered and unweathered mudstone respectively, slope stability analyses were carried out using the Talren programme to determine the necessary distribution of soil reinforcement. The minimum required factor of safety was 1.3 and this was assessed for the upper slope, the lower slope and the slope overall. Based on 38 mm diameter steel nails,

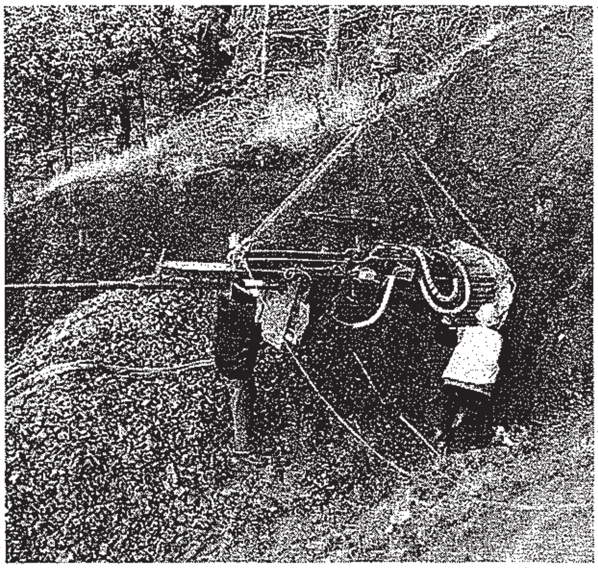

Figure 6 Air launcher slung from crane

both the upper and lower slopes required nail penetrations of 3 m with nails at one metre horizontal spacings and vertical spacing varying between 0.7 m and 1.0 m.

Nail installation commenced on the lower slope using the air launcher mounted on a tracked hydraulic excavator. Nails were supplied in 6 m lengths and on the nailed sections of the lower slope achieved a penetration of typically 4.5 m which exceeded the design requirement for a 3 m penetration. Progress was rapid with 108 nails being installed in 2½ days. It was not possible for the excavator to gain access to the upper slope berm and so the air launcher was suspended from a crane as shown in Figure 6. Even using this novel technique 72 nails were installed in just nine hours.

Once installed, the nail heads projected 1.5 m out of the slope face. This excess was cut back to 300 mm and a heavyweight needle punched geotextile was threaded over the nail heads to contact the face of the mudstone slope. Steel plates, 200 mm square, were welded to the nails, 200 mm out from the mudstone, with the 50 mm and 200 mm grids being slid over the 100 mm nail stubs to leave a 200 mm gap between the grids and mudstone face. Locking plates were used to fix the mesh to the nail and the gap behind the meshes filled with a 75 mm limestone. Finally the nail stubs were cut flush with the locking plates. Only 15 m of the lower slope was constructed in reinforced fill and this was completed in 3 days. Using this solution work was completed in 35 days with a large cost saving compared to the original proposal.

4 SLOPE REMEDIAL WORKS

Following heavy rainfall a secondary highway, constructed in sidelong ground, suffered a slope failure which extended back to the very edge of the road pavement construction. A survey of the site revealed that the road had been constructed on clay fill placed on a natural clay slope with a stream running along the toe of the slope. As a result of heavy rainfall the stream had become swollen and rapidly eroded the toe of the slope so causing slope instability. Both the footpath and crash barrier had been carried away by the slip leaving a rear scarp, approximately 1.5 m deep, immediately adjacent to the pavement construction. Cracks were appearing in the remaining pavement and it was feared that further slope movement might well remove the entire pavement construction.

4.1 *Design and construction*

This particular failure required the solution of two problems. The first was to urgently stabilise the edge of the pavement and the second was to stabilise the failed slope. Consequently it was decided to nail the upper section of the slope, to stabilise the edge of the pavement, but to take account of the effect of the nails in designing the final remedial works. The site survey indicated that the initial slip had removed practically all of the original clay fill and analyses showed that by replacing this with a granular fill, and regrading the slope, the combined effect, including the nails, was to return the required factor of safety, Figure 7.

