STABILIZATION OF SOIL EMBANKMENTS:

SOIL NAILING

National Rivers Authority

R&D Note 162

NRA

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Statement of Use
The report reviews the technique of soil reinforcement by fired soil nailing and considers its potential for improving the stability of river and sea defence embankments. It also considers its application for monitoring water and gasses within the ground. Application of the techniques should be considered by engineers involved in design of appropriate projects.

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EXECUTIVE SUMMARY

Soil nailing is a means of improving the stability of soil slopes by rigid rods, or 'nails', within a soil mass. The procedure has been used for over 20 years in continental Europe and is becoming increasingly common in other parts of the World but has not been used widely in Great Britain.

The established method of installing the nails is by drilling holes and grouting them in place. A variation of this has been developed by Soil Nailing Limited in conjunction with the University of Wales, College of Cardiff whereby the nails are placed by firing them into the ground from a compressed air gun. The main advantages of the fired soil nail lie in the speed and cost of installation. As the system requires less plant and support equipment than the drill and grout technique, the initial mobilization can be easier and provides a greater ability to accommodate any access restraints.

The fired soil nail has been used on only a limited number of occasions and is still undergoing some research and development both of the plant and equipment used and the design procedures necessary to support its use.

The mechanism by which soil nails function within the soil mass has been a matter of recent academic debate. A number of design procedures are available which are based on varying assumptions. Work by the University suggests that the general approach to soil reinforcement can be simplified. Although a number of design packages are available, the underlying disagreement about how soil nails operate means that any design techniques must be viewed as semi-empirical. At present, the design is best left to the specialist contractor against a performance statement provided by the Client.

To date, soil nails have been mainly used to provide stability to steep excavations. They have been rarely used in the stabilization of earth embankments, which forms the main application potential for the National Rivers Authority. Therefore only limited case histories exist on which the practicality of the application can be assessed. However, theoretical considerations suggest that the technique of soil nailing can improve the stability of earth embankments. The installation procedure of fired soil nails offered by Soil Nailing Limited has been demonstrated by them to be practical. Modifications to the form of the nail offer a number of potential benefits where environmental issues are a concern.

From the evidence available a potential exists for practical advantages and cost savings to be had with the use of fired soil nails over existing or alternative techniques to achieve the same end.

The likelihhod that the system of fired soil nailing becoming widely used in the near future in the United Kingdom is uncertain. Nonetheless, the National Rivers Authority should maintain its appraisal of the technique and an awareness of the potential in given situations.

KEYWORDS

Soil nailing, soil reinforcement, embankments, flood defences, slope stability, environmental engineering, contamination.

1. INTRODUCTION

The value of using inclusions to act as a reinforcement within a mass of soil to improve its overall properties and allow construction with material which would otherwise have not been possible was recognized in ancient times. Megalithic structures on the west coast of Ireland built about 4000 years BC successfully utilised the principle. For example, the Newgrange Cairn is a circular structure, about 82m in diameter, with vertical sides of about 4.2m. The walls retained rounded stones from local rivers, which were placed in layers separated by mats of grass turf. The mats reduced the forces acting on the walls and prevented their collapse (Kerisel 1992). Similar reinforcement was also used in the construction of the Mesopotamian ziggurats where mats of woven reed and cables of woven plant fibre were laid in beds of sand every few brick courses during construction. The reinforcement resisted the outward forces of the construction while the sand layers helped drain moisture from the newly made bricks to relieve excess pore pressure. Despite this legacy, the use of such reinforcement in soils in the design and construction of modern civil engineering structures is a relatively recent concept.

Soil nailing is a variant of soil reinforcement which itself forms one of a suite of techniques which define the geotechnical processes applicable to soils (Figure 1).

Many of the processes shown on the hierarchy in figure 1 are undergoing continual development and refinement. Developments in soil nailing include;

- the materials used,
- installation techniques and methods of construction,
- design methods and,
- application and use.

The technique incorporates the use of a grid of rods or nails within a soil mass which together act as a reinforcement. The idea was first devised in France in the 1970's and developed perhaps as an inevitable consequence of the Reinforced Earth method invented by Vidal in the 1960's although it was strongly influenced by existing tunnelling techniques and methods of rock slope support.

The principal application for soil nailing has been to provide temporary support to vertical and near vertical excavated slopes in soils and weak rocks. The nails are installed by drilling holes through the face and grouting rods in place at stages as excavation proceeds. Close monitoring of the performance of a number of successful structures has meant that soil nailing has become an accepted geotechnical construction process in continental Europe. In contrast, the technique has found less favour in Great Britain and so far has been used on relatively few occasions.

Independent research in Great Britain has devised the particular technique marketed by Soil Nailing Limited. This forms a major deviation from the systems available elsewhere in that the nails are fired into the ground by compressed air gun. The advantage of this is that installation is more rapid than by drilling and grouting and offers the possibility of causing less disturbance to the ground and surrounding area.

GEOTECHNICAL PROCESS

IMPROVEMENT

- Selection & Mixing
- Densification
  - Dynamic compaction
  - Vibrocompaction
- Grouting
  - Cementitious
  - Chemical

REINFORCEMENT

- Reinforced earth
  - Strips
  - Geogrids
- Soil Nailing
  - Drill and grout
  - Hammered
  - Fired
- Anchors
- Dowels
- Vibroreplacement (stone columns)
- Lime columns
- Reticulated pile

SUPPORT

- Anchors
- Retaining Structures

Figure 1 Principal Geotechnical Construction Processes Applicable to Soils

Soil Nailing Limited's company brochure is appended to this report. In addition, a marketing video, produced by them, is available as Project Record 342/4/A. These describe the system and demonstrate the installation technique, although continuing research has further developed the system from that described.

This research contract has been commissioned to investigate the application of the technique marketed by Soil Nailing Limited to the river and sea defence embankments of the National Rivers Authority. In the report the term 'soil nailing' is applied to all techniques where nails are installed in soils and this encompasses both 'fired soil nails' as marketed by Soil Nailing Limited and the 'drill and grouted soil nails' which are more widely available.

One of the main conclusions of the report is that a natural division will develop between the two sub-systems governed by their varying suitability to differing applications as well as the differing installation techniques used such that 'soil nailing' will become a generic term which associates a number of variants as shown in figure 1. The common elements in both systems has meant that it has not been possible to divorce the consideration of the fired soil nail from the more universal drill and grouted soil nail.

2. HISTORICAL REVIEW

Modern soil nailing was devised in the 1970's by a collaboration between the French contractors Bouygues and Soletanche. Summaries of the development of the technique are given by Bruce and Jewell (1986) and Gassler (1990).

The technique is based on the notion that rods placed within a soil mass will provide reinforcement to that mass. The concept is a refinement of the New Austrian Tunnelling Method (NATM) which had evolved in the 1950's and early 1960's as a hard rock tunnelling technique and developed into a means of providing temporary support during open face tunnelling through weak rocks.

NATM relies on a combination of sprayed concrete applied to the newly excavated tunnel walls and roof area together with rock bolts installed around the tunnel in a fan array. Together these produce a 'soft' support which deforms as stresses develop around the tunnel opening. Material is prevented from falling into the tunnel by the composite action of the concrete and rock bolts. This allows the maximum potential for a natural arch to develop in the ground around the tunnel.

The rock bolts bond the discrete blocks together to limit any large displacements. The concrete prevents surface ravelling and limits any deterioration of the material by weathering and reduces the likelihood of progressive failure. By monitoring the magnitude and rate of deformation around the tunnel opening it is possible to judge whether additional support needs to be installed. When the deformations have reduced to an acceptable level this indicates that the natural arching has fully developed and a lighter and more cost effective permanent support can be used than would otherwise have been the case.

The technique was found to work in progressively weaker and less competent materials and was eventually used in Germany in a number of tunnels driven in soils. At the same time dowels were being successfully used to provide support to rock slopes.

In 1972 Bouygues and Soletanche applied experience gained with the New Austrian Tunnelling Method to provide a temporary support to a 70^{o} slope cut into heavily cemented sands for a railway widening project near Versailles, France. Following the success of this project a number of others were completed. In 1974 Bouygues modified the installation technique and chose to drive the nails directly into the soil, rather than grout them into pre-drilled holes. This form of 'hammered nail' is a feature of the Bouygues system now known as 'Hurpinoise'.

A number of other French contractors, notably Bachy, Intrafor, Cofor, SEFI and Soletanche, have each developed proprietary systems based on the drill and grout technique. The contractor Solrenfor has also modified the installation to allow simultaneous driving and high pressure grouting.

Following the success of soil nailing for a variety of applications in France the government funded a number of research programmes to fully investigate the potential of the system. Work at CERMES, the research group at the Ecole National des Ponts et Chaussees, was carried out under the direction of Schlosser and Juran. A further research programme under the project title 'Clouterre' was commissioned by the government to establish a code of practice. This observed and instrumented a number of building sites and undertook three full scale experiments to investigate further the mode of failure of the nailed structure which were carried out at the Centre d'Etudes et de Recherches du Batiment et des Travaux Public (CEBTP) (Plumelle and Schlosser 1990).

During the 1970's developments in soil nailing were also taking place independently outside of France. For example, in 1975 in Germany the specialist contractor Karl Bauer AG in association with the Institut fur Bodenmechanik und Felsmechanik (IBF) of the University of Karlsruhe and the Federal Ministry of Research and Development completed eight instrumented field trials. At the same time the IBF undertook complementary theoretical research and model testing of soil nailing.

In North America the Transportation Research Board produced a report on soil nailing in the late 1980's (Mitchell & Villet 1987). More recently the United States Federal Highway Commission has undertaken research in order to prepare an Engineering Manual of Practice for Soil Nailing (Juran & Ellias 1990).

The first documented use of soil nailing in the United States was for the foundation excavation of the Good Samaritan Hospital in Portland, Oregon in 1976. The next major documented project was completed by Nicholson Construction for the foundation excavation for the PPG Industries headquarters in Pittsburgh (Bruce and Jewell 1986, 1987). This required a combination of soil nailing and pre-treatment by grouting of the soils near the face. More recently, Kirkgard (1992) describes the foundation excavation for new premises for Mercedes Benz in Hollywood. This was constructed to a depth of 6 to 11m in Recent alluvium comprising clay, sand, silty sand and clayey sand. The excavation was instrumented with inclinometers to monitor the behaviour of the system. The results indicate that although the excavation was successfully completed a shear plane had probably developed within the retained soil mass.

Soil nailing has also been used in New Zealand. The first application was in 1987 to construct a 12m excavation at Kitchener Park in Auckland through volcanic tuffs overlying residual clays and silts. Very high constraints on crest movement were imposed on the construction by the local authority to prevent any disturbance to services in the surrounding ground. The experience from the project concluded that the system would provide a more certain behaviour if used in conjunction with positive propping of the excavated wall through the use of pre-installed piles or pre-injected grout columns. It was also concluded that the excavation should be kept open for only a minimum of time before a permanent system is installed.

The use of soil nailing in Europe and North America has centred on the provision of temporary support for steep excavations in soils and weak rocks. However, in Hong Kong soil nailing has also become an acceptable method of improving the stability of new and existing slopes rather than being used primarily for temporary support (Powell and Watkins 1990).

The slopes in Hong Kong which have been treated have generally been formed by excavation into residual soils to form benches with back slopes of 60^{o} and slope heights of 15 to 30m. Detailed geotechnical assessments of the slopes usually show that they have only marginal stability against slope failure. Soil nailing has been used on a number of projects to improve the factor of safety of the slope. Prior to 1987 the preferred option had been to regrade the slope by cutting it back to a lower angle, or if space restrictions prevented this, then positive support from retaining walls or anchor systems were adopted. The increased use of soil nails is due mainly to the ease and speed with which they can be installed. Although the cost of installation is similar to that for regrading the slope, the reduction in associated land take means that the overall cost of the stabilizing scheme is reduced. So far most of the projects have been carried out by the Hong Kong government but there is an increasing use of the technique within the private sector.

Soil nailing has been used in Great Britain since 1985, although it has not seen the general acceptance that the technique enjoys in continental Europe. The main projects have been undertaken by Cementation Piling and Foundation Limited and Keller Colcrete Limited. These are listed in Table 1 which shows that the majority were carried out using the drill and grout technique.

The construction and methodology of soil nailing has developed in keeping with the range of application and scale of projects carried out. The original system relies on the installation of the nails at close centres grouted into pre-drilled holes, and this still forms the basic procedure used. Nonetheless, this has been modified and techniques developed which allow installation in differing soil types. Other modifications have improved the grouting procedures and in particular have been seen as a means to provide ways of improving the life expectancy of the nails.

One significant variation in the procedure is the 'Hurpinoise' system which has been developed by the French contractor Bouygues. This hammers the nails into the soil at very close centres.

The installation technique marketed by Soil Nailing Limited is a result of independent research in Great Britain and is fundamentally different to the drill and grout technique. The system fires the nails into the ground by compressed air guns. At present these are either 25 or 38mm in diameter and can be fired up to 6m in suitable soils.

The fired soil nail, the hammered soil nail and the original drill and grout methods of installation represent the major sub-systems of the soil nailing technique.

The design procedures appropriate to soil nailing are presently a matter of debate by the leading exponents of the techniques. This debate is centred around discussions on the mechanics of the composite soil/nail system. In particular, the way that the nail behaves within the stressed soil mass is crucial to the argument. Large scale tests based on purpose built shear boxes are currently in hand and it is expected that the results from these may rationalize some of the points of dispute.

A number of commercial computer design packages are available which are suited to either the specific or general case of soil reinforcement. Design can be carried out from first principles as discussed for example in Bridle (1989), Jewell (1990) and Jewell and Pedley (1990). The design techniques for soil nailing will also be described in the proposed British Standard on Reinforced Soil which is currently in draft form (BS 8009).

3. SOIL REINFORCEMENT

The purpose of soil reinforcement is to create a composite mass which can be considered as an homogeneous material which is more resistant and less deformable than the soil alone. The improvement can be achieved by a variety of procedures which come under the broad headings of:

- Reinforced earth
- soil nailing
- anchors
- dowels
- vibroreplacement
- lime columns, and
- reticulated piles

The reinforced mass is required to act as a traditional retaining wall which supports the unreinforced mass behind. However, unlike a traditional retaining wall the integral strength of the reinforced soil is of the same order as the stresses acting on it from self weight loading and it must therefore be designed to support itself as well as the retained mass (Figure 2).

Reticulated piles, stone columns produced by vibroreplacement techniques, lime columns and dowels are constructed in the near vertical and can be grouped together for the purposes of this report. Since they are near vertical and have some structural integrity they will carry load if surcharged. Although this will relieve the soil from the stresses induced by the surcharge, the members are usually too weak to act as traditional piles. It is the interaction between these and the surrounding soil which together produces an increase in bearing capacity and a reduction in deformability over that of the soil alone.

In contrast anchors and nails are more usually constructed horizontally or at a low angle to the horizontal. They therefore only carry loads which result from soil pressures. It is the ability of the reinforcement to accommodate the stresses induced by the soil which produces a consequential improvement in the strength and deformability of the reinforced soil mass.

The basic understanding of the mechanism of soil reinforcement stems from the developmental work on reinforced earth originally devised by Henri Vidal in 1965. This is a specific construction procedure which creates a composite soil system where tension resistant members are installed as strips, or more latterly a grid, in a placed soil mass. The resisting force which acts within the system to control the internal deformation and hence failure results from the tensile stress generated in the reinforcement. The resistance due to compression, shear and bending within the reinforcement is generally considered to be of minor additional effect.

Research has shown that the failure within the reinforced soil results either from breakage of the reinforcement itself or by loss of adherence along the reinforcement members. The design of reinforced soil structures therefore requires two separate considerations;

- to ensure the adequacy of the composite reinforced soil system against internal failure, and
- to ensure that the composite mass is designed as a conventional gravity retaining structure subject to earth forces from the retained soil.

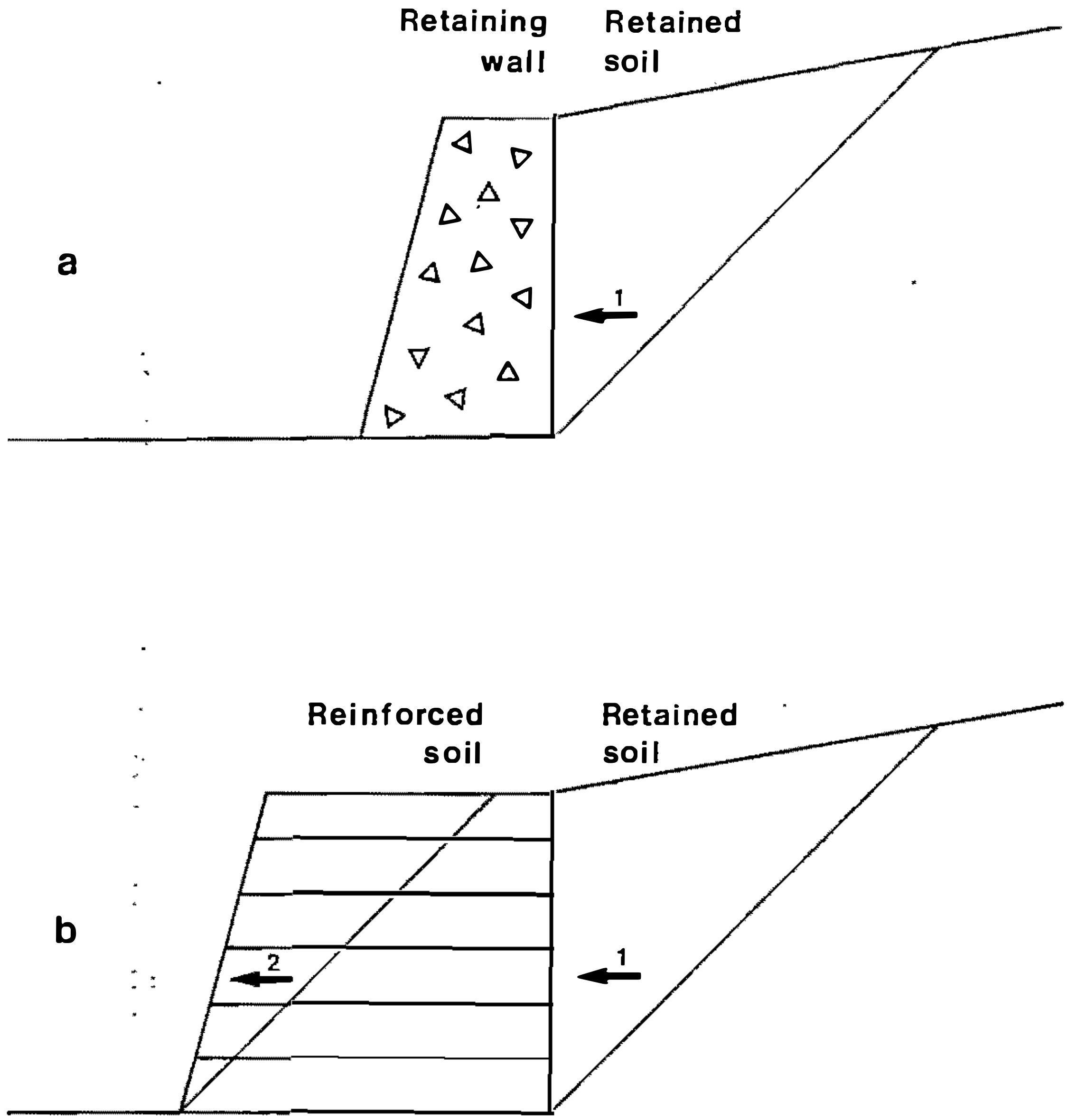

Figure 2 Design aspects for traditional retaining structures and reinforced soil structures

Traditional retaining structures such as mass concrete walls (a) need to be designed only against failure resulting from the stresses acting on them from the earth pressures (1) from the retained soil mass. Reinforced soil structures (b) need also to be designed against failure of the reinforced mass from the internal earth pressures (2) resulting from the self weight loading of the reinforced mass.

