Review of lime piles and lime-stabilised soil columns

Prepared for Quality Services (Civil Engineering), Highways Agency

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Executive Summary

The Department of the Environment, Transport and the Regions’s Highways Agency requires cheap, simple and effective methods of improving stability for ageing earthworks slopes on the national motorway network. To be acceptable, methods should be long lasting and not give rise to maintenance problems in the future; they also should not require excessive lorry movements during installation or much disposal of spoil.

Lime piles (small-diameter boreholes filled with quicklime) have been proposed as a method of improving slope stability, and this Report reviews their possible use for this purpose.

Lime-stabilised soil columns (larger-diameter holes filled with lime-stabilised soil mixed in place) have been used for many years to improve bearing capacity and reduce settlement and, because of their similarity to lime piles, are included in this review.

The proprietary Colmix process, which is a method of producing in-situ stabilised soil columns using a mixture of lime and cement as the binder, is also reviewed. It offers the advantage of a proven technique that has already been used to improve the stability of in-service embankment slopes.

Lime and the effects of lime on clay soils are also reviewed, and the clays most at risk from slope instability are compared with the clays most suitable for treatment with lime. It is concluded that all the clays most at risk would respond to lime treatment.

Some of the considerations that need to be borne in mind when designing a lime pile or lime-stabilised soil column are outlined and a simple design method is given by way of illustration. Worked examples show how pile or column spacing can be determined. The importance of obtaining reliable values for the pile-to-soil shear strength ratio is stressed.

The review concludes that both lime piles and lime-stabilised soil columns could be used to improve earthworks slope stability, because the shear strength of the pile or column is likely to be greater than the shear strength of the soil in which the installation is made. Reinforced lime piles (ones having a central, steel reinforcing bar) would be more effective than ordinary, non-reinforced, lime piles.

Lime piles give rise to spoil that may have to be transported off site and disposed of. Lime-stabilised soil columns, including Colmix columns, are said not to produce spoil but this needs to be verified for British clays. This may be an important operational consideration on motorways.
1 Introduction

The highway network includes a high proportion of ageing earthworks slopes that are showing signs of instability (Perry, 1989; 1991). The frequency of shallow slips is predicted to increase with time and there is a requirement to develop simple preventative measures and remedies. The traditional remedial approach of excavating the failed material and replacing it with granular fill or with geotextile-reinforced soil is disruptive. The former not only requires many lorry movements in transporting material to and from the slope, but also requires disposal of the failed material, or when using the soil-reinforcement technique, temporary acquisition of land to stockpile the material during double-handling.

A new technique for stabilising slopes has been developed that uses lime piles of small (≈200 mm) diameter. The technique involves filling boreholes with quicklime and offers a simple in-situ treatment with minimum disruption. However, its effectiveness needs investigating.

Lime columns of larger (≈500 mm) diameter, made from lime-stabilised soil by deep mixing methods, have been used for many years to improve the bearing capacity of soft ground, particularly in Sweden and Japan. Confirmation of the effectiveness of lime piles for preventing and repairing shallow slips on slopes would offer a potentially cheap and simple solution to the problem of maintaining highway earthworks with minimum disruption to the network. It is equally important to identify any drawbacks to using lime piles, particularly to avoid further maintenance problems in the long term.

In considering lime piles and lime-stabilised soil columns, it may be possible to make useful analogies between the two methods. Also, it is worthwhile appraising if lime-stabilised soil columns could themselves be used for the improvement of slope stability.

2 Lime

Lime is produced by calcining limestone in a lime kiln. When limestone (calcium carbonate, CaCO₃) is heated to 800-1000°C, it decomposes to give lime (calcium oxide, CaO) and carbon dioxide (CO₂) according to the following reaction:

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad (\ldots 1)
\]

When water (H₂O) is added to lime, calcium hydroxide (Ca(OH)₂) is formed according to the following reaction:

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 \quad (\ldots 2)
\]

This reaction is strongly exothermic and takes place vigorously with the formation of clouds of steam.

Strictly speaking, lime is calcium oxide, but both calcium oxide and calcium hydroxide are referred to as lime. When it is necessary to distinguish between the two, calcium oxide is called quicklime and calcium hydroxide is called slaked lime or hydrated lime.

If calcium hydroxide is exposed to carbon dioxide in the atmosphere or dissolved in rainwater, calcium carbonate is slowly formed according to the following reaction:

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (\ldots 3)
\]

This process is known as carbonation, and may account in part for the strong condition of lime mortar in old buildings. Carbonation takes place only slowly, and is limited by the availability of carbon dioxide to the lime.