Figure 7 Cross section of remedial works

Figure 8 Nails installed from pavement level

Construction involved the installation of four rows of 5 m long nails into the rear scarp of the slip to initially underpin the pavement, Figure 7. As shown in Figure 8, installation was achieved by mounting the launcher on a tracked excavator working from pavement level.

5 LINED SHAFT REMEDIAL WORKS

Early in 1996 the construction of a very large concrete lined underground storage shaft was in progress when a serviceability failure occurred. The shaft, 26 m in diameter and with a final depth of 18.5 m, was lined with precast concrete segments 2 m long, 1 m high and 0.5 m thick. Ground conditions were generally good and comprised stiff to very stiff clay with occasional pockets of sand and gravel. The ground water table was low, typically 9 m below ground level, which meant that approximately half the depth of the shaft would be below the ground water table. Construction involved excavating the shaft in 1 m increments without supporting the clay face. Following excavation, the precast concrete segments were placed with the void between the clay face and segments then being grouted. This process continued uneventfully until the shaft was excavated to a depth of some 12.5 m with the lowest one metre of the shaft unsupported in readiness to receive the liner segments. At this stage clay was observed to be extruding into the excavation over 20 % of the perimeter.

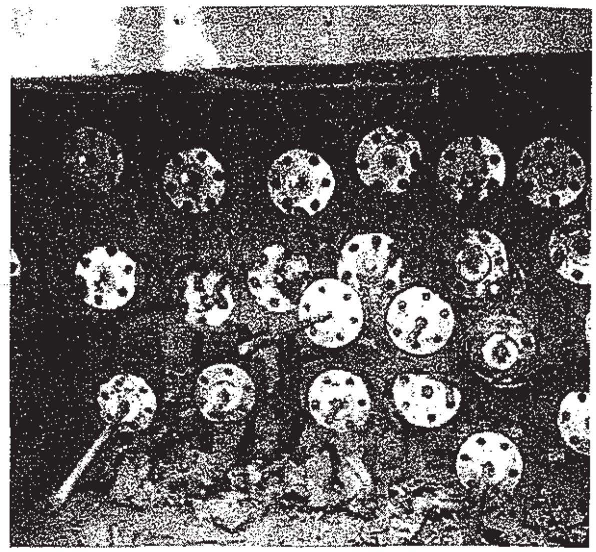

Figure 9 Nails installed in failed shaft face

As a result of the ongoing extrusion of the clay face into the excavation the liner segments above the extruded area began to move downwards, unevenly, and eventually deflected a maximum of 520 mm. Probing of the face revealed stiff clay beyond the soft clay causing the extrusion and so 6 m long soil nails were installed in the soft face at 300 mm centres, Figure 9. This controlled the extrusion and the shaft was then deepened, with further nailing, to allow a level ring of precast liner segments to be inserted below the upper sections of lining which had deformed. The resulting nonuniform gap, shown in Figure 10, was then filled with an insitu concrete liner.

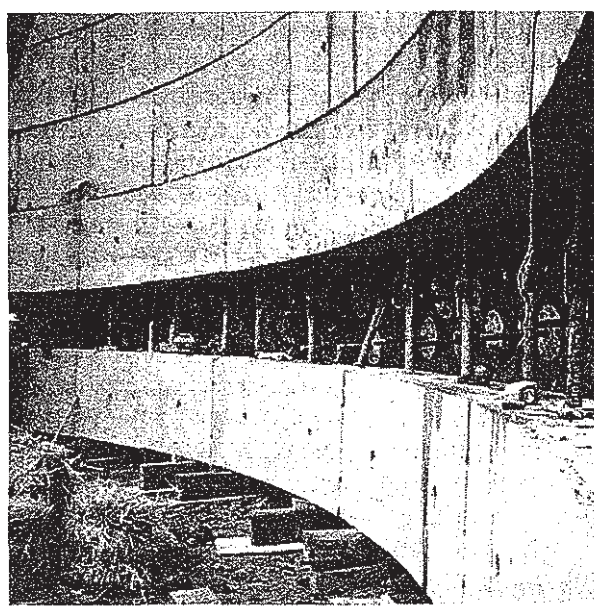

Figure 10 Face ready for insitu concrete lining