Reinforced earth structures are created by construction whereby the placed soil is reinforced with strips as construction proceeds. The particular use of soil nailing was developed for situations in which a soil slope was created as a result of excavation rather than construction. In this sense soil nailing is often described as a 'top down' procedure and reinforced earth as a 'bottom up' (Figure 3). The initial application for soil nailing also owes much to the experience gained in the New Austrian Tunnelling Method and rock slope stabilization with rock dowels. As the system was used on increasingly weaker materials the behaviour of the composite system was controlled by the soil mechanics rather than the rock mechanics aspect of the reinforced mass.

Within a soil mass the reinforcing effect from both strips and nails is basically similar, but with one notable difference. The nails are a rigid cylinder rather than a pliable strip. Consequently, in the case of the nails the resistance within the reinforcement due to compression, shear and bending has a potential to be of importance for both design and the behaviour of the system.

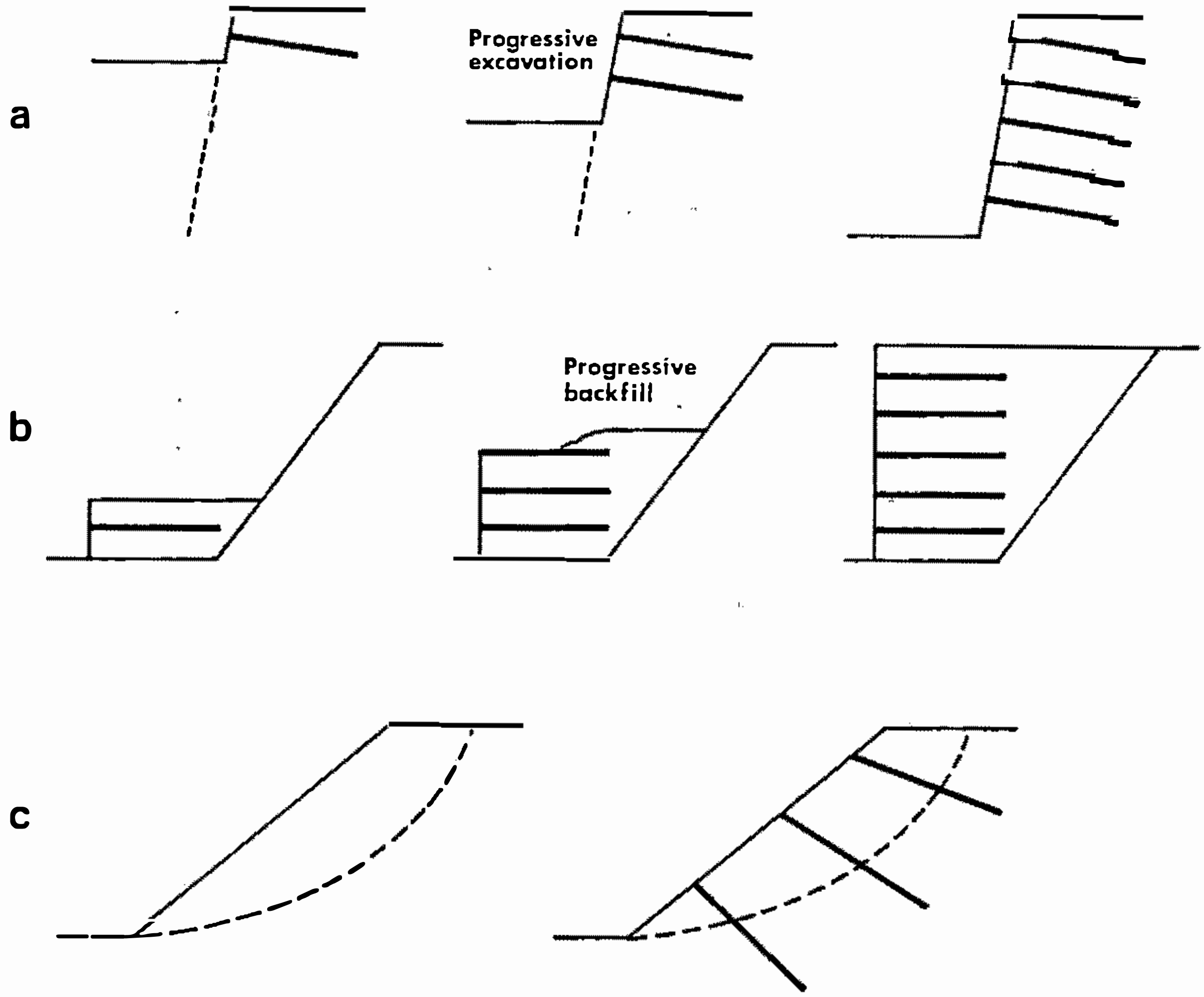

Figure 3 The use of soil reinforcement to enhance slope stability

Soil nailing provides for staged excavation of a slope from the top down (a) in contrast to reinforced earth which allows a slope to be constructed from the bottom up (b). Both can be used in temporary or permanent works design. The treatment of existing slopes by soil nailing (c) is a deviation from the established use of the technique.

4. SOIL/REINFORCEMENT INTERACTION

The principle of soil reinforcement is based on the notion that strips or rods placed within a soil mass will develop bonding or friction at the interface with the soil. This enables them to act in tension as a restraint to the total deformation within the soil. Installation across potential shear surfaces also allows them to act as keys to increase the shear strength of the soil mass.

Figure 4 shows the effect of a reinforcement on an element of soil subjected to vertical load. When unrestrained the soil may deform and eventually fail as load is applied to it. Where the conditions would otherwise cause deformation of the soil, the presence of a reinforcement will limit the amount of movement before the rod is either broken or the bond between it and the soil is exceeded. In contrast, where a discrete failure surface would otherwise develop in the soil it will only occur if the additional shear resistance in the bar is exceeded.

Where a soil mass is reinforced and deformation develops, stresses are built up in the reinforcement members which add to the resistance in the soil which is available to counter the disturbing forces which cause deformation and threaten failure.

The stresses which develop within the system are generally considered to be largely dependent on the attitude of the reinforcement member to the direction of deformation and can be resolved into those of tension, shear and bending. The satisfactory design of a reinforced soil structure is therefore based on the determination of the stresses and an assessment of a suitable reinforcement array which is able to accommodate the critical forces in the soil.

The detailed mechanics of the interaction which develops between the soil and a rigid reinforcement, such as a soil nail, and the relative importance of the separate forces which develop in differing circumstances is an area of continuing investigation and has fuelled considerable debate in the published literature (Barr et al 1991, Bridle 1989, Bridle & Barr 1990a and b, Jewell 1990, Jewell & Pedley 1990a and b, Pedley et al 1990).

Much of this discussion has been based on research projects undertaken at universities in the UK (Jacobs 1992, Pedley 1992). Now that both projects are complete it is anticipated that a rationalization and some agreement on the fundamentals will eventually be reached. This would establish the basic mechanics of the interaction so that rigorous design methods can be developed which can be used with confidence by the general practitioner. In the meantime, the existing techniques of design must be regarded as semi-empirical. Nonetheless, the broad principles of the interaction are understood so that the main factors involved can be appreciated. The refinement expected, once the rationalization is complete, will relate largely to the relative importance of these factors.

Laboratory tests on nail reinforcement within a soil mass subject to shear has shown that the stresses which develop during the interaction can be grouped into components of bearing and components of friction (Jewell 1990, Jacobs 1992). The bearing component includes the bending and shear stresses, and the friction component the axial stress which is either in tension or compression. These can be best appreciated by a consideration of a rigid reinforcement acting across a single rupture surface as shown in Figure 5. As displacement of the soil occurs the reinforcement will be subject to a build up of lateral stress.

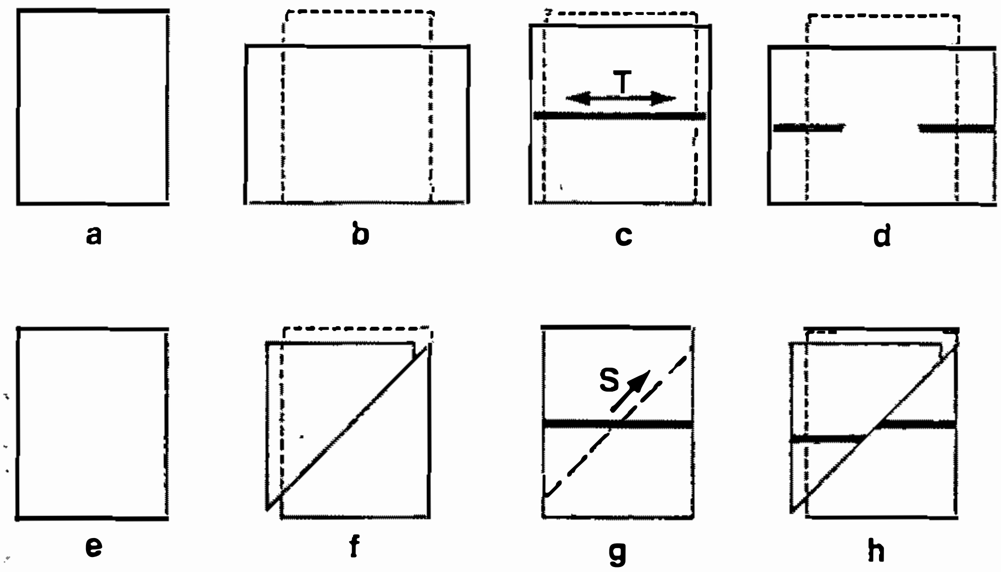

Figure 4 The effect of a reinforcement member in controlling soil deformation and shear failure.

i. Deformation
   a. Original soil element
   b. Deformation caused by a vertical surcharge load
   c. Restricted deformation resulting from a soil nail or other reinforcement member in the soil element. As deformation develops in the soil it pulls on the bar and develops tension (T) to counter the effect of the surcharge load
   d. When the surcharge load exceeds the tensile strength of the bar or the friction developed along the bar the reinforcement effect is lost and the deformation of the soil approaches that of the unreinforced soil element

ii. Shear failure
   e. Original soil element
   f. Shear failure caused by a vertical surcharge load
   g. Controlled failure resulting from a soil nail or other reinforcing member in the soil element. As shear develops in the soil displacement needs to overcome the shear resistance (S) of the bar which acts to counter the surcharge load
   h When the surcharge load exceeds the shear resistance of the bar the reinforcement effect is lost and the displacement approaches that of the unreinforced soil.

The response of the reinforcement is generally accepted to be analogous to the behaviour of a laterally loaded pile which is mirrored across the rupture surface so that the load applied to the reinforcement in one half of the soil is derived from the displacement of the other half. If the reinforcement is rigid and there is insufficient bearing capacity in the soil the stress build up will cause failure and allow the reinforcement to rotate through the soil.

If sufficient bearing capacity is present much of the movement of the reinforcement will be prevented. In this situation shear stress will increase in the reinforcement and, as it must deform across the rupture surface to maintain its integrity, an associated bending moment will also develop (Figure 6).

It is not possible to separate completely the two components of friction and bearing. Further consideration of Figure 5 shows that as the reinforcement is caused to rotate, if the friction along its length is insufficient to hold it within the soil, it will be pulled from the soil. Equally, where the friction is sufficient to hold the reinforcement in place an axial stress will develop within it which will result in tension or compression depending on the attitude of the bar relative to the sense of movement across the rupture surface.

If the reinforcement is fixed, by virtue of the friction and bearing which is available in the soil, the displacement across the rupture surface must manifest itself as a deformation in the bar over some central section as shown in Figure 6. This central section is defined by the points of the points of maximum bending moment which laboratory testing has confirmed coincides with the two points of maximum curvature in the deformed bar (Jacobs 1992). Beyond this the principal purpose of the reinforcement is to have adequate penetration into the soil to provide sufficient resistance against pullout or bearing capacity failure, that is to ensure that the reinforcement member is fixed in the soil element and does not rotate as in Figure 5.

When a compact soil is subject to shear it also undergoes a slight but measurable vertical displacement due to dilatency of the soil structure. This effect occurs because the individual soil grains need to ride over each other as shear develops. In doing so it causes the soil to be subject to a vertical component of movement at angle 'a' to the horizontal as shown in Figure 7a. The shear displacement therefore results in both vertical and horizontal components of movement (Figure 7b). As the contained reinforcement will be subject to the same movement the axial and shear displacement in the reinforcement can be resolved as shown in Figure 7c.

When the reinforcement is inclined across the shear plane as shown in Figure 7d Jewell (1990) proposes that the shear displacement should be measured normal to the long axis of the reinforcement. Comparison of Figures 7c and 7d shows that for a similar lateral displacement, when the reinforcement is offset to the shear surface the shear displacement is reduced and the axial load is increased. This suggests that as the inclination of the reinforcement becomes flatter to the shear surface the role of shear is reduced and the role of tension is increased. This has been confirmed by the laboratory testing.

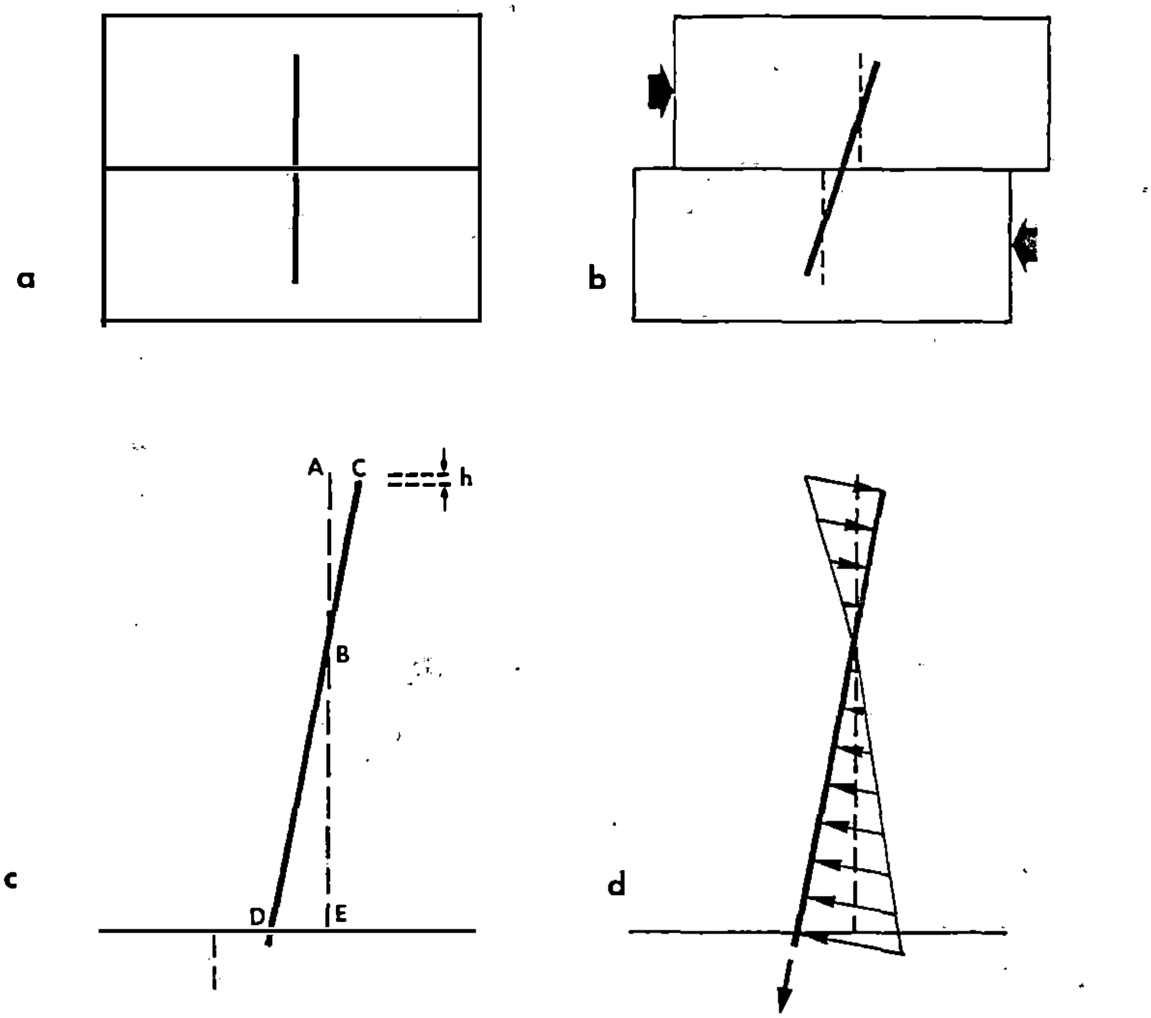

Figure 5 Response of a rigid reinforcement member subject to lateral load by a soil element undergoing shear displacement in plane strain

a. Before displacement
b. After displacement
c. Detail of one half of the soil mass shows that the displacement requires the reinforcement to cause a bearing capacity failure through the soil in the zones ABC and DBE. Similarly, consequential axial load experienced by the reinforcement causes it to pull out from the soil or develop tension depending on the frictional resistance available along its length. This is demonstrated by the change in relative elevation, h, of fixed point X on the reinforcement within the soil mass. In order for there to be no change in elevation the reinforcement would need to have been extended and developed tension.
d. The idealized distribution of lateral stress along the reinforcement and the axial load which develops during displacement of the soil.