In the presence of water, lime is capable of reacting with certain materials called pozzolanas to form hydrated cementitious compounds. Pozzolanas can be of natural or of artificial origin, and characteristically consist of reactive silicates or aluminosilicates of some kind. Pozzolanas were the basis of the cements used by the Romans. The following chemical equation for the pozzolanic reaction between an aluminosilicate and lime has been given by Lea (1956):

\[2(\text{Al}_2\text{O}_3\cdot\text{SiO}_2) + 7\text{Ca(OH)}_2 \rightarrow 3\text{CaO}\cdot2\text{SiO}_2\cdot\text{aq.} + 2(2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{SiO}_2\cdot\text{aq.}) \quad (\ldots 4)
\]

Calcium hydroxide is slightly soluble in water, and partially ionises to give calcium ions (Ca²⁺) and hydroxyl ions (OH⁻) according to the following equation:

\[
\text{Ca(OH)}_2 \rightarrow \text{Ca}^{2+} + 2\text{OH}^- \quad (\ldots 5)
\]

2.1 Reactions between lime and soil

Lime stabilisation of soil has been practised for many years and there is now much information about the effects of lime on the properties of soil, both in principle (Bell, 1988a) and in practice (Bell, 1988b). Details on the theory and practice of lime stabilisation of soil are given by Sherwood (1993) and by the British Lime Association (1990).

In general, mixing lime with soil has the effect of improving many of the geotechnical properties of the soil. However, to be most effective the soil needs to be a clay or to have a high clay content. Evidence seems to suggest that kaolinite clay soils respond more rapidly to lime treatment than do montmorillonite clay soils, with illite and chlorite clay soils having an intermediate response. However, montmorillonite soils give higher final strengths, kaolinite soils give intermediate final strengths, and illite and chlorite soils give lower final strengths when mixed with lime.

Clays containing sulphates or a high content of organic matter are not suitable for treatment with lime. This is because sulphates themselves react with lime, and organic matter may inhibit the reaction between clay and lime. As an indication, the limiting value of total sulphate content is 0.25-1.0% and that for organic matter is 2%. Further guidance on these matters is given in HA74 (DMRB 4.1.6). A review of the regional distribution of sulphates in British clay soils is given by Forster, Culshaw and Bell (1995), who report that sulphates occur widely in the weathered zone of pyrite-bearing clays such as the London Clay and the Gault Clay where it is formed by the weathering of the pyrite. Sulphate-bearing clays can...
sometimes be recognised by the presence in them of white or colourless crystals of gypsum (West, 1991).

It is generally considered that when lime is mixed with soil, two stages of reaction are involved. The first stage is an immediate improvement in soil workability resulting from an increase in the plastic limit. The amount of lime required to produce maximum increase in plastic limit is termed the lime fixation point, and the process up to this point is referred to as lime fixation. In the second stage, lime in excess of the lime fixation point is utilised in a cementation process which gives rise to an increase in soil strength. In some texts the first stage is referred to as lime modification and the second stage as lime stabilisation.

A number of mechanisms have been proposed to account for the changes in the engineering properties that occur in a clay soil when it is mixed with lime, and these are:

(a) drying (applicable to quicklime only)
(b) cation exchange
(c) flocculation
(d) change in pH
(e) carbonation
(f) pozzolanic reaction.

It should be borne in mind that more than one mechanism may occur in the same soil, and that the various mechanisms may take place at different times after mixing.

2.1.1 Drying

If quicklime is mixed with soil, or is in contact with soil, two things occur which lead to the drying of the soil. Firstly, the quicklime takes up moisture from the soil in order to convert to hydrated lime (see equation 2). Each kilogram of quicklime requires 321 g of water to do this, and this water is extracted from the soil, reducing its moisture content. Secondly, in the course of the hydration, quicklime releases much energy in the form of heat, which can also dry the soil further if the steam or water vapour generated can escape.

2.1.2 Cation exchange

The ionic equilibrium of hydrated lime is given in equation 5; the cation released is Ca\(^{2+}\) which is then available for cation exchange. The calcium ions can replace any sodium, potassium and hydrogen ions (Na\(^{+}\), K\(^{+}\) and H\(^{+}\)) present in the clay minerals. Because divalent calcium ions have replaced the univalent sodium, potassium and hydrogen ions, the attraction between individual clay mineral particles is increased.