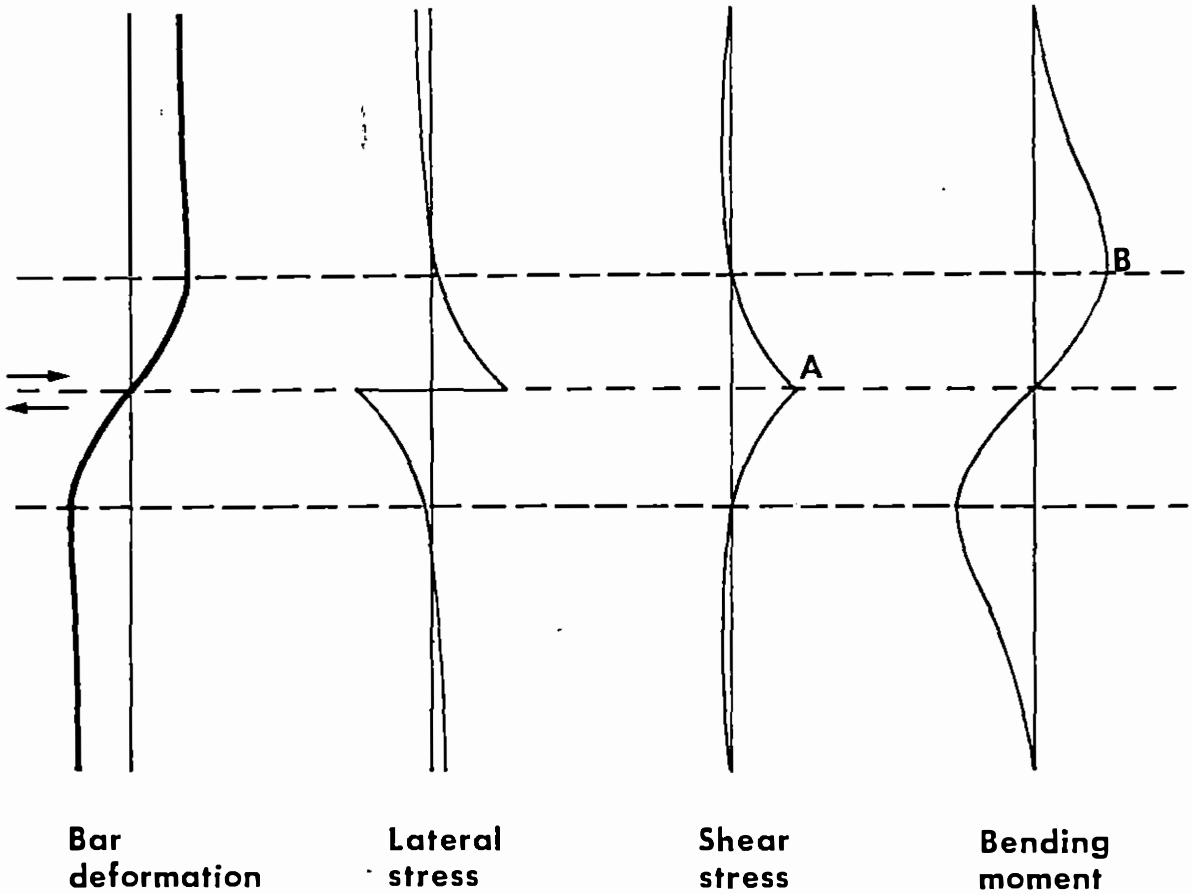

Figure 6 Response of a rigid reinforcement member subject to lateral load by a soil element undergoing shear displacement in plane strain where the reinforcement has sufficient length to prevent turning

The bar deforms into an approximate 'S' shape in response to the lateral stress build up which concentrates at the shear plane. Shear stress development in the bar is at a maximum at the shear plane (point A) and the bending moment is a maximum at the point of maximum curvature of the bar (point B).

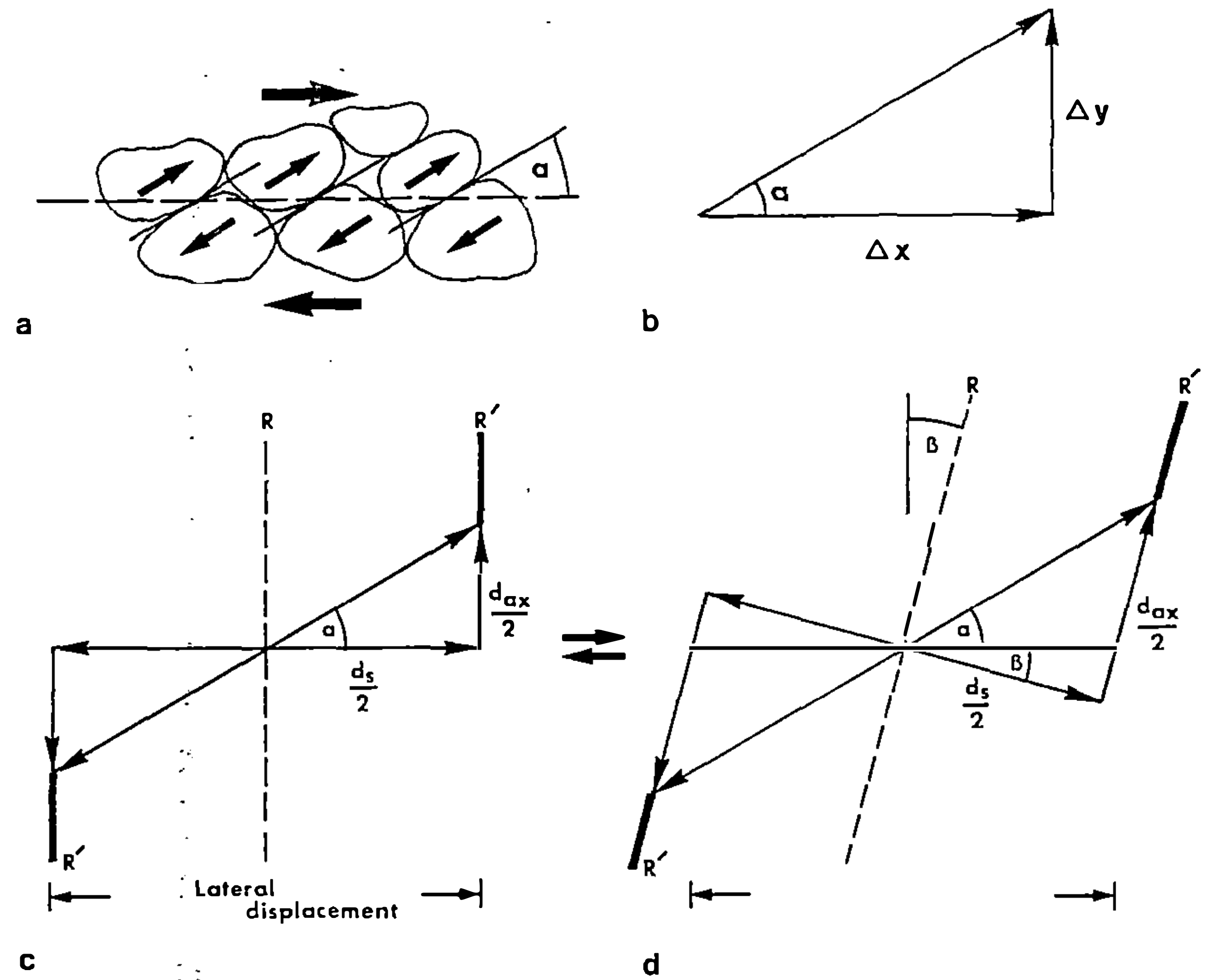

Figure 7 Effect of dilatency on soil and reinforcement displacement during shear

a. Dilatency develops as soil particles ride over each other in order for the strain to develop along the shear surface.
b. Dilatency can be resolved into a vertical component Δy and a horizontal component Δx with a resultant at angle 'a' to the plane of shear.
c. Strain on the reinforcement from the soil in shear can resolved such that an axial, d_{ax} and a shear d_s displacement is represented as the reinforcement is moved from the original position R to new position R'.
d. The axial and shear displacement varies as the reinforcement is inclined at an angle to the normal to the shear plane, B

The relative importance of the components of induced stress result from;

- the attitude of the reinforcement to the direction of shear,
- the engineering properties of the soil,
- the engineering properties of the reinforcement,
- the relative properties of the soil and reinforcement and,
- the geometry of the reinforcement.

From the foregoing, a number of general principles can be identified which underlie the interaction between soil and a contained reinforcement.

Principle 1: Where a discrete failure surface is present in a soil mass and stresses are acting in plane strain, the presence of a reinforcement nail or strip across that surface can not cause additional normal load to that of the self weight of the soil unless tension is applied to the member.

Principle 2: Any additional shear resistance under plane strain due to the presence of an untensioned reinforcement member results from bending and shear resistance which develops in the member and which must be overcome to allow the deformation.

Principle 3: As plane strain develops, tension will develop in the member where it crosses the failure surface. This will add to the resistance of shear and bending and may be resolved to apply an increased normal force across the shear surface.

Principle 4: The ability for the resistance, which is developed in the reinforcement member, to be transmitted usefully to the soil mass depends on the engineering characteristics of the soil and its capacity to support the induced load from the reinforcement.

If shear and bending is to be developed as a measurable factor within the action of the reinforcement, then the member must be rigid. In addition to the conceptual differences in the method of construction, it is this which differentiates reinforced earth from soil nailing. As a consequence of the method of installation soil nails are required to be stiff. They can therefore sustain a greater element of shear and bending than can the pliable strips and geogrids used in reinforced earth.

Principle 3 states that tension will develop in the reinforcement as strain occurs within the reinforced system. This is governed by the relative moduli of the reinforcement and the soil. The soil has a very much lower modulus than the reinforcement therefore as strain develops and stress is applied between the two the soil will pull on the reinforcement and develop friction load between the two and consequential axial load in the reinforcement. If the reinforcement is angled to the failure surface and inclined in the direction of the sense of movement the postulated tensile stresses will develop within it. Conversely, if the reinforcement is angled against the direction of movement the deformation will cause compression in the member. If the member is rigid the resulting effect will be to apply support to the soil mass and thereby reduce the normal stress across the shear surface and cause a reduction the shear stress acting on the shear surface.

The tension which develops within the reinforcement member is a result of the stress developed along the reinforcement between it and the soil. This adhesion is governed by the friction between the two and any cohesion present. The extent to which this is mobilized is a result of the strain within the system while the friction and any cohesion is dependent on the soil, its condition and the particular installation or construction technique.

In compact granular soils deformation causes a dilatency in the soil fabric. This results in an apparent increase in the internal friction angle of the material as the individual grains are required to ride over each other. This causes the friction component to increase between the member and soil and the adhesion so generated. The situation is sensitive to a number of factors. In particular, the relative density and grading of the soil affects the amount of dilatency which it is able to develop. It is also affected by the stress condition in the soil. Although there is a reduction in the dilatency effect in a soil as overburden stress increases, this is compensated for by the associated increased normal stress. In simple terms these two factors can be taken to cancel each other out within the system.

Adhesion is also affected by the installation technique and the material and surface characteristics of the reinforcement member. If the adhesion is high as a result of the installation technique the failure may develop within the soil at some distance from the soil/reinforcement interface. The consequence is that the effective diameter of the reinforcement member is increased to the advantage of the system.

Although the interaction between soil and reinforcement is governed by the material properties of each component and the stresses induced within the system, additional practical limitations relate to the long term behaviour of the system. For example, the long term effectiveness of the design must also take into account the durability of reinforcement. Corrosion of the nail will weaken it so that design of the system must also take into account its ability to retain the tension mobilized within the nail. This may also be lost if the frictional resistance between the nail and the soil is also reduced by the corrosion. However, Soil Nailing Limited believe that the use of galvanised mild steel nails eliminates this concern since the coefficient of friction of the corroded zone is always greater than the surrounding soil.

5. SOIL NAILING SYSTEMS

5.1 Development

Soil nailing has developed within the last 20 years for the stabilization of steep excavated slopes in soil. Its construction procedures owe much to the developments in tunnelling for the New Austrian Tunnelling Method while the mechanism by which the system works has more similarity to the reinforced earth technique of soil reinforcement.

The reinforced earth technique relies on the reinforcement being added between layers of placed soil as construction proceeds and the reinforced mass is raised progressively. In contrast, soil nailing provides a means of installing the reinforcement in a slope formed by excavation, hence the notion of the one being a 'bottom up' and the other being a 'top down' construction procedure.

5.2 Drilled and Grouted Soil Nails

The original system of soil nailing installs the nails by drilling a hole and grouting the nail in place. It requires progressive excavation of the slope face in steps of perhaps 1 to 2m. The depth of stepped excavation is controlled simply by the short term stability of the excavated material and the response of the soil mass behind. The face of each excavated step is then stabilized by an application of shotcrete, which is a dry mixture of sand and gravel fired at the face under pressure with water being added at the nozzle to produce a layer of concrete typically 100mm to 120 mm thick. This is in intimate contact with the face of the excavation and prevents surface ravelling and deterioration of the soil.

The nails are steel bars typically of the order to 20 to 28mm in diameter which are fully grouted into predrilled holes at a spacings of about 0.7 to 1m. However, the diameter of the grouted section forms the true diameter of the nail and this is more regularly in the order of 100mm, although grout sections as small as 45mm are common in the USA and Japan. The effective diameter is also increased where the grout permeates the surrounding soils.

The nail length is a subject of design for any given situation but is typically 0.5 to 0.7 times the height of the excavated slope, although nails up to 24m in length have been used in certain circumstances.

The hole into which the nail is installed can be formed by a variety of techniques. The choice is largely governed by the ability of the soil to remain open. The following methods may be adopted each of which can be used with or without casing to support the hole formed:

- Rotary boring to displace the soil,
- Rotary or rotary percussive with air flush,
- Dry auger boring.

The nails are designed to act in tension and are installed across an actual or potential failure surface in the soil mass. The technique was originally intended only to provide a temporary support to the slopes, but an increasing confidence which has developed in the ability of the system, together with the use of visually acceptable finishes, has meant that the technique is now also used in permanent excavations.

5.3 Hammered Soil Nails

The Hurpinoise system hammers the nails without grouting and are typically installed to depths of 6m. The displacement induced in the surrounding soil develops high friction loads and it is therefore most suited to dense granular soils. The nails are often formed from angle iron which increases the surface area of the nail in contact with the soil and are installed at closer centres than the drill and grout system. As it is not possible to provide any protection to the nail they are only suited to temporary support situations.

Hammered soil nails have been used in UK by Thyssen Geotechnical Limited at Llanbardach in Wales to provide temporary stability to the exposed slope during the replacement of a masonry retaining wall.

5.4 Fired Soil Nails

A recent development of the soil nailing technique in the United Kingdom has resulted in the method of installation of the nails by compressed air gun. The system is marketed by Soil Nailing Limited, a wholly owned subsidiary of Ryan International Limited and was jointly developed by the University of Wales, College of Cardiff and Soil Nailing Limited. The technique is undergoing continuing development both of the launch system and the understanding of the mechanics of the reinforced system. The hardware development has been through site trials and the theoretical work has been based on research carried out at the School of Engineering, the University of Wales, College of Cardiff into the behaviour of nails in a large shear box which was part funded by Soil Nailing Limited.

The fired soil nails comprise either 25 or 38mm diameter bright bar steel rods to former British Standard BS:971 in either 3, 4.5 or 6m lengths which can be fired to varying depths into the ground.

The nails are fired by a compressed air gun as described by Myles and Bridle (1991a, 1991b). The gun consists of a breach, breach interlock, release valve and a noise and debris shroud as shown in Figure 8. The action of the gun is relatively simple. A compressor maintains a reservoir of compressed air which is supplied to the gun at anything up to 2600 psi. Release of this into the breach causes the nail to be fired at 200 miles per hour. The nail is held at the tip in the breach by a plastic collet. The compressed air acts on this collet so that the nail is fired from the tip. The momentum of the nail is therefore concentrated at the tip and places the nail in tension. This keeps it straight during flight although this is maintained once in the ground by the support of the surrounding soil.

As the nail enters the ground a bearing capacity failure is developed which causes the soil to displace and create an annulus slightly larger than the diameter of the rod. Extraction of nails after firing has shown that the installation causes no abrasion along the length of the rod. This may be due to the compression of the soil following the bearing capacity failure at the tip. It is also possible that the loading induced by the nail as it enters the soil causes an increase in the pore pressure immediately around the tip. This would cause a consequential reduction in the effective stress and therefore the resistance of the soil to the penetration of the nail. Once it has entered the ground the resistance from the ground returns, either as the displaced annulus closes back or the excess pore pressures are dissipated. It is possible that tension induced by the firing procedure is retained in the nail. However, this premise and the behaviour of the nail and the soil

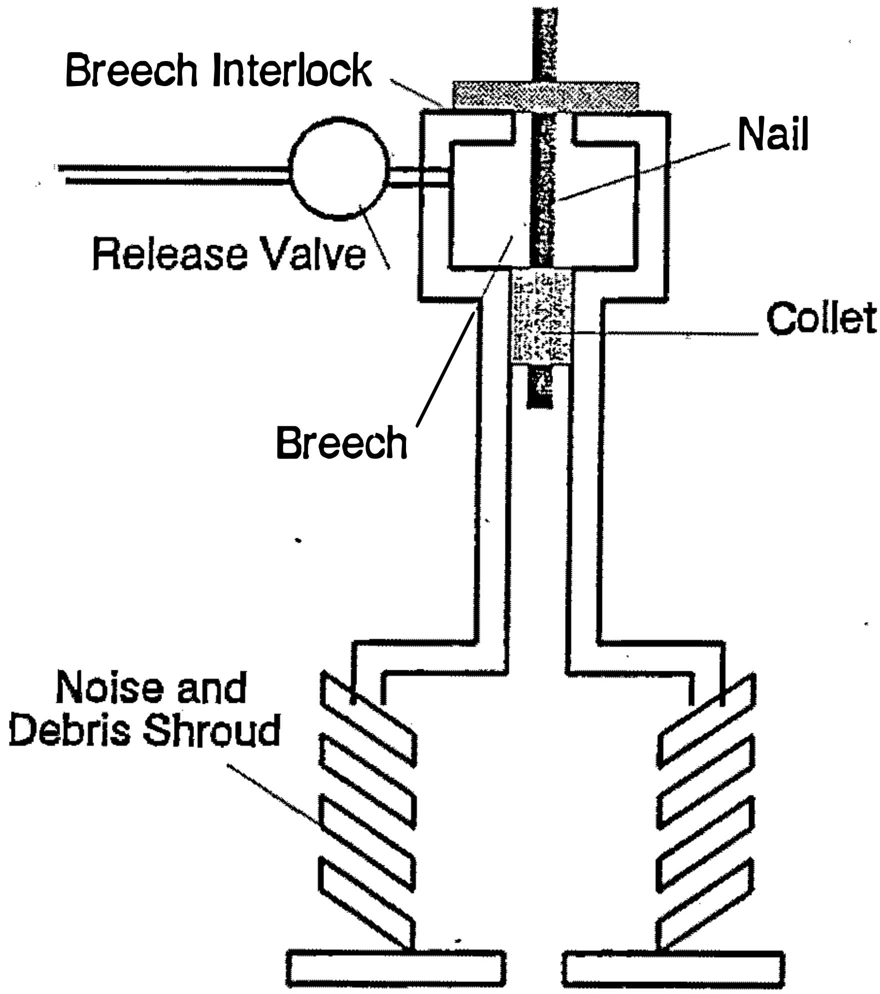

Figure 8 **Schematic diagram of the fired soil nail launcher**

during and following the launch has not undergone any research and is a matter of speculation.