2.1.3 Flocculation

Flocculation is closely associated with cation exchange, and is a process whereby clay mineral platelets associate in an edge-to-face, face-to-face or edge-to-edge manner depending on the balance between the attractive and repulsive forces involved (Gillott, 1987); these arrangements are of an open nature, thereby tending to produce a less dense soil structure. Cation exchange and flocculation of the clay minerals result in physical changes to the soil including an increase in the plastic limit, and are the two mechanisms mainly responsible for lime fixation. The increase in the plastic limit results in the soil behaving as a drier material at the same moisture content.

2.1.4 Change in pH

When lime is added to moist clay soil, the calcium hydroxide partially ionises and hydroxyl ions (OH\(^{-}\)) are released according to equation 5. This raises the hydroxyl ion concentration of the soil which means that the pH value is increased and the soil is more alkaline. At high pH values, silicates and aluminates in the clay dissolve, allowing a pozzolanic reaction with the calcium (see Section 2.1.6).

2.1.5 Carbonation

Carbonation is the reaction of lime with carbon dioxide (see equation 3). There are two different views on carbonation. The first is that it is undesirable because it uses up some lime which would otherwise be available for other reactions. The second is that it is desirable because the product of carbonation, calcium carbonate, is itself a cementing agent. The second view does however require further justification.

2.1.6 Pozzolanic reaction

An example of the pozzolanic reaction is shown in equation 4. Clay minerals are layer-lattice silicates in which the essential structure is one of silica and alumina sheets. When lime is added to a clay soil, a pozzolanic reaction has been postulated between the lime and the alumino-silicate clay minerals in the clay, that leads to the formation of hydrated cementitious compounds in the soil.

3 Suitability of clay slopes for treatment with lime

The suitability of clay slopes for treatment, either with lime piles or with lime-stabilised soil columns depends on identifying two factors. The first is to identify which clays are at risk from slope instability on the highway network; the second is to identify which clays are suitable for treatment with lime. The latter factor is less important for lime piles than for lime-stabilised soil columns.

3.1 Clays at risk from slope instability

The clays in England and Wales on the motorway network that are at risk from slope instability have been identified by Perry (1989) from a survey of 570 km of motorway slopes. Table 1 shows the clay formations that are at risk from slope instability in order to convert to hydrated lime (see Section 2.1.6).
tested after 12 weeks can be taken as a criterion of the suitability of the clays for treatment with lime. Namely, an unconfined compressive strength of 1720 kN/m² (250 psi in the original work) or greater indicates a very good reaction between the clay and lime. The results, in rank order of strength, are shown in Table 2.

Table 1 Clay formations with percentage of slope failures

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<th>Clay geological formation</th>
<th>Percentage of failures</th>
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<tr>
<td>Embankments</td>
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<tr>
<td>Gault Clay</td>
<td>8.2</td>
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<tr>
<td>Reading Beds</td>
<td>7.6</td>
</tr>
<tr>
<td>Kimmeridge Clay</td>
<td>6.1</td>
</tr>
<tr>
<td>Oxford Clay</td>
<td>5.7</td>
</tr>
<tr>
<td>London Clay</td>
<td>4.4</td>
</tr>
<tr>
<td>Cuttings</td>
<td></td>
</tr>
<tr>
<td>Gault Clay</td>
<td>9.6</td>
</tr>
<tr>
<td>Oxford Clay</td>
<td>3.2</td>
</tr>
<tr>
<td>Reading Beds</td>
<td>2.9</td>
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On the basis of these results it was concluded that all the clays except the Weald Clay and the Upper Coal Measures Clay responded well to lime treatment. The Oxford Clay and the Lower London Tertiaries Clay responded to lime treatment particularly well. (Note: The Lower London Tertiaries is a small group of geological formations that includes the Reading Beds).

Comparing Tables 1 and 2 it can be seen that the Gault Clay, the Kimmeridge Clay, the Oxford Clay and the London Clay are all materials that are at risk from slope failures; these clays are also responsive to treatment with lime. The Reading Beds may also be responsive to lime treatment. Therefore, all the clays most at risk from slope instability would seem to be suitable for treatment with lime.

### 4 Lime piles

#### 4.1 Precursors

The idea of inserting lime into the subgrade of roads in order to improve the engineering properties of the soil can be traced back to 1961 when, in Oklahoma (USA), engineers faced with the failure of a road that could not be closed for reconstruction, placed a charge of lime at the bottom of holes drilled into the subgrade. This technique was referred to as **drill-lime** (Noble and Anday, 1967). From 1961 to 1963 further drill-lime jobs were carried out in Oklahoma, and the technique was also employed in Wyoming, Tennessee and Louisiana.

A modification of the drill-lime technique, utilising lime slurry injected under controlled high pressure with specialised equipment that is tractor-mounted and able to operate on sloping ground, has also been used in the United States to increase the stability of highway embankment slopes (National Lime Association, 1985).

Ingles and Metcalf (1972) have described a method of inserting lime piles into very soft soils that involves pushing a hollow tube into the ground to the required depth, and then forcing quicklime under pressure into the tube as it is withdrawn from the soil. After each metre of hole is filled, the end of the tube is closed and it is then used to compact the lime. Finally, the top of the hole is plugged with clay to prevent carbonation from the atmosphere.

In Thailand a process described as **deep hole lime stabilisation** has been used to stabilise highway embankments and cuttings in clay shales (Younger and Rananand, 1985). It consists of hand-augering a series of holes (150 mm diameter, 6-10 m deep, at 3 m spacing) in the slope to be treated, and then filling them with a lime-water mixture. As the solution flowed out into the soil, it was topped up three or four times a day for a period of 1-2 months. An increase in the shear resistance of the soil around the holes of 3-8% was reported.

Neither the lime slurry drill-lime technique nor the deep hole lime stabilisation process are likely to be suitable for British conditions because of the potential risk to stability of raising the pore water pressure in the earthworks slope.

#### 4.1.1 Other reviews

Coincidentally, at the same time that the work for this review was being carried out, the Scottish Branch of the Transport Research Laboratory, in conjunction with Babtie Geotechnical, made a review of lime piles and lime-stabilised soil columns for the National Roads Directorate of the Scottish Office Development Department. The Scottish Branch’s review (Harper and Winter, 1996) covers some of the same ground as this review, although with a less analytical treatment, and was for the same purpose - namely to identify cost effective soil slope retaining and strengthening systems - but with particular reference to Scotland. The Scottish Branch’s review is one of a series of such reviews, the others of which deal with soil nailing, crib walls, and bio-engineered slope retaining systems.

The main proponents of the use of lime piles for deep slope stabilisation in the United Kingdom are the Department of...
Civil and Building Engineering of Loughborough University. They have collaborated with various industrial partners (Geotechnics Ltd, Cementation Piling and Foundations Ltd, Buxton Lime Industries, and British Waterways) in an EPSRC LINK project which had as its aims:

(a) making a literature review
(b) considering explanations for the stabilising mechanism
(c) establishing the rudiments of a design method.

The investigation was completed in 1994 (Rogers and Glendinning, 1994) and current work is concentrating upon further quantification of the stabilising mechanisms and refining of the design method (Glendinning, 1996). As well as the literature review, some field and laboratory experiments have been conducted which are referred to in Section 4.3.

4.2 Present proposal

It is presently proposed that the installation of lime piles would be a suitable method of improving the stability of highway earthworks slopes, particularly those with shallow failures (Rogers and Glendinning, 1993; 1994). Lime piles consist essentially of regularly spaced, small-diameter (typically 200 mm), power-augered boreholes completely filled with compacted quicklime.

Five mechanisms contributing to slope stability have been proposed for lime piles. These are:

(a) Lateral consolidation. Quicklime in converting to hydrated lime undergoes an increase in volume and this could lead to a theoretical increase in diameter of the pile. If proven to occur, this expansion could cause some lateral consolidation of the ground surrounding the pile. However, initial laboratory and field evidence indicates that little or no lateral expansion occurs from the pile, the expansion within the pile only increasing the density of the lime.

(b) Moisture content reduction. The slaking reaction utilises water which is drawn from the surrounding soil, reducing its moisture content. The radial extent of such a reduction, however, is yet to be proven.

(c) Reaction between lime and the surrounding clay. It was hoped that lime would migrate from the pile into the surrounding soil and a pozzolanic reaction would take place leading to cementation. There is now evidence from several sources that lime migration only occurs over a very small distance from the pile (20-30 mm) so that this mechanism would be restricted in its effect to a thin skin around the pile. In fissured clays, lime migration may be greater along the fissures. (But see Section 4.4.2).

(d) Pore water pressure reduction. The stability of highway embankment slopes is critically dependent on the pore water pressure in the soil (Crabb and West, 1986). The reduction in moisture content in the soil caused by (b) above leads to a reduction in pore water pressure in the soil, which would have the effect of improving slope stability.

(e) Hardening of the lime. Rogers and Glendinning (1994) have shown that lime in the borehole hardens with time to the extent that it becomes stronger than the surrounding soil. The lime piles themselves thus contribute to the shear strength of the ground and improve the stability of the slope. Possible hardening mechanisms that have been suggested are hydration, crystallisation and carbonation, but hardening is a relatively long process. There is a need to establish quantitatively the hardening of lime piles, and also, if carbonation is the hardening process, how far it extends down the pile from the surface.