The compressed air gun is fitted to a long reach boom and swivel head mounted on a suitable tracked vehicle. At present Soil Nailing Limited use the Case 668 tracked vehicles which have the advantage of a load sensing hydraulic system as standard, but other suitable plant can be used. The standard boom is modified to increase the reach to 9m on the Case 668 (Fig 9) with a projected reach capacity of 11m on the larger Case 888. The swivel head attached to the boom is controlled by the hydraulics of the vehicle and enables the gun to be placed precisely and positioned at any angle from the horizontal to the vertical at any attitude of the boom.

The actual launching sequence is controlled by microprocessor with keyword security which ensures safe and correct usage. A marketing video by Soil Nailing Limited annexed to the report in project record 342/4/A gives a good representation of the installation procedure.

5.5 Design Principles

The basic principle behind the design of a soil nail system is similar to that used for any soil reinforcement. It assumes that the reinforcement is required to provide additional resistance along a slip surface that is either present or would otherwise develop in the unreinforced soil. The nails are able to act in shear and in tension as the nail deforms into an 'S' shape as movement in the soil takes place. The design procedures do not take into account behaviour of the combined system, rather they take the view that the nails add to the existing soil situation.

The design of a soil nail system requires an assessment of the position of the natural slip surface. From this the out of balance forces can be determined which gives the load to be supported by the nails to provide a required factor of safety. As the geometry of the failure mass is known the pattern of nails can be designed so that each individual nail carries a similar or appropriate load to its size or the soil conditions.

A computer program called CRESOL has been developed by one of the inventors of the system (Bridle 1992) which utilises the results obtained from the research programme at the University of Wales, Cardiff College. This offers a procedure to allow the design of a soil nailed solution. It is not intended to be specific to fired soil nails and should therefore be applicable to any of the variants of the system.

At present, the rigor of the design principle adopted by the program is subject to the resolution of the theoretical discussions of the mechanics of the behaviour of the nail and the combined soil/reinforcement system. Initial assessments of various design techniques have been carried out at the University of Wales, Cardiff College. This suggests that CRESOL offers the best comparison with the experimental results. However, there is some circularity in this conclusion since CRESOL uses the experimental conclusions of the University in the development of its design approach.

CRESOL has not yet been used for the design of a real construction and consequently has not been tested in the field. However, its validity would only be proven if field trials were conducted which included a fully monitored structure. It seems therefore that for the time being that while the precise interaction between nail and soil is a matter of debate, any design procedures must be viewed as semi-empirical.

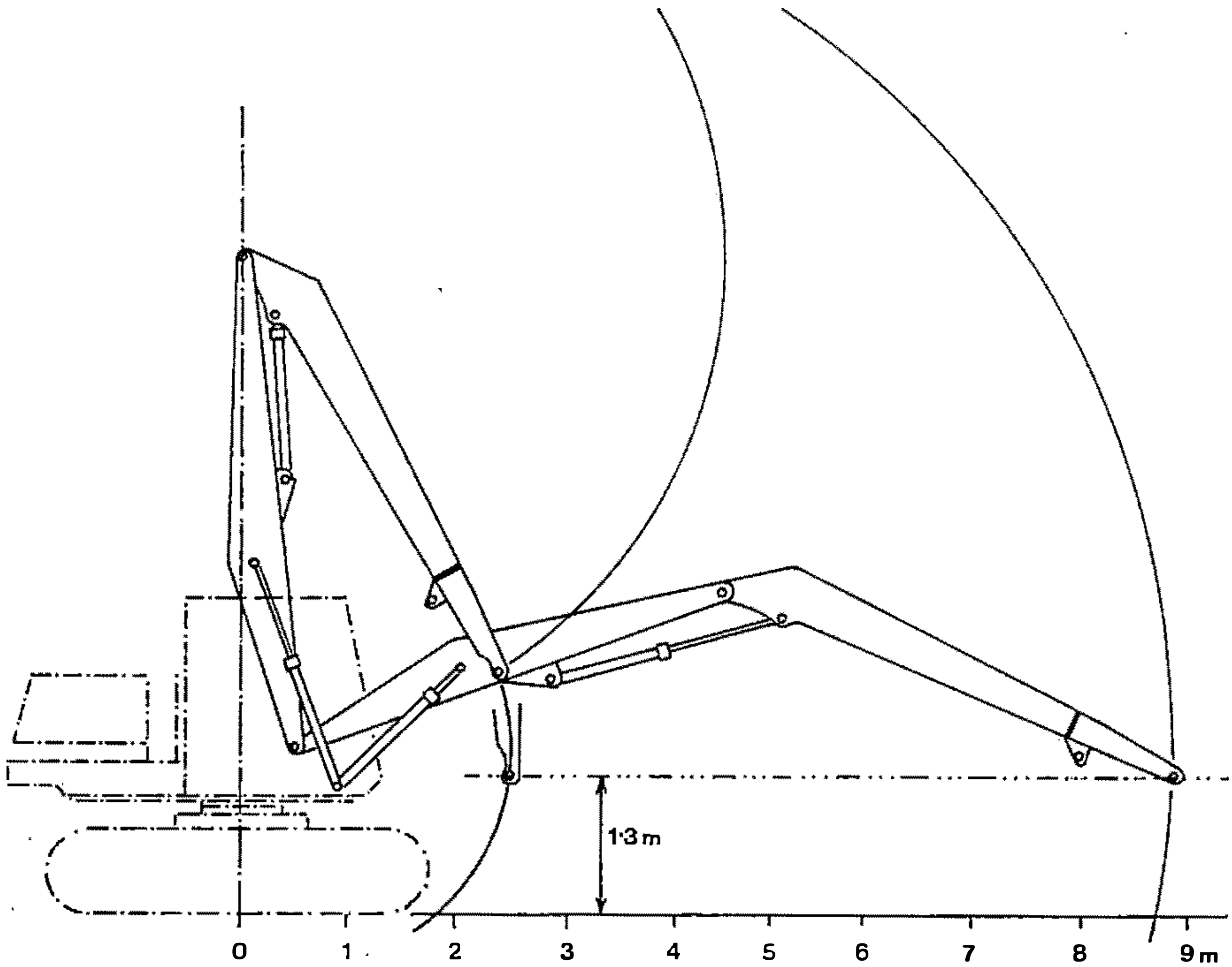

Figure 9 Boom arrangement for the Case 688 tracked excavator developed to carry and launch the fired soil nail

The principal uncertainty in the debate relates to whether the nails act as tension members, and have a behaviour which is associated with anchors, or whether they act purely in shear and should therefore be treated as dowels. One suggestion is that fired soil nails should be more appropriately described as 'fired dowels'. This may be the case if tension is not maintained in the nail after firing. The likelihood is that both arguments have an element of truth within them and that under differing conditions, for differing soils or for differing installation techniques they may act as either one or other, or a composite of the two.

It is necessary for there to be some displacement within the soil in order to mobilize stresses which would put the nails into tension or shear. Indeed, it is necessary for some displacement to develop in order for the nails to operate; without the displacement there would be no benefit from the presence of the nails. Apart from the work at the University of Wales, Cardiff College the existing design procedures are based on the action of tension forces being developed in the reinforcement and in this sense have close similarities to the techniques developed for reinforced earth. In the traditional soil nailed excavation where vertical or near vertical slopes are required, the design is checked by monitoring the field condition by measurement of the displacements of the retained mass.

In the absence of established design procedures it is useful to be able to use case histories as a precedent for the use of the system. The main use of soil nails has been for temporary support of steep slopes formed by excavations in soil. The design and subsequent monitoring procedures have been largely concerned with the displacement of the facing of the structure and the settlement at the top as staged construction occurs. The reinforcement is necessary in these circumstances to limit the stress relief of the ground.

Much of the work on design methods for the soil nailed systems and reinforced soil masses in general relates to granular materials. The behaviour of such materials is very well documented and they have the advantage that few factors will affect their condition during the design life of the structure. In contrast, many of the embankments under the control of the National Rivers Authority are constructed from heterogeneous materials, which often comprise a variety of clays and silts. Unlike the cohesionless behaviour of granular soils, these have a greater component of cohesion, both in the drained and undrained state. In addition the on-going condition of the material is very sensitive to a wider range of outside factors;

1. The frictional resistance of both granular and cohesive soils will be reduced if groundwater develops within the reinforced soil mass.

2. In cohesive soils the presence of water will also affect the volume of the material. Such materials are plastic and will shrink or swell in response to changes in their natural moisture content.

3. Swell pressures can develop on reinforcing members, but equally they may loose adhesion if the soils shrink away.

4. Once shrinkage cracks develop in the soil mass it is possible that the groundwater conditions may be very uneven.

5. Rapid and possibly local filling of these tension cracks by water will also develop local groundwater pressures. These may be hydrostatic over the depth of the crack, but local in extent due to the distribution of the cracking.

6. The bulk density of the soils will vary by the presence of water in the capillary zone. Since friction is directly proportional to the normal loading resulting from the weight of soil above, the loss of density will also reduce the friction component in the system.

7. Cohesive soils are more susceptible to burrowing animals than granular soils. The presence of a network of burrows would affect the idealized stresses within the soil mass.

5.6 Design Method

Design procedures appropriate to soil nailing are based on the need to balance the forces acting in opposition across a given failure surface. That is to ensure that the restoring forces is greater than the disturbing force in order to provide a suitable factor of safety against the out of balance condition. The basic principles are discussed in the British Standard Code of Practice on Reinforced Soil (BS8009) and are used in a number of commercially available computer design programs.

The failure surface is generally assumed to take the form of a log spiral. This is a curve which reduces its curvature as the angle that the radius makes with the horizontal increases. The movement on such a surface is kinematically admissible and ensures that the disturbed zone is able to slide in the rotational mode. In essence, a particle on the slip surface must move away from the slip surface and not into the resisting zones as it would do if the curvature of the slip surface grew sharper. The form of the slip surface is controlled by the properties of the soil mass and the exit and entrant angles of the slip surface at toe and crest and the angle of the slope face. The curvature reduces because the normal to the slip surface is constantly at the angle of friction to the radius. On this basis if the soil has a zero angle of friction the slip surface would take a classic circular form. The determination of typical form of the log spiral slip surface is discussed in Bridle (1989).

Once a critical slip surface has been identified the out of balance forces can be determined using conventional slope stability equations based on the method of slices. Failure will occur when the disturbing forces exceed the restoring forces. The design assumes that failure can be prevented by locating the reinforcement across the failure surface to increase the restoring force.

The disturbed zone for which the steel requirement is greatest is not necessarily the zone for which the out of balance force is also greatest, that is the zone for which the conventional factor of safety on slope movement is least. Rather, it is that zone for which the added shear necessary to achieve equilibrium is greatest.

6. PREVIOUS USES OF SOIL NAILING

Soil nails have been used with increasing confidence since the 1970's and the range of applications in which they are being used is also widening. Whereas they were originally only used for temporary support, they are now also included into permanent support systems. As a consequence the use of the system is becoming more common and the situations in which they are being used more varied.

In 1989 the rate of installation in France of soil nails had risen to 80,000 m^2 of facing supported by nails, while in Japan a total length of 100,000 m of soil nails was installed. In Germany in the 1980's the use of nailed systems was about 25% that of France. In the United States where development has been reasonably autonomous, a number of individual projects have been undertaken while a number of US government agencies are currently reviewing the use of the system on a more general basis.

Soil nailing has not yet found general favour in the United Kingdom. A number of drilled and grouted applications have been completed by specialist contractors. These have followed the system developed abroad in which the nails are installed by drill and grout techniques. Active research and development is underway by these contractors to improve the system and widen its application even further.

The majority of uses of soil nailing still relate to the construction or stabilization of steep slopes. When the slope to be treated is at a steep angle some form of facing is required to provide local stability and prevent ravelling or erosion at the slope face. In temporary slopes this has tended to be a sprayed concrete and in permanent slopes more aesthetic facings have been used.

The first reported use of soil nailing in Great Britain was for the stabilization of the dry stone walls in northern England using the drill and grout installation technique. Since then a number of other examples have been completed as shown in table 1.

There has been little experience of the use of soil nailing in the stabilization of earth embankments and other low angle slopes. Although the procedure developed by Soil Nailing Limited would seem to be ideally suited to the application it has only been used on a few occasions.

Table 1. SOIL NAILING SCHEMES CARRIED OUT IN THE UK

a. Schemes carried out by Keller Colcrete Limited using drill and grout soil nails

SITE	PURPOSE	SLOPE DETAILS height	horizontal angle	material	NAILS length	spacing	horiz'l angle	number
Denholme Clough, Bradford	Remedial treament to bulging dry stone walls	2.5-3.0m	wall retaining 22^{o} slope	wet sands, gravels and clays over bedrock	4-5m	1-1.5m	15	200
Cymsifog School, Glamorgan	Remedial treatment to bulging wall	2.2m	80^{o} wall retaining 19^{o} slope	wet granular soils, some clay	5-6m	H 2m V 0.75m	c15	90
Beaufort Rd, Bristol	Stabilization of prior to building work above slope	2.5-3.8m	wall retaining 26.5^{o} slope	made ground over fiss'd silty clay siltstone	9m top 7.5m middle 6m bottom	H 2m V 1.5m	20	53
Ampthill, Bedford	Stabilization of brick wall	1.5-2m	wall retaining	firm/stiff silty clay including sand and gravel	8.5-12.5m	H 3m V 0.5 stag'd	10-20	88
Birmingham	temporary support for excavation	8m	c80	firm/stiff clay over sandstone	5 & 8	1.5	15	300
Dolywern, Clwyd	stabilization of earth embankment	10m	45	silty clay some gravel	5	1.5	15	180 7 rows
Lakeside, Thurrock	stabilization of disused chalk quarry face	9m	70-75	chalk, with chalky sand infill to solution features:	3 - 4 1.0 in sol'n feat's	1.5	10-20	1500 8 rows
	with sandy chalk slope above	6m	40	sandy chalk	6	1.5	70	

Table 1. SOILNAILING SCHEMES CARRIED OUT IN THE UK (cont)

b. Schemes carried out by Cementation Piling and Foundation Limited using drill and grout soil nails

SITE	PURPOSE	SLOPE DETAILS height	horizontal angle	material	length	NAILS spacing	horiz'l angle	number
A2, Cobham, Kent	Road embankment stabilization	9m	30-60	Blackheath Beds and Woolwich Beds	18m	3m	18-60	670
Topsham, Exeter	Stabilise a masonry gravity wall	8m	vertical	clayey sand	5m	1.5m	25	600
St Peter Port, Guernsey	Steepening a cliff for development at the toe	22m	Original 53 cut to 70	clayey silty sand overlying granite gneiss	10m	H 1 to 2m V 1.5m	c 15	300 13 rows
Peasmarsh, Sussex	Steepen an existing slope	6-8m	cut to 70	Tunbridge Wells Sand overlying Wadhurst Clay	6-7m	H 1.5 to 2m V 2m	c 15	250 6 rows
Mount Street, Bangor	Steepen an existing slope	7m	70	weathered rock	6m	1.5m	25	100
Leeds-Liverpool Canal	Wall stabilization	3m	vertical	ash fill over clay	5m	1.25m	20	70
N. Berwick, Scotland	Stabilisation of slope above an excavation	9m	25	Superficial deposits	3-7m	1.25m	70	234

Table 1. SOIL NAILING SCHEMES CARRIED OUT IN THE UK (cont)

c. Schemes carried out by Soil Nailing Limited using fired soil nails

SITE	PURPOSE	SLOPE DETAILS height	horizontal angle	material	NAILS length	spacing	horiz'l angle	number
Ashby de la Zouch, Derby	stabilization of railway cutting	5m	40	weathered mantle over Etruria Marl	2 - 3m	3	70-90	3 rows
DanbyWiske	Stabilization of railway embankment	5m	40	Ash shoulder over clay core	4.5m	H 1.5 V 1.1		500
Duckpool, Lincs	Stabilization of river embankment	4m	35 (approx)	clays and sandy clays	3m	1.5m approx	45	
Wolverton, Milton Keynes	Refurbishment of a masonry wall	6m	vertical		6m	1.5m	5	200
Blaenau Gwent	Stabilize slips on valley side	22-30m (slip area) 60m (valley side)	24 (slip area) 18-22 (valley side)	Mine waste over head (clays to boulders, over stiff clay	6m (penetrated length 3.7 to 6m)	1.5m approx	45	50
Low Gil, Lancs	Replace a failed soil mass above a rock slope	15m	60	4m sandy drift cap to rock	4m	1.0-1.5m	5	200
Hounslow, West London	Provide methane gas monitoring points	n/a	n/a	landfill	3m	1m		

7. REVIEW OF SITES WHERE FIRED SOIL NAILS HAVE BEEN USED

7.1 General

The fired soil nail procedure offered by Soil Nailing Limited has only had very limited use. It has not been used outside of the United Kingdom although the Company report that there is positive interest in the systems from Japan and America. However, to date it has only been used on seven sites which approach a commercial setting. One of these was for the National Rivers Authority and was required to stabilize a slipped mass on a slope at Duckpool Drain, Lincolnshire. Two others have been for British Rail, one to provide remedial treatment to a cutting at Ashby-de-la-Zouch, Derby and a second to improve the stability of an embankment at Danby Wiske, Northallerton. The technique has been used in a number of other instances which demonstrate a potential for a wider application than the traditional engineering setting. In particular, a variant of the nail which was manufactured with a hollow section has been used to install a gas venting system in west London. This suggests that opportunities exist for the system also within environmental engineering situations.

7.2 Ashby-de-la-Zouch

The Ashby-de-la-Zouch site was a railway cutting with private residential properties above and backing onto the cutting. It was formed in natural ground through the Etruria Marl. The slope height was about 3m and had an angle of about 20^{o} to the horizontal. The toe of the slope had a berm which extended about to 2.75m from the base and stood about 0.8m above the level of the railway.

General movement had been experienced in the slope over a length of about 30m. This extended from the toe and emerged about 3m into the gardens where a tension crack of about 0.75m depth developed. The movement had not been catastrophic but caused disruption to the boundary fences of the gardens of the residential properties. General maintenance by British Rail had provided reinstatement of the slope on a number of occasions by using the failed material to re-shape the slope. In order to provide a more lasting solution and also to use the opportunity to evaluate its use, British Rail commissioned a fired soil nail solution to treat the slope.

A failure surface for the slip was conjectured to be a log spiral between the tension crack and the toe of the slope. The geometry suggested that the slip surface was about 4.5m below the slope surface over the mid-height of the slope. This took it below the level of the toe of the slope and represented a fairly deep failure. Independent work supplied by British Rail suggested that the soil properties for the material at the failure level were 14 kNm^{-2} for cohesion and about 15^{o} for the angle of shearing resistance. The information does not specifically state that these are effective strength parameters, but it is reasonable to assume this to be the case.

Soil Nailing Limited carried out an assessment of the slope and provided a design to install an array of 3m long nails in six rows. The nails were placed at 1.5m spacing in the rows along the length of the slope and up to 3m spacing up the slope. The individual row of nails were also staggered and not continuous along the slope.

The nails were installed either in the vertical or at an angle of 10^{o} from the vertical and were intended to be either overdriven or surface arrested. The overdriven nails concentrated around the crest of the slope in the centre of the failed area and again at the toe. Although all the actual nails were 3m long the amount of overdriving meant that they were installed to varying depths. The amount to which they were overdriven was dictated by the depth to the slip plane and ranged from a minimum of 0.75m to a maximum of 1.5m.

The procedure was designed to provide a reinforcement across the supposed existing shear surface before the reforming of the slope was completed.

The experience on site was that many nails were cut off by up to 0.5m suggesting that they did not reach their designed depth of penetration. There are no records to show the actual depth of penetration of each nail installed and so it is not possible to evaluate the actual installation compared to that proposed in the design. Similarly, it is not believed that a back analysis of the actual installation was checked.

The work was carried out in May 1990. British Rail report that the slope has experienced continued movement since. Soil Nailing Limited have carried out an assessment of the continued movement following a subsequent site visit, although a back analysis of the actual installation was not carried out they have suggested that the cause was unknown but could relate to one or more of the following;

a) overdriving of some of the central nails together with the subsequent regrading of the slope may have left an un-nailed zone of soil,
b) the number of nails in the slope may be insufficient due to the re-profiling being greater in the upper part of the bank than had been assumed in the original design,
c) the soil properties used in the analysis of the slope may have been optimistic and that the regrading and activity on the bank may have reduced the shear strength of the soil.

A number of inclinometers which were installed in the slope in August 1989 have been monitored by British Rail and show the subsequent movement to be up to 140mm to January 1991. A number of the instruments had become inoperable due to the extent of distortion stopping the inclinometer probe from being lowered down the inclinometer tube.

The project represented the first commercial application of the system of the fired soil nail and a number of lessons are admitted to have been learned from the experience. In particular a number of changes were subsequently made to the hardware. The host vehicle was upgraded to a larger tracked vehicle to allow greater flexibility in reach and positioning. Also the shrouding device on gun was modified to control the debris fly and limit the damage caused to the gun itself. Similarly the design principle has also been modified. The current procedures are likely to produce a different array if the exercise was repeated. In particular, the nails would be expected to be installed at a flat angle rather than the near vertical to achieve their optimum benefit. Regardless of these points a number of aspects can be identified about the project which are unlikely to be affected by these changes.

1. The accuracy of the soil parameters in any design procedure is crucial to the validity of the design. The uncertainty factor is implicit in the factor of safety built into the design formula either as a partial factor of safety

applied to the individual parameters or final factor of safety applied to the balanced forces. However, any design approach should include a sensitivity analysis to test the findings for reasonable ranges of variation in the values of the input data.

2. There remains some uncertainty as to the depth to the failure surface in the project. If the original data was correct, such that the failure surface was over 3m below ground surface, as the nails were only 3m long, any which failed to reach full penetration are unlikely to have crossed the failure surface.

3. The nails which did cross the failure surface would have had a limited penetration into the passive side of the slip surface. It is doubtful whether sufficient resistance could be obtained against the disturbing forces from the disturbed mass.

The viability of the scheme for British Rail was based on the economics of the solution. The movement of the slope was not life threatening and was not likely to cause a disruption the rail service. A high expenditure on treatment could not therefore be justified. The project was undertaken at a cost of £8,500. The technical alternatives to soil nailing were to provide support at the toe either by a gabion wall construction or a sheet pile retaining wall. These were considered to be unacceptable due to the estimated costs which were about ten times as great. In addition, the alternatives would produce a greater disruption to the area because of the associated support plant which they require. On this basis the only practical alternative to the soil nailed solution would have been to maintain the on-going maintenance programme. Re-nailing of the slip is planned for the summer of 1993 on a shared cost basis.

7.3 Danby Wiske, Northallerton

The mainline London to Darlington railway has a short section of unstable embankment about five kilometres north of Northallerton to the east of Danby Wiske.

The embankment has a maximum height of about 7m with a slope angle of about 28.5^{o} to the horizontal. Information on the form and construction of the embankment from a previous investigation carried out by British Rail showed it to have a clay core at depth with shoulders being made up of ash and other granular material with relatively soft alluvial material present beneath. Minor movement had been experienced along much of the embankment for a number of years and in 1978 a slip on the downside (west) of the embankment had required a section of sheet piles to be constructed to provide support to the toe. Movement was later detected on the upside (east) in 1991 over the section with the greatest height. British Rail were concerned that progression of the movement up the embankment would affect a stanchion carrying overhead power cables for the line and would disrupt the service.

The information on the embankment was extrapolated from an investigation carried out on the downside for the 1978 slip. Based on this information, and assuming a comparable construction and soil type on the upside, Soil Nailing Limited devised a scheme for a nailed solution. This comprised a number of 4.5m long nails installed over the lower and mid height section of the slope. The nails were installed on a square grid at 1.5m centres along the slope and 1.1m between rows upslope. Seven rows were installed over a 40m length of slope within the central or primary section of the embankment where the movement had been detected. A further 40m on either side was also treated although the number of rows were reduced to five row as the height of the embankment reduced away from the central section.

It had been anticipated that the movement was mainly a result of the ash shoulder sliding over the clay core, perhaps with some movement through the clay core itself. The nails were therefore designed to act into the clay and provide additional resistance against movement along that surface.

A number of inclinometers were installed in the treated area after installation of the nails which have been monitored by British Rail. They suggest that relatively minor movement is continuing which is generally in the order of 5 to 20mm at the surface decreasing to a depth of 4m. No further analysis of the information has been made.

The work was carried out between 29 January and 19 February 1991 at a cost of £60,000. Again, the limited need for support vehicles and ancillary equipment required by the fired soil nailing procedure was of particular advantage. The embankment was in a rural area and access to the slip was only possible along farm tracks under private ownership. The limited vehicle movement which was necessary meant that the track required only relatively minor initial improvement and later making good in order to carry out the work.

An alternative approach for British Rail would have been to have used a piled solution similar to that which had been used on the downside of the embankment. This had an estimated cost of £250,000 and would have involved a greater amount of disruption to the access route and the works area. The use of toe weighting was also considered. Although this had a lower cost compared to the piled solution the need to transport the fill material over the private access roads it would have caused a greater disruption to the local landowners.

7.4 Duckpool Drain, Bucknall, Lincs

Duckpool Drain forms part of the extensive artificial drainage measures associated with the River Witham in Lincolnshire. The alluvial flats of the Witham form an extensive low lying area of poorly drained land which links into the Fens to the south east. Much of the drainage measures in the area possibly pre-date Roman settlement of the region and have been modified and added to since. The Duckpool Drain flows to the south west into the Witham on its north bank. Originally, it was probably a natural stream but has been deepened and widened to help enhance the drainage of the area.

The continued deepening of the drain has meant that the Duckpool section flows in a cutting up to 6m deep. The northerly bank of the deepest section of this cut has always been prone to failures. The National Rivers Authority have inherited the responsibility for the drain from the former water authority. The maintenance of the drains has not been systematically recorded by either body and the best indication of the history of the area has been obtained from the former maintenance engineer for the area.

The drain is believed to have been last deepened towards the end of the 1940's when the bed level was lowered by an estimated 2 to 3 feet (1.0m). Cross sections are not available from this time but it is understood that the side slopes were left comparatively steep at a single batter and that the spoil was left as a bank along the top of the slope which increased the effective height of the slope. The sidewalls began to fail during the following period and these were reinstated using manpower and hand tools in the manner of working of the time.

During the 1970's an attempt was made to improve the stability of the sidewalls by cutting a berm into the middle to upper part of the slope. At the same time the bank at the crest of the slope, which had been formed from the previously excavated spoil, was lowered and together with the spoil from the berm excavation was spread out over the adjacent ground. Failures have continued to develop in the reformed slope. These typically extend from the toe of the slope to above the crest at the first berm level. During these failures the bed of the channel in the drain heaves and the channel becomes very restricted and can close completely. These failures are treated by pulling the failed material back up the slope by plant tracking along the berm and reforming the profile.

A system was devised by Soil Nailing Limited to stabilize one such failure. This required 4 rows of 3m long nails. Initially, the section of bank was reinstated using a mechanical excavator and the section nailed up before renewed movement developed. The nailed section was relatively short and extended over perhaps only 20m. The slope either side had also experienced movement but was left untreated as a control.

No systematic monitoring of the treated section has been undertaken since the work was carried out. It is believed that while the nailed section has not shown extensive movement, the slope immediately adjacent has failed and has required reinstatement since the nailing was completed.

A walk-over survey of the area on 27 January 1992 identified some tension cracks which appeared to be developing along the upper section of the nailed slope. This may herald the start of some movement. However, a further inspection by NRA on 11 November 1992 showed that the cracks had seemingly not developed further. It is therefore possible that they have merely resulted from the initial take-up of the stresses by the support system following its installation. Unless systematic instrumentation and monitoring is carried more positive conclusions can not be drawn.

7.5 <u>Blaenau Gwent</u>

Many of the valley sides of the South Wales coalfield are unstable. Slips are present on a variety of scales from small relatively shallow movements to major deep seated failures which can involve much, if not all, of the valley side. The slips also range in age from geologically ancient to modern, although many may be reactivations of older movements.

The instability on the valley sides causes many problems because of the congested nature of the area. Roads and other developments encroach on many of these and are threatened by the associated movements. Blaenau Gwent District Council investigated the possibility of using fired soil nails as a means of stabilizing an area of slip in their jurisdiction. The soil profile at these slips typically comprises a complex head deposit ranging in grain size from clay through to boulders. This may be covered by a veneer of mine waste and together these overlie the bedrock.

The slip chosen for the trial had a vertical height of about 22 to 30m and covered part of the valley side which had a height of about 60m. The overall slope of the valley side was about 18 to 22 degrees but this steepened locally to 24 degrees in the area of the slip. Soil Nailing Limited were commissioned to fire a test run of 50 nails to allow the procedure to be validated by the Council. Six metre long by 25mm diameter nails were used. These were placed principally in the toe area, although this was governed somewhat by the access for the machine. They achieved penetration depths of 3.7 to 6m. They were excavated after firing and in most cases were found to have penetrated the head deposit but pulled up in an underlying stiff clay which formed the bedrock.

It was known that a number of slip surfaces were present about 2m below ground level, but a more extensive slip was also present at about 7m depth. It was judged that the technique would not provide sufficient penetration to fully stabilize the slope and as a consequence the trials were discontinued and drill and grout soil nails were adopted for the final solution.

7.6 Wolverton, Milton Keynes

In order to refurbish an existing 6m high vertical masonry wall in Wolverton, Milton Keynes the contractor chose to use fired soil nails. The wall had a series of existing terrace houses within a metre of the crest above and within 3m of the toe below. The use of the nails provided a solution to two problems.

The existing wall could not be taken down and rebuilt and therefore a means of improving its stability was to provide anchor ties through the retained ground. This was done by firing 6m long soil nails through pre-drilled holes in the wall. Two hundred nails were used spaced at about 1.5m and angled at about 5 degrees to the horizontal.

Secondly, along part of the wall the level of the ground at the toe needed to be lowered by about 1.5m. This would not only increase the final height of the wall but would result in the wall being unsupported as excavation proceeded. Temporary support was provided by anchoring the wall in a similar manner to that described above enabling it to be underpinned.

7.7 Low Gil, Lancashire

Fired soil nails were used by Lancashire County Council to repair a failure of a five metre wide unclassified highland road in the Forest of Bolan, Lancashire. The road ran along the edge of a 60 degree slope about fifteen metres above a small river. The main part of the slope was formed in rock but the upper four metres consisted of a sandy drift with occasional boulders. Failure occurred when the drift became saturated and flowed off the rock head. About half of the width of the road was lost leaving a four metre high backscar.

The initial treatment used a gabion retaining wall constructed along the leading edge of the slope. This failed shortly after construction because it was surcharged by excess topsoil placed by the contractor. Following this a composite system was devised using fired soil nails and netlon tensar geogrid.

Soils nails were fired into the remaining material behind the backscar and left with about 2m outstanding from the face. The tensar geogrid was attached to this to form a series of bags which were filled with stone. The slope was constructed by filling the bags with high quality stone. Every so often the netlon was returned along the nails through the placed material to form a 'reinforced earth' effect. The slope was able to be constructed to the desired angle by careful positioning of the netlon bags. These were finally anchored to the nails by flanges before the excess nail was cropped off.

The failed section extended over a length of about 20 metres. Sixty nails were used in three rows giving a spacing of about 1.0 to 1.5 metres.

The remedial works which were possible at this location were governed largely by the restricted working space present above the steep slope and the inability to establish a working platform below the failure. However, it was also influenced by the nature of the road and immediate surrounding area. This included not only the value of the land but environmental acceptability of the solution.

The cost of the fired nails was about £10,000 plus the additional costs of the netlon and the placement of the stones. This compares to about £45,000 for a mass retaining wall. In this instance, Lancashire County Council judge that the soil nails offered a cost effective solution. However, they have judged that in the general situation the cost of soil nails exceeds that of the alternative of mass replacement using high quality locally won stone which is available for about £8 per cubic metre.

In September 1992 the second slope of Low Gil was nailed. This time the road had not failed but tension cracks had appeared in the road surface. One hundred nails were used with surface plates.

The Council anticipate using the system elsewhere in the County they do not anticipate a wide application unless the cost is reduced.

7.8 Hounslow, West London

A variant of the fired soil nail system has been used on a landfill site in Hounslow, west London. This had been backfilled in the 1950's and 1960's and during an audit of land in the borough, the London Borough of Hounslow found that part of the site had been built over so that the waste extended under gardens and garages.

Wimpey Environmental Limited proposed the use of fired soil nails as a means of monitoring the area to determine the presence and distribution of methane gas which was anticipated to be generated from the landfill. The nails which were used were modified to provide a perforated hollow section through which the gas would vent. These were fired vertically into the ground and successful monitoring of gas was reported to be practical in about ten seconds after installation. It is also possible that the action of firing the nails may have improved the permeability of the soil, although this supposition is so far untested.

The hollow section of the nail enabled monitoring to be carried out over a wide area with sufficient sample points that the areas of methane generation could be mapped and a more permanent venting system devised for the site.

The advantage that the procedure offered was based on;

- cost and,
- speed of installation and therefore,
- number of monitoring points provided.

The installed cost of the perforated nails proved to be similar to those used for soil reinforcement, that is about £100 per nail. This compared to about £300 for a conventional borehole and installed standpipe. This cost would increase with the depth of borehole and sophistication of the standpipe installation required.

The disadvantages of the perforated soil nails was found to be;

- the final depth of penetration was sensitive to the actual ground conditions at the installation point,
- sampling of the encountered ground was not possible,

The inherently variable nature of landfill meant that the energy necessary to achieve a given depth of penetration was not easy to predict. It was found that some nails refused on obstructions and others were lost where they were fired into softer pockets. The final costs of the scheme would therefore reflect the element of redundancy of a proportion of the nails installed. It also meant that the final installation pattern varied from the design pattern.

The approach has been used to provide such monitoring on four separate sites within Hounslow and on a fifth near Southampton.

8. POTENTIAL FOR THE NATIONAL RIVERS AUTHORITY

8.1 Background

The NRA consider that the technique marketed by Soil Nailing Limited has a potential for use on river and sea defence embankments including natural banks and cuttings and see its use for improving stability of embankments and use in emergency repairs.

There is a significant difference between the fired soil nails and the more usual drill and grout systems which have been used more widely in continental Europe and elsewhere. This difference is confused by the use of the same generic name for both systems and the present controversy about the technical aspects of their method of operation and appropriate design procedures. There are a number of differences which exist between the soil nailing projects completed by the drill and grout system and those foreseen by the NRA which makes a direct comparison of case histories of limited value. These differences can be summarised as;

1. Previous projects have involved steep slopes, whereas the batters of slopes on NRA sites will be much flatter,

2. Previous projects have an extensive soil mass behind the slope, whereas this is not necessarily the case on NRA sites since embankments have two sides which limits the extent of mass of soil behind the slope,

3. Previous projects have involved granular soils, whereas at many of the NRA sites the embankments are constructed with cohesive soils,

The fired soil nail of Soil Nailing has been used on only a very limited number of sites. The system is undergoing active research and development and a direct use of these case histories should therefore be treated with caution. The support hardware has recently been modified to allow improved accessibility for the equipment and an increased flexibility in the attitude of the gun and fired nails, particularly allowing it to fire nails below the level of the machine. The launch system has also undergone improvements to give more control on the penetration of the nail and to control debris fly during installation. Continued work is seeking to provide alternative materials for the nail itself to improve the durability of the nails, once installed, beyond the present galvanizing specification of the Department of Transport. Design methods are also undergoing refinement and improvement although the CRESOL computer programme is presently offered as the principal design approach.