It should be noted that the beneficial effects of (b) and (d) will tend to diminish gradually with time because the loss of moisture from the soil by the slaking of the quicklime will be replenished by rainfall and migration of ground water.

It should also be noted that, although the boreholes for lime piles are of small diameter, a large number of them on a site will produce a considerable amount of spoil which may have to be collected, transported off site and disposed of. Instead, it has been suggested that the spoil could be expediently disposed of by spreading it on the slope, but a simple calculation of the quantity involved shows that there may be too much spoil for this to be done for an array of piles. For example, it takes only five 200 mm diameter boreholes, 6 m deep, to produce a cubic metre of spoil.

4.3 Practical experience in the United Kingdom

4.3.1 British Waterways sites

Three trials of lime piles have been carried out, all on sites that were cutting slopes of canals owned by British Waterways. At present the results of these three trials have not been published, but the following brief details of the installations are available.

The first trial, in 1992, was a canal cutting slope in Lower Lias Clay near Fenny Compton, between Coventry and Banbury. The trial was of small scale and included the installation of hydraulic piezometers. It was done primarily to see if there were any installation and monitoring problems in preparation for a second, larger, trial to follow at the same site.

The second trial, in 1994, was at the same site as the first. Here, a 30 m length of failing slope was treated by the construction of 75 quicklime piles, 150 mm in diameter and 2.3 m long, installed at a spacing of 1.2 m in three rows. The holes were drilled using a small, lightweight, Minuteman drilling rig; the holes were then filled with quicklime by simply pouring it in from the top and compacting it. Pore water pressures were monitored regularly, and slip indicators were installed. Large sections of the untreated cutting nearby have slipped since the trial, but no movements have been detected in the treated section.

The third trial, also in 1994, was a canal cutting slope in London Clay situated on the Slough arm of the Grand Union Canal at Iver. Some 150 lime piles, 200 mm in diameter, were installed to a depth of 3 m within a two-week period, using a much larger drilling rig than had been used in the second trial. One problem encountered at this site was that some holes rapidly filled with water from a previously buried stream. As at Fenny Compton, pore water pressures
were monitored regularly, and inclinometers were installed. Again, no further movement has been detected.

Eighteen months after installation of the lime piles, the treated section of cutting at the Iver site was excavated to a depth of about 2 m and the following observations were made. The stabilised zone of lime around each pile was only about 10-15 mm and not the greater distance that had been hoped for, although pH changes were detected up to 50 mm. Falling weight cone penetrometer tests were carried out on each of the piles excavated, and it was noted that when struck with a trowel, the lime pile emitted a ringing tone suggesting some significant hardening had taken place. Laboratory testing indicated an undrained shear strength of 400-450 kN/m².

Laboratory tests on model lime piles gave quick, undrained shear strengths of 300-500 kN/m² (Rogers and Glendinning, 1994). Taking the quick, undrained shear strength of the London Clay to be 75-150 kN/m², this gives an estimated pile-to-soil shear strength ratio of 3.3 to 4.

### 4.3.2 London Underground site

Lime piles have been used recently to improve the stability of embankments along a 1.8 km section of the London Underground’s Jubilee Line between Canons Park and Finsbury (Oliver, 1995). The embankments in which the lime piles were installed were constructed from poorly compacted London Clay in the 1930s. The lime piles were 200 mm in diameter and up to 7 m long depending on their location; over 1000 have been installed. Each pile was formed by augering a borehole using a Casagrande C6 drilling rig; the borehole was then filled with quicklime powder by blowing it in from a delivery hopper using compressed air. All operatives wore full dust suits, masks and face protection when placing quicklime. Each pile also contained a single, centrally placed, 25 mm diameter, steel reinforcing bar, so that these particular lime piles are composite structures that do not rely solely on the lime for their effectiveness. A steel plate was placed at each end of the bar to prevent vertical expansion of the lime. It was reported that the lime had hardened very little one month after installation, although subsequent study has shown that considerable hardening had taken place after ten months. Access to the embankments was by specially constructed haul roads alongside the track.

Two things should be noted. Firstly that safety precautions have to be taken when using quicklime, and hydrated lime, in order to protect the health of the workforce. Lime suppliers must, therefore, provide specific safety advice in the form of Chemical Safety Data Sheets. These must be included in the risk assessment for the Control of Substances Hazardous to Health (COSHH) Regulations. Secondly, in the installation described above, the lime piles probably owe much of their effectiveness to the steel reinforcement, on which the design was solely based (see below).

London Underground Limited considered the work between Canons Park and Finsbury to have been successful and work has now commenced on two new contracts for similar lime pile installations between Wembley Park and Kingsbury, and between Moor Park and Rickmansworth. The techniques are still considered to be very empirical and lessons learned from the Canons Park contract have been incorporated into the new contracts. One interesting outcome of the Canons Park work was the decision taken at the design stage that in this application the overall stability comes from the reinforcing bar within the pile rather than from the benefits of the lime (Wheeler, 1996). Work is underway to quantify the benefits of lime in the composite pile.

### 4.4 Laboratory experiments

#### 4.4.1 Bamboo-lime piles

Laboratory experiments with lime piles containing a centrally placed bamboo culm (stem) have been reported by Fang, Moore and Rovi (1981). A hole slightly larger in diameter than the bamboo culm was excavated in the soil and the cane inserted centrally, the space between the bamboo and the hole then being filled with pulverised quicklime. The idea was to form a composite pile using materials that are readily available in certain developing countries. It was found that although a satisfactory bond between the lime and the bamboo was formed, the heat generated by the hydrating quicklime can damage the bamboo’s natural fibre and thereby weaken it; ways were proposed to overcome this problem but they complicated the simplicity of the original idea. Also, it is not known how long the bamboo would last when installed in the ground.

Bamboo-lime piles, of course, would have no application in the UK but are included in this review for completeness. They do, however, indicate a belief that lime piles may not be adequate by themselves and require some kind of strengthening.

#### 4.4.2 Lime piles

A laboratory experiment to study the migration of lime into surrounding clay from a lime pile has been reported by Narasimha Rao and Rajasekaran (1996). A 50 mm diameter quicklime pile (called a ‘lime column’ in the paper) was constructed in the centre of a 600 mm square test tank filled with a marine clay of liquid limit 85% and plasticity index 53%. Migration of lime into the soil was studied by measuring Ca²⁺ ion concentration, CaO content and pH value at different distances from the pile and at different times after installation of the pile. It was found that all three parameters indicated effective lime penetration into the soil up to a radial distance of 250 mm and that the penetration was complete in about 15 days. Furthermore, measurements of laboratory vane shear strength indicated that the strength of the soil had been increased by five to eight times, and X-ray diffraction studies showed new hydrated reaction products had been formed in the soil by reaction of the soil with the lime. Scanning electron micrographs of untreated soil and soil treated by means of the lime column showed considerable difference: in the latter could be seen aggregated particles with open type of fabric elements.

This experiment is of interest because the reported distance of lime penetration into the soil is about ten times further than that reported hitherto (see Section 4.2), and the following explanation for this is offered. Narasimha
Rao and Rajasekaran do not report the moisture content or density of the soil in their experiment, but they do report the shear strength as being 14 kN/m², which indicates that the soil was in a ‘very soft’ condition as classified by the Geological Society Engineering Group Working Party (1977). It is likely, therefore, that the soil was at a high moisture content and low density, conditions that would favour the migration of Ca²⁺ ions. For this reason, the result of this experiment should not be extrapolated to soils in a stiffer condition.

5 Lime-stabilised soil columns

5.1 Practical experience in Scandinavia

Lime-stabilised soil columns are often referred to in the literature as lime columns for short, as they will be in this Section. Lime columns consist essentially of large-diameter (500 mm or 600 mm) boreholes filled with lime-stabilised soil, and were developed in Sweden in 1975 (Broms and Boman, 1979a; Holm, 1988). Lime columns are constructed using a special auger that consists of a shaft with a purpose-designed horizontal and D-shaped blade at the bottom end referred to as the “egg beater”. The auger is screwed down to a depth corresponding to the length of the desired pile. Powdered quicklime is forced into the soil with compressed air through a hole located just below the horizontal part of the blade of the auger, and the lime is mixed thoroughly with the soil by rotating the blade. The tool is then slowly withdrawn with the direction of rotation of the auger reversed, and during withdrawal lime continues to be injected, thus forming a vertical column of lime-stabilised soil in the ground. The amount of quicklime used is 15-20 kg per metre of 500 mm diameter hole, which corresponds to about 7-10% of the soil dry mass (Bredenberg and Broms, 1984). It should be noted that there is no spoil produced, all the soil remaining in the hole.

The lime columns, of up to a maximum length of 15 m, are installed using specialised equipment. A 10 m high drilling mast is mounted on a special motorised carrier, the Linden-Alimak LPS-3, which tows a container for the quicklime. Both carrier and quicklime container run on pneumatic tyres but can be fitted with caterpillar tracks for work on site. The drilling mast is usually used to install lime columns vertically, but they can be installed at angles up to 10° from the vertical in any azimuth if required. Some 300-500 m of lime columns can be installed per 8-hour shift. The auger cannot penetrate coarse material (e.g. rock fill, bouldery or stony soils) and any stumps or thick roots have initially to be excavated.