The principle use of soil nailing for NRA seems to be for the remedial treatment of earth embankments and the construction of new ones. A flow diagram to illustrate when the technique may be considered and how it compares to alternative techniques is offered as Figure 10. This, and the other potential use of fired soil nails can be summarized as;

- *Improve the stability of existing flood defence embankments.*
  To allow existing embankments to be raised yet maintain an adequate factor of safety against slope failure.

- *Improve the stability of new embankments.*
  To improve the stability of any given embankment geometry and increase its factor of safety.

- *Carry out repairs to failed sections of slopes.*
  To provide remedial treatment to failed slopes on either a permanent or temporary basis.

- *River bank stabilization.*
  To improve the stability of river banks which may or may not form part of any defence embankments. This could benefit both stability of the bank slope and provide erosion protection.

- *Sea cliff stabilization.*
  Sea cliffs are best protected by preventing erosion at the toe. The upper levels will continue to fail unless they are protected by a positive stabilization system.

- *Anchoring of other defence structures such as geotextiles, gabions, mats etc to aid stability against erosion or scour.*

- *Provide a pore pressure relief system as part of the construction of earth embankments or to aid soil consolidation.*

In addition to the use of nails in soil reinforcement a further potential exists for their use in the field of environmental engineering. This is based on the use of a modified nail with a perforated hollow section. The potential can be separated into two broad categories;

- *Investigation and subsequent monitoring of soil gas and water over extensive areas where a large number of sample points are required,*

- *Provide a sustained gas venting or pore pressure relief system as a standalone or as part of a more structured remedial treatment.*

These can be considered in more detail.

8.2 <u>Improving the stability of existing flood defence embankments.</u>

Many of the existing flood defence embankments have been constructed over historical time and many have stood the test of time. However when these banks are analysed by current design techniques they are often found to have only a marginal stability against slope failure. This means that under given conditions the structures could fail, or can be shown to have an unacceptably low factor of safety against failure.

The reason for this apparent anomaly stems from two factors:

The first factor relates to the inherent conservatism which is built into modern analytical approaches used to determine the stability of slopes. All of these assess the stability by comparing the forces acting to cause failure and the strength available to prevent such movement occurring. The analysis procedure first requires a series of input parameters to define;

- the basic slope geometry,
- the soil sequence within and underlying the slope,
- the engineering parameters for each of the soil types present,
- the water levels and pore pressures active within the slope and underlying soils, and
- any loading conditions on the slope.

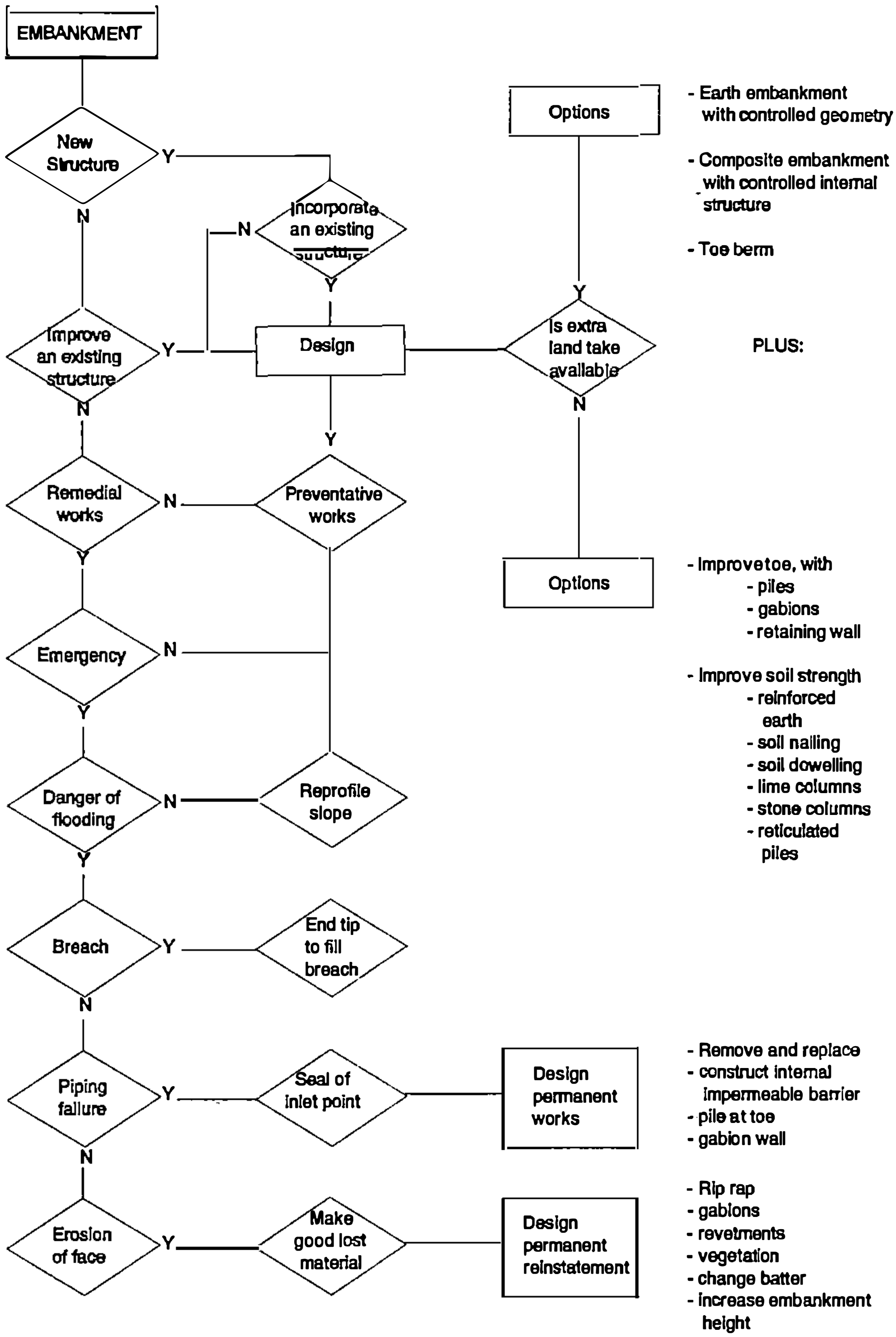

Figure 10 Flow Diagram illustrating the principle construction options in embankment construction and remediation

The stability of the slope is then determined as a factor of safety which is defined as the ratio of the disturbing forces to the restoring forces on the critical slip surface. This is based on a worst case scenario such that the condition analysed is the most likely in which failure will occur. In addition, the input parameters tend to be conservative in order to accommodate any further uncertainty in the representativeness of the analysed situation to that actually present in the field.

The second factor relates to the methods of construction used in the past. This has allowed many embankments to be constructed much closer to their true limit condition. The earliest methods of construction used only manpower, consequently embankments were raised only very slowly. This gave many of the conditions which would otherwise be adverse to the stability of the embankment time to equalize and the effect on the surrounding soils time to dissipate. Similarly the occurrence of a local failure could be more readily accommodated as the scale of the works meant that modification to the procedure was more readily achieved. This contrasts with modern construction procedures which are more rapid and give little time for the soils used in the embankment or those forming the foundations to adjust to the changing stress conditions. Modern embankments can therefore be very sensitive to stability in the short term. This fact can even dominate the final profile of the embankment if the construction period can not be adjusted to take this into account.

In essence, the slower construction procedures used previously allow any excess pore pressures which develop within the foundation and construction soils as a result of the surcharge loading of the embankment itself, to be dissipated. This allows the foundation soils to consolidate and improve in strength as the loading is placed. The personnel often had a closer understanding of the behaviour of the particular materials in their area which allowed an intuitive understanding of the material behaviour and which helped to raise the embankments yet maintain an adequate factor of safety against slope failure. The proof of the ability and success of these old procedures is shown in the overall success that was achieved.

The general conclusion reached when the existing embankments are analysed is that they are not able to be raised further and also satisfy modern design requirements. Therefore, in order to raise the level of existing flood defences it is often necessary to form a new embankment with the old structure being relegated to form a toe within the new. The effect is a significant increase in land take and earthmoving requirements. This is also aggravated by the need to provide a greater width at the crest to allow access to modern maintenance plant and vehicles.

Clearly, in situations where the height and width of an existing embankment per se, is not an issue modern analysis can still show that it has inadequate stability and thus provides an unacceptable flood defence. Under these circumstances techniques which would allow the existing structure to be improved can have significant advantages over the option to rebuild the embankment.

The use of soil nails provides a means of improving the stability of an existing slope by increasing the restoring forces active within the slope. Thus, the ratio of restoring to disturbing forces would increase and hence so would the factor of safety of the slope.

The analysis procedure offered by CRESOL and other design procedures are able to determine optimum array of nails and assess the increased factor of safety that they produce. However, an assessment of the use of a nailed solution must also need to take into account the durability of the nails once they are installed as the increased factor of safety will reduce if the nails corrode or the active system deteriorates. In addition, the sensitivity of the calculated benefits of the system should be assessed against the placement accuracy of the nails during installation so that the assessed improvement is assured even if the actual array installed varies from that used in analysis.

As the launch system allows the nails to be installed at any attitude and to a range of depths it is possible to provide an improvement in the soils forming both the slope and the founding conditions.

Unless a particular situation allows the option of total reconstruction of a slope the ability to reinforce the soils can have obvious advantages. Where reconstruction is not a possibility, the existing alternatives to fired soil nailing are;

- toe berms using gabion constructions or similar,
- sheet piles walls
- gravity retaining walls, and
- less commonly, reticulated piling, or
- lime columns,

8.3 Improving the stability of new embankments.

The geometry of new embankments is largely controlled by the factor of safety determined in analysis, subject to providing adequate access for maintenance plant etc.

The restoring force in the analysis is governed by the effective shear strength along the potential failure surface under consideration. The effective shear strength is made up of separate cohesion and friction components which relate to the innate properties of the soil involved. The effective cohesion of a soil is governed by the interparticle bonding of the soil fabric and is essentially independent of the surrounding conditions. However, the frictional resistance is also a function of the surcharge load across the failure surface and this increases with the relative depth of the slip surface or the surcharge load on the slope.

The disturbing force is largely governed by the mass of the block contained by the slip surface wishing to slide under gravity. Clearly as the depth of the slip surface under consideration increases so does the size of block and consequently the magnitude of the disturbing force. The value of the disturbing force is determined by resolving the mass of the block in the direction of the sliding surface. Consequently, as the slip surface decreases in curvature the relative increase in disturbing force is reduced while the increase in restoring force is increased.

As the angle of any slope is reduced the potential slip surfaces become flatter so that the friction component on the slip surface increases disproportionately to the disturbing force. Thus, as the slope geometry develops a flatter slope angle the overall factor of safety of the slope increases.

The factor of safety of a given slope geometry can therefore be increased if the restoring force can be increased. Fired soil nails placed across the potential slip surface will provide an additional restoring force and a consequent increase in the factor of safety. This allows steeper side slopes to be considered for the structure with the advantage that;

- smaller land take would be required to accommodate the reduced width of the overall structure, and
- less earthmoving would be necessary.

However, there are some possible disadvantages. In particular;

- the slope geometry may become more visually obtrusive,
  the angles may be steeper than would occur naturally and this may be environmentally unacceptable, also
  steeper slopes are less easily maintained by plant and machinery.

The increased factor of safety achieved by the fired soil nails is also dependent on the long term durability of the nail and the placement accuracy and sensitivity to the nail array at installation.

The effective shear strength of a material is an inherent property of the soil itself. Therefore, it is generally not possible to increase the effective shear strength of a material to be used in the construction without modifying the material itself. Methods have been developed to do this. In particular, the incorporation of lime into a suitable soil can increase its cohesion because of the increased cementation which results within the soil fabric. However, this also has the effect of increasing the stiffness of the material and makes it more brittle. This can be unacceptable where the foundation is a relatively weak material.

The frictional nature of a soil can be increased by providing a greater granular content. The reliable mixing of materials can be difficult to achieve and the necessary handling increases the earthworks cost involved.

The construction of a new slope provides more opportunity to incorporate an engineered support system into the structure as a means of improving its stability. Typically this includes the use of drains to control the pore pressures. It also allows materials to be selectively placed within the construction so that the properties can be best matched to the benefit they can provide to the structure. For example, the core of an embankment can be an constructed from an impermeable but relatively weak soil while the shoulders, which act to support the core, can be a more permeable but much stronger material. Soil reinforcement is designed for systematic inclusion within a structure during its construction and affords an absolute placement control and the means to match the properties of the contained soils to the needs of the system.

8.4 Carry out repairs to failed sections of existing slopes.

A slope will fail once its factor of safety falls below unity, that is the disturbing forces become greater than the restoring forces. A consequence of a slope failure is that the shear strength of the soil along the failure surface reduces to the residual and results in a loss of cohesion. Once this occurs, the factor of safety can not be restored to the original value merely by reforming the slope to the pre-failure geometry. The evidence of this is commonly seen where attempts are made to pull failed material back up slope. This always proves to be a fruitless exercise unless some other remedial action is taken. This can include:

- the installation of drains,
- providing toe weighting,
- reducing surcharge loading,
- reforming the slope to a lower batter,
- replace the failed material with other material,

- providing additional shear resistance across the slip surface by,
  - sheet piles
  - reticulated piles
  - lime columns
  - stone buttresses
  - soil nails

Soil nails can be used to increase the shear resistance across the failure surface to compensate for the loss of strength in the reduction to the residual condition. Fired soil nails have been used in this way by the National Rivers Authority at Duckpool Drain seemingly with some success.

The advantage that the system has over many of the other options relates to;

- the speed of response,
- maintenance of the *status quo* by keeping existing slope profiles and land takes,

The soil nailing equipment can be mounted on similar plant to that already used by the National Rivers Authority for the general maintenance of banks. It is designed for installation on a tracked hydraulic excavator with a specially extended jib. If the launch system is readily available the system could be mobilized relatively easily and quickly. The total system is largely self contained and requires very little on site support facility, other than a means of access for the plant on which the launch system is installed and a means of transporting the nails to the site.

It is feasible that the fired soil nail system could be used economically on small value projects because the mobilization costs are relatively low. This means that individual slips could be treated, even where these have a limited extent.

The size and nature of the plant required also means that access does not become restrictive or provide a limitation as can be the case for systems that require a large on site support facility.

The speed at which the remedial treatment can be applied is governed not only by the rate at which plant can be mobilized but also by the speed with which a design for the treatment can be produced. Clearly, their are advantages if the treatment can be generalized so that detailed design is not necessary. This can only be achieved if the cost of the system is low so that overdesign does not impose a severe cost penalty and if the system is relatively simple in concept, or supported by sufficient precedent that standard approaches can be automatically adopted.

An advantage with soil nailing would appear to be the ability to view it as a two staged treatment. A rapid response could be adopted to provide 'instant' remedial treatment based on an empirical approach. This could be later supplemented as required by a permanent system once a detailed design has been formulated. The permanent system may or may not necessarily be based on a fired soil nailed solution.

8.5 Bank stabilization

River banks may form part of a defence embankment. More typically the bank merely defines the edge of the stream channel and in lowland settings the crest coincides with the 'bank full' level beyond which overtopping and flooding will occur.

In either case it is also necessary to consider erosion control as well as the slope stability of the embankment. Excessive erosion of river banks is often unacceptable for a number of reasons. In a natural state there is usually a balance between erosion and deposition which produces a variable bank profile depending on whether net erosion or deposition is taking place at any given location. The position of the channel will therefore vary with time as points of erosion and deposition cause the channel to meander. Where rivers have been canalized and the banks are artificial there is a need to maintain these against erosion as the natural hydraulics of the river attempt to reassert itself.

Bank protection may also be necessary to guard against erosion from wave action. This can occur on lakes and reservoirs as well as in rivers.

Although local slips occur in river banks these generally develop in response to undercutting and scouring and are not usually rotational in nature. Unless the bank is an integral part of a more substantial embankment, which can be considered as a discrete entity, the principle concern is not to improve the stability against slope failure but to prevent erosion.

Bank protection may provided by either hard or soft systems. The hard options offer a physical barrier against erosion and can be provided by sheet piles, gabions, revetment or rock armour. The soft options are based on systems which reduce the energy within the erosive system. Bank side plants provide a natural buffer able to dissipate the erosive energy in stream currents or in wave action. Although suitable plants may be used specifically for the purpose their effectiveness lasts only as long as the plants survive. If the conditions do not support adequate growth or cover is lost for any reason, then erosion may develop. A number of revetment are available which provide a durable surface but which also allow plants to grow through. Although in these circumstances the revetment is designed to provide the main erosion protection the environmental effect of a hard system is lessened with the incorporation of the plants.

Although the materials used in hard systems are durable and will readily stand up to the erosive forces from which they provide protection the weak point is very often at their edge. Here the erosive effects are unchecked and can in fact be aggravated. Local erosion at these points can undermine the hard defences and can leave them open to disruption and subsequent failure of the system.

Fired soil nails, in themselves, are unlikely to provide a means of bank protection as they are not able counteract the erosion. However, they can be used in conjunction with some other system to provide an anchorage. The detailed design of any hard defence is often governed by the need to prevent its failure from localized erosion or movement. This can be done by adding sufficient weight to counteract these effects. The use of an anchorage system would therefore enable the system to be less massive.

Soil nails could be installed prior to construction of the hard protection which can then be bonded to or integrated with the nails. Alternatively the nails could be fired through the placed defence structure to pin it to the bank. Both of these approaches as yet have no precedent.

8.6 Sea cliff stabilization

Existing sea cliffs have been traditionally protected from coastal erosion by hard defence systems. These are usually designed to prevent erosion at the toe of the slope. There is an increasing concern that protection of this sort affects the sediment budget along a larger section of coastline and that erosion elsewhere is aggravated as the sediment supply is affected. Where increased beach erosion has occurred the situation can be alleviated by the importation of material to replace that lost. However the loss is likely to continue unless the natural replenishment can keep place with the erosion.

The alternative to this approach which tends to be piecemeal is the use of a soft system. The philosophy requires a wider overview and argues that the coastline should be allowed to develop naturally. Although this requires an acceptance that erosion will not be prevented and that land will be lost, the resulting balance will result in the overall coastal erosion being less severe in other places as the sediment replenishment is maintained.

The prevention of the continued removal of material from the toe by whichever system will cause the upper levels of the slope to continue to fail. In situations where this is unacceptable they can either be cut back to some safe angle of stability or the movement controlled by a positive stabilization system.

The methods available to provide for the positive stabilization of cliffs is determined by the height of the cliff and the properties of the soils which form the cliff. Techniques available include:

- drainage
- buttressing
- retaining walls
- re-profiling
- anchorage
- dentition

These can be used in isolation or in combination.

Fired soil nails can be used as a standalone system where the height and nature of the material allows sufficient penetration that support through the critical slip surface is achieved. In this sense the system can be considered in the same way as the discussion above on improving the stability of an existing embankment. Where the height of the cliff is greater the lengths of fired soil nail which are currently available are unlikely to be sufficient to provide improvement as a standalone system. In these circumstances they may be designed as an adjunct to other methods and in particular to act as suitable means of anchoring.

8.7 Anchoring for other defence structures

It can be seen from the discussion above that the fired soil nail has some potential for use with other structures and construction systems by providing a means of anchorage. The system could be used with geotextiles, gabions, revetments, mats, retaining structures etc to enhance the overall stability of the combined system. Consequential savings could be made where the primary system has a reduced specification as a result of the improved stability.

The nails can be fired in advance of the installation of the primary system and then the nail used as an anchor point to which the main system is tied. Alternatively the nail could be fired through the primary system, if necessary through a preformed hole and used to pin the structure.

In order to do this effectively the depth of peneteration of the nail needs to be controlled. The energy in the nail can be controlled by varying the pressure at which it is fired, but this only provides a coarse control. Where better accuracy is necessary, for example where it is to form an anchor point, then the final penetration can be limited by the inclusion of an arrestor plate. This is positioned so that the nail is fired through a central hole in the plate so that an angled collar fixed on the nail engages in the hole to prevent further penetration.

8.8 Provide a pore pressure relief system during construction.

During the construction of embankments across fine soils the surcharging caused by the embankment will raise the pore pressure within the founding soils. The rate at which this increased pore pressure dissipates very often controls the rate at which the construction can take place. A number of proprietary systems designed to provide vertical drains are available which can be used to aid the rate of dissipation. The essential nature of these systems is that they are flexible and therefore they will collapse as consolidation settlement takes place. If developments in soil nail materials provide a similar flexible material then they would offer an alternative to the systems presently available. The limitation will be that the depth of penetration of the nails limits the depth of zone that could be treated in this way. However, those soils which generally need to have their consolidation enhanced are at the softer end of the strength spectrum and it is feasible that nails with ribbons of a suitably flexible drain material could be fired to considerable depths in such materials.

Pore pressure dissipation is practical with current nail technology where the need is to provide drainage of existing slopes and embankments. Hollow section perforated nails can be installed at low angles to the horizontal and are less sensitive to the movements of a slope than to the consolidation below an embankment. The nails would have the dual benefit of providing reinforcement to the soils as well a drainage of the pore pressures, both of which have the effect of improving the factor of safety.

8.9 Investigation and monitoring of soil gas and water.

Modified nails have been used on a number of landfill sites where nails formed as a perforated hollow section have been used to monitor the distribution of landfill gases. The rate of installation and the cost involved allows a large number of nails to be placed. This has particular advantages in large areas where discrete zones of gas generation may be present and allows the areas of concern to be identified.

The system can be used in a similar way to a spiking survey which was first advocated by the Building Research Establishment as an inexpensive and rapid means of investigating soil gases. This requires a steel spike to be driven into the ground and withdrawn. The resulting void is used as a monitoring point for gas using a portable gas detector. The effective depth of penetration is usually 0.5 to

1.0m, but is very sensitive to obstructions and ground conditions and the muscle power of the operators. In contrast, the soil nail can achieve greater depths of penetration and can therefore sample over a greater depth. However, this may not always be an advantage since often the investigation may be only concerned with the gas which is escaping at surface.

The fundamental work on the use of fired soil nails in soil reinforcement has shown that the adhesion is well developed between the nail and the surrounding soil, indeed they would not operate without such. This factor may offer a further potential for selective monitoring or sampling of either soil gases or soil water. If the soil is well adhered to the hollow section nail an escape path will not be present along the outer contact with the soil. This means that sampling or monitoring could be achieved by the use of a packer device. This is inserted down the nail and a section isolated by inflating two seals against the sides of the tube. Gas or water could then be sampled or monitored from the isolated section. Although the bonding between nail and soil has been demonstrated in natural soils the effectiveness of such bonding in the more variable nature of landfill has not been tested. The procedure is therefore likely to be more effective where the investigation is for gas or water in natural soils rather than in landfill.

The soil nail will also have the effect of keeping the formed void open and this allows later monitoring to be achieved. This is less practical with spiking surveys since the void formed by the spike can be quickly lost as it closes up, becomes filled with soil or the immediate area becomes overgrown. Some of these problems may also occur to the nail and further protection may be offered by installing a headworks over the protruding end.

Research has suggested that there is limited influence of the surrounding soil by the fired soil nail as it is installed. This fact may also present particular advantages for environmental engineering uses of the system. The monitoring of the Hounslow landfill sites showed that effective readings of the landfill gas could be obtained within about ten seconds of installation. It is likely that this occurred because installation of the nail did not cause any modification to the surrounding soil. This contrasts to the situation when monitoring or sampling is carried out in conventional boreholes or from instruments constructed in boreholes. The action of advancing the borehole is very much slower than the installation of the nail and the procedure causes inevitable disturbance of the immediate surrounding soils. Most notably is that the surface atmosphere is transferred to the soil at depth. This can cause a change in the ambient conditions which would affect the soil environment and hence the chemical character of the immediate soil gas or soil water. It can therefore take a period of time for such instruments to give stabilized readings.

The overall speed of installation and the immediacy of representative readings allows the final pattern of investigation holes to be dependent on the results. Consequently, if a coarse grid of sampling points is initially adopted the spacing can be reduced in areas providing appropriate readings or in areas of other sensitivity. The decisions can be made at the same pace as the installation. This allows the advantages of phased investigation to be had within one period of investigation.

As the technique can be carried out in even large areas in very short periods and the on site presence of the operation is relatively low, the political and environmental consequences of such work may be more acceptable than alternatives.

8.10 Provide gas venting or pore pressure relief for the remedial treatment of contaminated ground.

Soil gas and soil water can permeate through the ground under the control of the operating fluid dynamics. It is therefore possible that landfill gas may migrate beyond the confines of the landfill area in which it is being generated. The migration of liquid contamination, or the soluble phase of other contamination in existing groundwater, could similarly occur. It may be necessary to control or limit such migration where it proves a hazard or is otherwise unacceptable.

The traditional means of achieving such control is to contain the source of contamination. However, a number of proprietary systems are also now available which are based on methods of cleaning the contamination on site. For soil gases it may also be appropriate to provide a means of safely dissipating these to the atmosphere.

Many of these treatment options require a means of accessing the contamination, be it gas or liquid. In many instances multiple entry points are preferable to a smaller number as this requires a smaller volume of ground to be dealt with by any individual point. This must offer a greater efficiency to the overall treatment system because of the shorter flow paths involved.

The potential seems to exist for fired soil nails to be used with advantage in this area of activity. For example, soil gases migrating from landfill are often dealt with by intercepting them by cutoff drains and venting these to atmosphere. In places where the cutoff can not be constructed, for example because access is difficult, then fired soil nails may be used as an alternative. Similarly, where a horizontal blanket is to be installed the nails could be used as a vertical collector system discharging into the blanket.

Liquid contamination could similarly be abstracted through the nails, although for landfill leachates these are perhaps unlikely to be a serious substitute for fully engineered solutions because of the volumes of leachate involved. However, they may offer a use in the treatment of smaller isolated problems. In particular the spillage of fuel oils can be treated by aeration of the contaminated soils and lifting off the liquid and vapour phases. In other instances less volatile oils can be treated by encouraging them to migrate to collection points by injecting other fluids into the surrounding ground. The ability of the perforated nails to be fired without disruption of the surrounding soils has a particular advantage in that it will minimise the disturbance of the contaminated ground during installation. In the same way that selective monitoring and sampling of soil gas and soil water could be achieved with a packer system from the perforated hollow section nail it would also allow the injection of appropriate gas or liquids to assist the treatment procedure.

9. DESIGN CRITERIA

9.1 Background

The documented projects which have been carried out using drilled and grouted soil nailing have been mainly for constructed slopes. The design procedures which have been used are based on an expected or potential failure condition against which the nails, acting as a reinforcement, should act.

The stabilization of embankments with soil nails has some similarity, but also some fundamental differences, to their use in the construction of a slope. The nails, in either situation, impart an additional stability against the stresses which act to cause failure of the slope. The failure surface used in the analysis only exists as a potential until such time as movement and consequent failure occurs. The approach to design seeks to modify the stresses across the potential failure surface in order to increase the factor of safety and prevent the movement developing. The possible modification of the position of the potential failure surface by the presence of the reinforcement is not readily taken into account in the general design process.

Where the technique is to be used for remedial treatment of failed slopes, a discrete failure surface already exists for which the reinforcement will need to provide a stabilizing influence. The effect of the reinforcement across this surface can perhaps be judged with more certainty.

The fundamental mechanism whereby the nails impart a reinforcement to the soil mass is a point of debate in the literature. The published work of those involved with the fired soil nail, as marketed by Soil Nailing Limited, have a contrary opinion to the majority of other workers whose background is derived from the use of drilled and grouted systems. The supporters of the fired soil nail argue that shear resistance in the nail is a substantial factor in the behaviour of the system. This contrasts with the majority of opinion from the work on drilled and grouted soil nails which suggest that the shear resistance is negligible and that all the support is derived from tensile resistance developed along the length of the reinforcement member.

Work done at the University of Cardiff has led to the development of a design procedure using a computer program called CRESOL (Bridle 1992). The theory and methods on which it is based are general and, it is argued, can be applied to any reinforced soil structure. In view of the limited use of the particular system there is little case history evidence with which to assess the validity of the design technique although in the back analysis of the laboratory test data from the large scale shear box tests it gave the best results in a comparison of the actual to predicted results from three differing sets of analyses (Jacobs 1992).

9.2 General Principles

The principle behind any of the established design techniques is based on limit state analysis in which the balance between disturbing and restoring forces is a measure of the factor of safety of the structure. It requires an initial model to define the geometry of the collapse system and then seeks to calculate the loads in the various components in that system at the point of collapse.

The loads used in this procedure are actual loads determined from the geometry of the model and the appropriate parameters of the materials involved. Partial factors may be applied to these to take into account the uncertainty of the values used or the variability in the true system.

The effect of the reinforcement within the model is to cause further loads which form in and around the reinforcement and act to increase the restoring force in the system and hence the increase in the factor of safety. These additional loads are induced by bending and stretching of the reinforcement. In addition, the friction between the reinforcement and the surrounding earth induces both tension in the reinforcement members and bearing pressures along their length which results in shear and bending developing in the reinforcement.

The reinforcement members are then checked to see if the loads imposed on them can be carried by them with a suitable factor of safety.

There are two types of reinforcement which can be used to strengthen soil structures. With respect to lateral load they can be considered as 'stiff' or 'pliable' and with respect to axial load as 'extensible' or 'inextensible'. Fired soil nails require the reinforcement to be stiff and inextensible and the design principles adopted in CRESOL are based on this premise.

9.3 The Design of Soil Nailed Structures by CRESOL

9.3.1 General

The analytical procedure carried out by CRESOL provides the following.

- Determines the log spiral which describes the critical failure surface for a given slope geometry.
- Calculates the shear and the tension in each member of the reinforcement array.
- Checks that each reinforcement member can carry the load imposed on it.

CRESOL is written in BASIC for the Amstrad PCW 8256 and consists of two separate programs called SOLNAL and EANAIL. SOLNAL is run initially and produces all the data necessary for the solution of the forces in any single array. This creates a data file which is read by EANAIL to solve the forces and produce a table of forces within the array and soil system.

It is understood that it will be rewritten as a single program to run on industry standard microcomputers.

9.3.2 SOLNAL

Data Entry

Once SOLNAL is installed it will prompt the user for a series of input data which define the system to be analysed. These consists of:

- Ground levels
- Strata levels
- Strata soil properties
    - cohesion

- angle of friction
    - density
    - mean cohesion for the initial calculation
    - mean angle of friction for the log spiral calculation
- Surcharge loading
- Slip parameters
    - entry and exit points of the log spiral slip surface
    - angle which the log spiral makes with the vertical on exit
    - angle which the log spiral makes with the horizontal at the toe
- Number of intervals into which disturbed zone is to be divided

Ground levels: The ground levels which define the surface geometry of the slope to be analysed are described by X-Y coordinates from an origin of 0,0. The origin is an arbitrary point, usually located at some real ground point but should be positioned so that the full range of possible failure surfaces can be considered. The system first requires the number of points to be entered to a which a ground level will be assigned, not including the origin. It then prompts for the X and Y coordinates at each of these points.

Strata levels: Strata levels are input in a similar way to the ground levels. Initially, the number of strata is defined and then the number of points which define the lower surface of each of those strata prompted for and entered as X-Y coordinates. It is necessary that the strata fill the area under analysis and extend from both extremities. The strata should not overlap or extend above the ground surface. This can be achieved using false coordinates so that strata have zero thickness in some places.

Strata soil properties: The system next prompts for the cohesion, angle of friction and density for each of the soil strata defined.

Mean cohesion for initial calculation and mean angle of friction for log spiral calculation: Following the soil properties for the individual soil strata, the system prompts for a mean cohesion for initial calculation. A judgement is made from the data entered for the prediction of the critical slip surface and prompts for the mean angle of friction for the log spiral calculation.

Surcharge: If appropriate, the system prompts for the number of vertical and horizontal surcharge loads together with the number of external moments. These can also be featured on a global basis following a prompt which seeks a load factor for the surcharge loads. The value and coordinates of each surcharge load is entered by following screen prompts.

Slip Parameters: In order to define the slip surface the system prompts for the coordinates of the exit point of the slip surface at the toe and the Y coordinate of the point of entry. This later parameter can be estimated from rules but the critical position can be found by iteration as the exit point will be known with greater certainty.

The angle which the log spiral makes with the vertical on exit and the angle that it makes with the horizontal at the toe: The purpose of defining the slip surface is to fit a log spiral to the critical failure surface. Where the exercise is carried out for remedial treatment to an actual failure the geometry of the existing slip surface will be known. Where the analysis is for preventative works so that the position of the critical surface is unknown the slip surface must be postulated. A curve can be created which keeps the entry and exit angles of the slip surface constant while changing the individual values. The system allows the routine to be re-run with a differing values until a critical value is established.

Number of intervals into which the disturbed zone is to be divided: Once this is entered the datafile is complete. SOLNAL will allow the user to print the parameters in a tabulated format if required.

Assessment of the critical failure surface

The assessment of the critical failure surface is divided into one of four options which determine the process of iteration which is followed. These allow:

- an assessment of the best fit log spiral to the known data where the slip surface is known (Type 1),
- the critical slip surface to be found where iteration is to take place by incrementally changing the position of the point of exit (Type 2),
- the critical slip surface to be found where iteration is to take place by incrementally changing the position of the point of exit at the toe (Type 3), or
- a one off analysis which avoids returning to modify the input data or test other possible slip surfaces (Type 4).

Under Type 1, the system prompts for a deterioration factor which when multiplied with the effective shear strength values of the soil predicts their lowest future values. It is assumed that the existing slip surface is at the limit of equilibrium such that the disturbing moment is equal to the restoring moment. Consequently, the reinforcement is being provided to meet the out of balance moment that would arise from the deterioration of the soil strength with the application of the appropriate partial factors given by the deterioration factor.

Following the partial factors for the soil parameters the system prompts for a load factor to apply to the earth loading together with the diameter of the nails and their probable penetration into the undisturbed zone.

The program determines the approximate number of nails and their likely condition which is dependent on the condition of pressure below the nail.
Under Types 2 and 3, iteration is based on the position of the exit position of the slip surface to provide the critical position. Once this is done the system prompts for the diameter of the nails and their probable penetration into the undisturbed zone.

The iteration procedure seeks to find a maximum value of the total shear to be provided by the nails acting normal to the slip surface to achieve equilibrium, SSR. If a maximum value is not found then the program will prompt for a modification to the data.

Once the iteration is complete the data is stored and transferred to EANAIL for further processing.

9.3.3 EANAIL

The essential information determined under SOLNAL is passed to EANAIL to allow further assessment of any number of nail arrays without the need to recalculate the earlier information.

The system prompts for the following details of the nail array:

- number of nails,
- the Youngs Modulus of the nails,
- diameter of the nails,
- transverse spacing of the nails,

and then for each nail in the array,

- the angle of depression of the nail,
- their X and Y coordinates, and
- the length of the nail.

The system then asks whether checks on pullout, stress, bending and bearing are wanted.

A positive response to this leads to;

- a comparison of the values of induced shear and tension for each nail with their allowable levels,
- the modulus of soil reaction for each nail,
- the distance along the nail from the slip surface to the point of maximum bending moment,
- the ratio of principal stress to fracture stress at the slip surface, and
- the ratio of direct stress to fracture stress at the point of maximum bending moment.

Finally, it is possible to repeat the computation for differing transverse spacing or for differing input parameters for the nails and consequently arrive at an optimum design of nail length and spacing.

10. SUMMARY

10.1 Introduction

The contract was commissioned to review the technique of soil reinforcement by fired soil nailing and considers its potential for improving the stability of river and sea defence embankments and its viability for use in emergency repairs.

The study has found that the technique has been little used commercially so that only limited information was available from existing case studies. Nonetheless, a review of the theoretical behaviour of the nails acting as a reinforcement, together with the information gained from full scale trials, suggests that the system does offer a potential for use as a rapid response for the remedial treatment of soil slope failures.