Since 1975 approximately 1.3 million metres of lime columns have been installed in Sweden, Finland and Norway. The principal applications have been to improve the bearing capacity and reduce the settlement of soft clays in order to provide foundations for embankments and light structures. Lime columns have also been used, as contiguous piling, to provide walls for trenches and other excavations. There would seem to be no reason why lime columns should not be used to improve the slope stability of highway earthworks, provided that the auger was powerful enough, and robust enough, to deal with stiff clay. In this context, it has been suggested that a hollow-stemmed, multiple-auger rig such as used in the Colmix process (see Section 5.3) might be suitable for installing lime columns in stiff clays.

The shear strength of lime columns has been observed to be considerably greater than the shear strength of the ground in which they are installed, typically by some three to four times (Broms and Boman, 1979b). If lime columns were used to improve highway earthworks slope stability, the increase of shear strength along a potential slip surface through the soil would depend on the shear strength of the columns, their spacing and their orientation.

There is much literature on the use of lime columns in Scandinavia, but much is repetitive in content, and will not be further considered here. An engineer from the Department of Environment, Transport and the Regions Highways Agency’s South-East Region has visited Sweden to see the lime column technique being practised to increase the bearing capacity of soft alluvial deposits, with a view to its adoption for this purpose beneath highway embankments in the UK (Patterson, 1994).

Two recent developments in the Swedish lime column method have been the introduction of larger diameter augers so that columns of up to 1 m in diameter may be constructed, and the provision of facilities for using mixtures of lime and cement, instead of lime by itself, as the binder.

5.1.1 Swedish manual

In 1995 the Swedish Geotechnical Society published a manual giving guidance for project planning, construction and inspection of lime-stabilised soil columns and lime-cement-stabilised soil columns. The original manual is in Swedish, but in 1996 the Transport Research Laboratory commissioned an English translation (Swedish Geotechnical Society, 1995). The manual summarises present knowledge in design, construction and inspection of lime columns and lime-cement columns of shear strength up to 150 kN/m² which interact with the surrounding soil. The contents of the manual are:

1. Introduction
2. Examples of fields of application
3. Requirements for column reinforcement
4. Design assumptions
5. Design
6. Stabilisers
7. Recommendations for project planning
8. Construction
9. Inspection

Appendix A - Geotechnical laboratory test methods
Appendix B - Description of field inspection methods
Appendix C - Examples of design calculations.

The manual also sets out a recommended procedure for mixing trials in the laboratory, on the basis of which, the choice of binder is made. A suitable formulation for construction
documents and invitations to tender is given, together with recommendations for inspection and monitoring.

The fields of application of lime columns and lime-cement columns covered by the manual are for improving the bearing capacity and reducing the settlement of soft clays (e.g. shear strength 15 kN/m²) used as foundations for road embankments, railway embankments, bridges and buildings. The use of lime columns to increase the stability of slopes has been used on so few occasions, and then in conjunction with other measures, that this aspect of their use is not covered in the manual.

5.2 Practical experience in Asia

5.2.1 Japan
The method used in Japan is referred to as the chemico-pile method or the activated lime-column method (Kitsugi and Azakami, 1985), and is applied to the soft alluvial clays found in drowned valleys. The method of forming the lime column in the ground is similar in principle to the Swedish method described above, but uses heavier plant. There is another important difference in that a mixture of quicklime and a powdered chemical activator is used instead of quicklime by itself. The chemical activator is calcium silicate or calcium aluminate, or a mixture of both, and its purpose is to accelerate the pozzolanic reaction of the lime with the clay. The lime columns, which are typically 200-400 mm diameter and 6-35 m length, have been mainly used to prevent heave in excavations, and to increase the bearing capacity and reduce the settlement of foundations. The spacing between lime columns is typically 1.0-1.5 m. Lime columns have also been used to prevent slip failure in cuttings and embankments, but at the construction stage rather than during service as presently envisaged. The activated lime-column method has been used in Japan since 1965, and a total length of lime columns of 7430 km had been installed by 1980.

The use in Japan of a powdered chemical activator together with the quicklime is interesting. If this practice were to be taken up in the UK, suitable activators might be pulverised-fuel ash, ground granulated blastfurnace slag or microsilica (condensed silica fume) - each of these materials being capable of reacting pozzolanically with lime.