The fired soil nail system is contained on a single tracked vehicle and requires only limited additional vehicles or plant in support. This offers a benefit over other variants of soil nailing and other construction methods which could be used as an alternative. The inherent mobility of the tracked host vehicle means that it requires only a limited access and working area for the system to operate and leaves little damage beyond the width of the tracks of the host vehicle. This also makes the technique suited to situations where environmental considerations are important.

Therefore, in addition to the original use as a solution to a civil engineering problem, it also has a largely untapped potential for use where environmental engineering factors are also paramount. Bedsides the concept of providing soil reinforcement, the ability to install a variety of nail types means that they can also be used to monitor water or gases within the ground. Postulation also suggests that it would also be possible to extend the technique and incorporate the use of the nails in the control or treatment of contaminated ground.

10.2 Soil nailing

Soil nailing was developed as a means of improving the stability of slopes by rigid rods acting to provide additional strength within a soil mass. It resulted from a combination of practical experience developed in tunnelling through poor ground and the understanding of soil reinforcement following the success of the 'reinforced earth' system. Soil nailing has been used in continental Europe for over 20 years and is becoming increasingly common in other parts of the World.

The established technique is to drill holes into the soil and grout steel rods in place. A variation of this has been developed in the United Kingdom whereby steel rods are fired into the ground by a compressed air gun. The system can launch such nails up to 6m long and 38mm in diameter using pressures up to 2600psi. The nails provide a reinforcement to the soil which restricts movement along actual or potential shear surfaces. This results in an increase in the stability of a slope which will provide an acceptable factor of safety against failure or form the basis of a remedial treatment where failure has occurred.

Research has been undertaken at Cardiff University to monitor the behaviour of nails as they are subjected to displacement. This has shown that friction anchors the nails within the soil over much of their length. The benefits to the soil mass occurs where the nails cross the shear surface. This results from a combination of effects resulting from;

- the inherent shear strength of the bar,
- the bending moment which develops as it deforms, and
- the tension which develops along its length.

The research indicates that the improvement caused by the nail is not sensitive to the attitude of the nail across the shear surface. The main concern is that sufficient penetration exists to ensure that the nail is anchored within the soil on either side.

10.3 Operation and benefits of the fired soil nail

The compressed air gun is mounted on the boom of a standard caterpillar tracked vehicle. A modified boom can be used to increase the reach of the machine. Positioning and firing the gun is achieved with the hydraulics of the host vehicle and from a fixed position it can be angled at any attitude from the horizontal to the vertical within the swing radius of the machine. The gun is primed by a compressor mounted on the vehicle and powered by the vehicle's hydraulics. Increased firing rates can be achieved by mounting an additional compressor. Nails are supplied fully assembled on pallets and can be moved to the machine using a relatively small support vehicle.

The total plant required to install the nails is therefore restricted to the main host vehicle for the gun and necessary support vehicle.

Each nail is installed by mounting it in the breech block of the gun. This is then placed, primed and fired. The procedure allows the nails to be installed at up to 100 per day.

10.4 Use of the fired soil nail

Fired soil nails were initially devised as a means of providing soil reinforcement and the principle use to NRA is anticipated to be for the remedial treatment of earth embankments and the construction of new ones.

The main benefits of the system arise from:

- the speed with which nails are installed,
- the cost advantages over alternatives, and
- that the effectiveness of the nail is unaffected by a wide range of construction conditions and variables.

There are however, a number of other potential uses which fall outside the bounds of soil reinforcement.

The standard nail necessary to operate effectively in soil reinforcement has a circular solid section. The nails can be constructed with other sections, they could also be made of different materials and have differing surface treatments applied to them. They have already been made and fired with a hollow perforated section. These possibilities over the standard nail offer a potential for the use of the system where environmental factors are important.

The range of proved and potential uses for the system are;

- **Improve the stability of existing flood defence embankments.**
  To allow existing embankments to be raised yet maintain an adequate factor of safety against slope failure.

- **Improve the stability of new embankments.**
  To improve the stability of any given embankment geometry and increase its factor of safety.

- **Carry out repairs to failed sections of slopes.**
  To provide remedial treatment to failed slopes on either a permanent or temporary basis.

- **River bank stabilization.**
  To improve the stability of river banks which may or may not form part of any defence embankments. This could benefit both stability of the bank slope and provide erosion protection.

- **Sea cliff stabilization.**
  Sea cliffs are best protected by preventing erosion at the toe. The upper levels will continue to fail unless they are protected by a positive stabilization system. Nails could be used in conjunction with both aspects.

- **Anchoring of other defence structures such as geotextiles, gabions, mats etc to aid stability against erosion or scour.**
  Revetments and surface treatments can fail if they are not adequately anchored to the underlying soils. Nails can either be fired through the surface treatment directly to pin it to the substrate, or in advance to provide anchor points to which the treatment can be tied.

- **Provide a pore pressure relief system for the construction of earth embankments or to aid soil consolidation.**
  If the nail could be made from, or the firing used to install a flexible and permeable material then it would provide a means to speed up the dissipation of excess pore pressures as construction proceeds.

- **Investigation and subsequent monitoring of soil gas and water over extensive areas where a large number of sample points are required.**
  Hollow section perforated nails provide monitoring points for gas or water. As the surrounding soils are little disturbed by the installation procedure representative readings can be taken almost immediately without the equalization period usually required with more usual instrument installation methods.

- **Provide a sustained gas venting or pore pressure relief system as a standalone or as part of a more structured remedial treatment.**
  The perforated hollow section nails can also be used to extract gas or water or alternatively inject gas or water and therefore can be used to control fluid movements where they derive from or have been polluted by contamination.

10.5 Existing cases

Fired soil nails have been used in a commercial setting on only a few instances. The most pertinent to the NRA was the use of the technique to stabilize a section of cutting at Duckpool Drain, Bucknall, Lincolnshire commissioned by the Lincoln office. This has prevented further failure of the treated section and reduced the on-going maintenance otherwise necessary.

The other uses of the system have been for a variety of purposes and although they have met with varying success they do show its versatility.

Fired soil nails have been used, with success, by British Rail to stabilise a section of railway embankment constructed of ash over a clay core; with less success to stabilise a section of railway cutting through Etruria Marl. They were unsuccessful when used to stabilise a large section of valley side in South Wales. However, the attempt was carried out as an evaluation exercise and did not form part of a final engineered scheme. Nails have also been used to tie back existing masonry gravity walls and to provide anchor points to which gabion type structures were fixed in order to reinstate a failed section of road in Lancashire.

10.6 Design guidelines

The developers of the system intend that it should be operated by major contractors under a franchise arrangement. To date they have not let any licenses and the system is not generally available. Nonetheless, the developers will contract to do any work which may be required. They will also provide a design service but it is expected that a computer program will eventually be made available by one of the original inventors. In the meantime the design of a soil nailed solution can be carried out from first principles, or by using other proprietary design packages developed for use with drill and grouted soil nails.

Where the nail is intended to act as a soil reinforcement, the design requires the number, length, position and attitude of the nail array to be determined to provide a sufficient increase in shear resistance across the actual or postulated shear surface. Nails are typically 25 or 38mm in diameter come in 3, 4.5 or 6m lengths. Experience, and the work at Cardiff University suggests that some 2m of nail must be present either side of the shear surface to provide sufficient anchorage. Typically nails are installed at centres of 1 to 1.5m and although the effect is not sensitive to attitude these should be generally normal to the slip surface but angled downslope to ensure that tension and not compression develops in the nail.

For other situations than soil reinforcement the number and position of nails will be governed by other factors so that similar generalizations can not be made.

Nails have been installed at about £100 per nail. Under a full commercial situation the price may be affected by an economy of scale but other factors will also come into play and it seems unlikely that the price would vary significantly from this.

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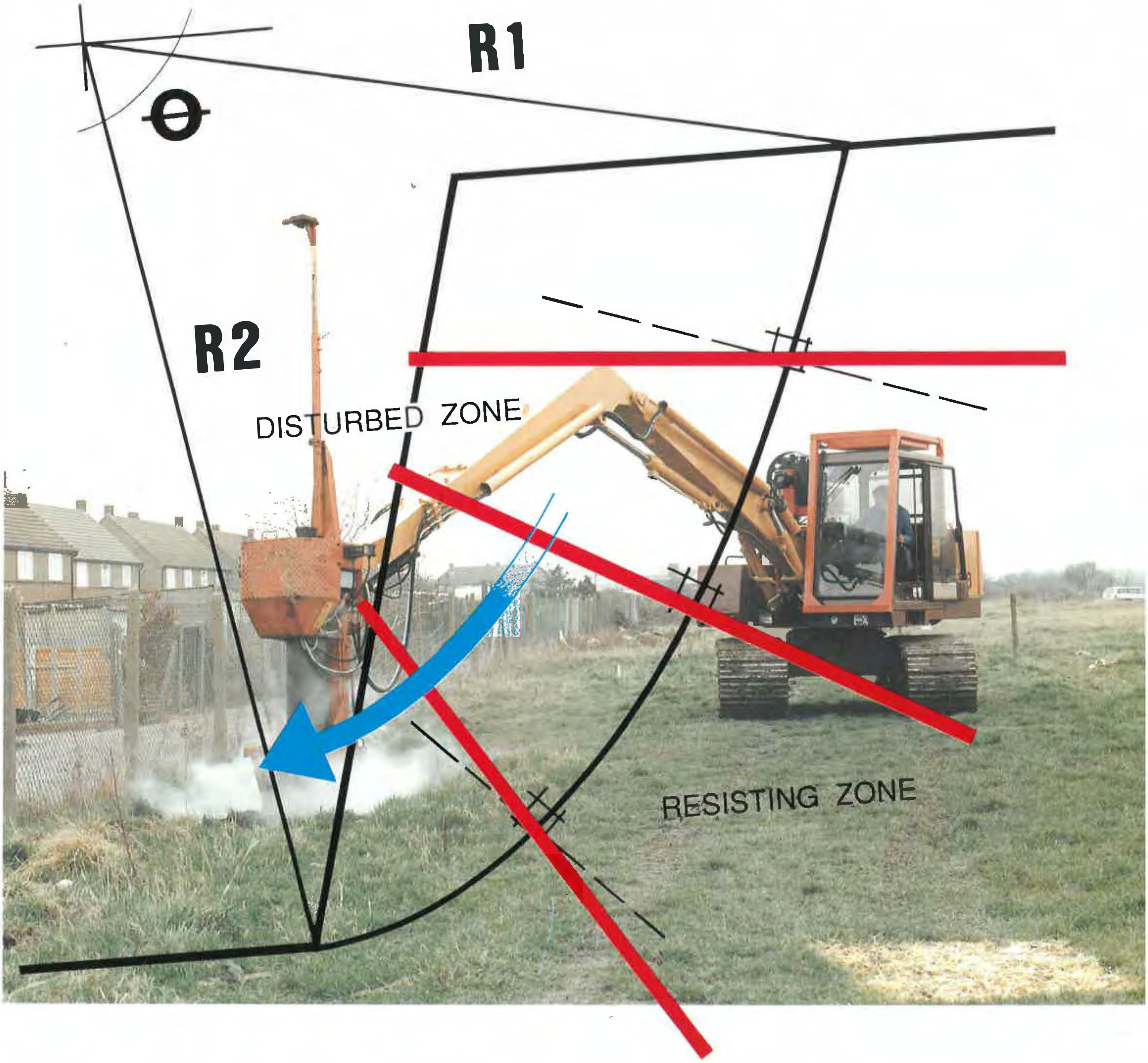
APPENDIX

Marketing Brochure of Soil Nailing Limited

SOIL NAILING LIMITED



The machine that shoots soil nails at 200 mph

Soil Nailing Limited offers a design and installation service for soil strengthening based on shot nails.

SOIL NAILING

Soil nailing is a method of strengthening existing in-situ soil by inserting thin, long, metallic or synthetic nails. The increase in strength of the soil is effected by transferring the tensile and shear resistance of the nail by friction and bearing. The ratio between tensional and shear contribution will depend on size, rigidity, position and orientation of the nail.

THE PROCESS

The Soil Nailing machine is capable of installing nails of:

- *Diameter 25 to 38 mm*
- *Lengths 2 to 6 metres*
- *To predetermined depths*
- *To any angle of inclination*
- *At a rate of 15 nails per hour*

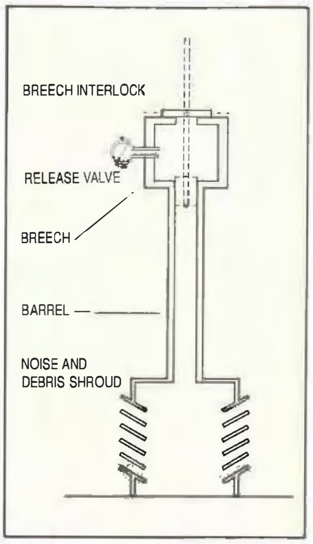
The installation of nails by means of compressed air is rapid, flexible and economical. It enables an optimization of nail placement and a minimum of site disruption.

The nails are installed at speeds of 200 mph with an energy transfer of up to 100 kJ.

The ground around the nail is displaced and compressed reducing the corrosive effect of the soil.

The annulus of compression developed at entry reduces the surface friction and minimizes damage to protective coatings such as galvanized and epoxy.

THE LAUNCHER



The compressed air launcher consists of a:

- ***Breech***
- ***Breech interlock***
- ***Barrel***
- ***Release valve***
- ***Noise and debris shroud***

The force from the air pressure is transferred to the tip of the nail thus placing the nail in tension, assuring straightness and preventing buckling on entry.

The Soil Nailing launcher is mounted on a standard wheeled or tracked vehicle with a special arm capable of positioning the nail precisely and at different inclinations.

The whole launching sequence is controlled by a microprocessor, keyword cycle which ensures correct and safe usage. Location and positioning sensors protect the launcher against discharge when not in soil contact.

The noise produced by the air launcher when discharged is a sharp boom; this is reduced by a baffled shroud which also captures any surface debris.

THE NAIL

The current steel nail is 25mm or 38mm bright bar (EN 3B) to BS:971.

The nail is fitted with a disposable plastic collet through which the compressed air energy is transferred to the nail.

The nail can be located at specific depths by the use of an arresting collar or over driven by pressure selection.

The nail can be in the form of a perforated tube for drainage or gas extraction.

The nail can be galvanized or epoxy coated.

The head of the nail is fitted with a threaded portion to allow the attachment of facing or nail extensions.

A 30mm synthetic nail is under development for use in highly corrosive soils

THE THEORY OF SOIL NAILING

Soil nails may be used in:

Shear

Tension or Compression

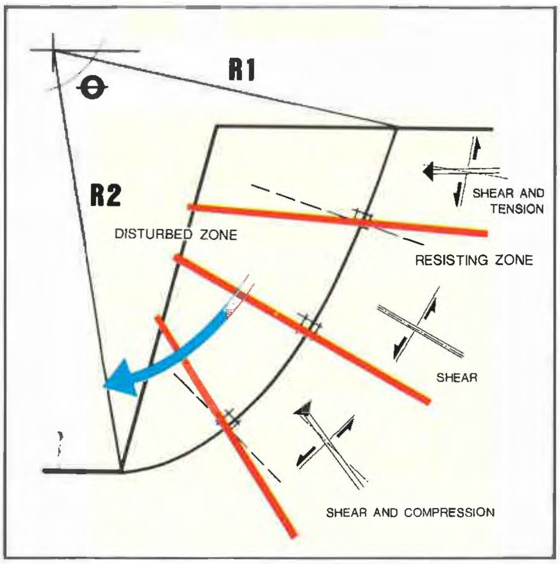
Combination of Shear and Tension or Compression

The soil movement will deform the nails and induce loads which will support the disturbed zone of soil, attaching it across a slip surface to an undisturbed zone.

The nails will be anchored within the soil by friction and bearing.

Nails aligned normal to the slip surface are wholly in shear.
The shear is resisted by soil-nail bearing and the ultimate bending moment of the nail must not be exceeded.

Nails aligned at 45° to the normal of the slip surface are wholly in tension or compression.
The tension is resisted by soil-nail friction, compression nails have the additional resistance of end bearing.

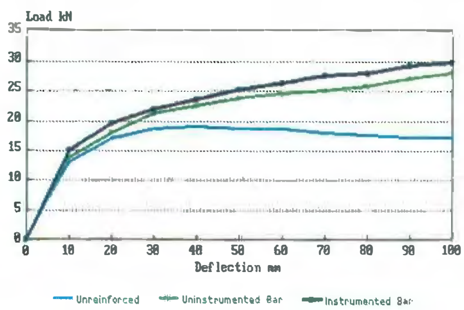


RESEARCH

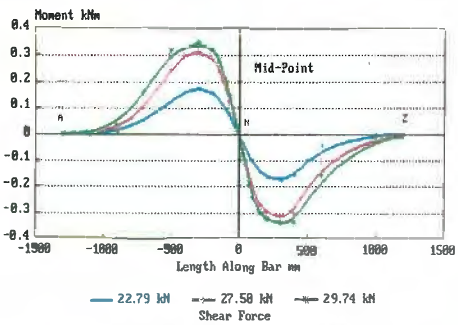
Considerable research has been carried out on soil nailing in France by the Ponts et Chaussees and recent observations in a large shear box at Cardiff University have substantiated the application of the French findings applied to compressed air launched nails and confirm the predictive analysis used by Soil Nailing Limited.

Fig 1 shows the shear resistance of a 1.5 x 1.5m sand filled shear box 3m long with and without the inclusion of a 20mm diameter steel nail normal to the shear surface.

Fig 2 shows the bending moment developed along the 20mm diameter steel nail.



Load Deflection Graph



Bending Moments Along Bar

APPLICATIONS

THE COMPANY

Soil Nailing Limited is a wholly owned subsidiary of Ryan International Limited and has been established to develop and commercialize the "Process" of soil strengthening by launching long reinforcing nails into the ground by compressed air.

The "Process" and the prototype equipment was organized and patented by the Industry Centre at Cardiff University. The compressed air launcher is produced by Ferranti Limited for military use.

The University College Cardiff Consultants Limited (U.C.3.) has granted Soil Nailing Limited the exclusive world wide licence to exploit the "Process".

Soil Nailing Limited offers a comprehensive service to:

Design

Supply

Install

Soil strengthening solutions to both Permanent and Temporary Works.

Soil Nailing Limited employs a group of engineers with special interest in geotechnics and soil reinforcement. They have at their disposal sophisticated programs and facilities to produce complete solutions or to assist clients and consultants with their designs.

SOIL NAILING LIMITED

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