5.2.2 China
Since 1982, in several coastal districts of China, lime columns have been used to improve soft clay foundations for building projects (Wang, 1989). The columns were formed by driving in to the ground, to the required depth, a steel pipe fitted with a concrete pile tip. Quicklime was then withdrawn, leaving the concrete pile tip. Quicklime was then poured into the steel pipe which was then withdrawn, leaving the concrete pile tip in place. Finally, the top of the hole was plugged with clay. The published account does not state whether the quicklime was mixed with the soil. If it was not, although called ‘lime columns’, it can be seen that the method is more akin to lime piles, except that the holes are not augered but driven in to the soil. The published account does not state whether the quicklime was mixed with the soil. If it was not, although called ‘lime columns’, it can be seen that the method is more akin to lime piles, except that the holes are not augered but driven in to the soil. The columns had a diameter of 325-377 mm, a length of 5.5-9.0 m and the spacing between columns was 1.2-1.3 m. Between 1982 and 1989 the total length of lime columns installed was about 80 km.

In Thailand, laboratory model tests to see if the soft Bangkok clay would be suitable for lime column stabilisation have been reported by Balasubramaniam et al (1985). The test samples were very small (thin columns installed in clay in a 150 mm Rowe consolidation cell), but the results were considered to be promising except when the samples had a high salt content or a high content of organic matter. No field trials of the method were reported.

5.3 Colmix process
The Colmix process was developed by the French firm Bachy in the late 1980s in response to a request from the French railway and highway administrations for a process to stabilise existing embankments with the minimum of disruption (Harnan and Iagolnitzer, 1992). It is also used for improving the bearing capacity and reducing the settlement of soil for foundations. In principle, it follows on from the Scandinavian and Japanese lime column techniques.

In the Colmix process (Bachy Limited, 1996), columns are constructed in the ground by means of multiple, overlapping, hollow-stemmed augers which rotate in opposite directions. The augers can be double, treble or quadruple, giving columns of different size and shape. The augers are mounted on a long, sliding boom that is supported on the end of the articulated arm of a tracked, hydraulic excavator. The process is carried out in two stages.

In the first stage, the hole is drilled and the in-situ soil is disaggregated by the counter-rotating augers. Binder is introduced down the stem of the augers, injected into the soil and mixed with it to form a homogenous mass. The binder can be cement or lime, or a mixture of both. The binder is injected as a dry powder (the dry process) when treating soils with a high moisture content or, more usually, as a liquid grout (the wet process). The composition of the binder depends on the clay content of the soil to be treated, more lime being used if the soil contains clay that reacts pozzolanically.

In the second stage, the direction of rotation of the augers is reversed and they are extracted while simultaneously applying a downward thrust. This compacts the treated soil in the column. There is said to be no spoil produced, all the soil remaining in the hole. The Colmix process is often used in weak clays, but is unsuitable for bouldery soils or those containing hard bands of strata. A servo-control box controls the supply of grout to the column, and composition of the grout, the mixing and the compaction are all recorded graphically.

The diameter of the individual augers varies from 230 mm to 500 mm, and the cross-sectional area of the columns varies from 0.08 m² for a small double-auger column to 0.765 m² for a large quadruple-auger column. Columns can be up to 10 m long normally.

The hydraulic excavator, together with its boom and auger assembly, used in the Colmix process is on the heavy side, and because of this a temporary access road at the top or bottom of the slope to be treated would be required for operation of the excavator and the associated batching plant while the columns were being installed. For the less-heavily trafficked motorways it might be possible
temporarily to make use of the hard shoulder instead. In British conditions it is envisaged that the dry process would be used, so that the only lorry movements to and from the site would be for periodic deliveries of lime and cement to the batching plant, and the hard shoulder might have to be used for this purpose.

5.3.1 Applications
Three applications will be described; the information for these comes from Bachy Limited’s case history data-sheets and is summarised here. All are from sites in France and consist of Colmix columns installed in the slopes of embankments, the first two being railway embankments, the third a road embankment. All installations were done with vertical double-auger columns, located in parallel rows along the embankment slope. The kind of slope instability at two of the sites was not reported, but that for the Chaillot embankment was shown on a cross-section as a set of multiple, shallow, curved slips about 2-3 m deep affecting the embankment side slope. Further details of the three installations are given in Table 3.

Table 3 Details of Colmix installations in France

<table>
<thead>
<tr>
<th>Site and column details</th>
<th>Chaillot Railway</th>
<th>Seuillet Railway</th>
<th>Tarbes-Capvern Road A-64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year installed</td>
<td>1986</td>
<td>1988</td>
<td>1990</td>
</tr>
<tr>
<td>Embankment length (m)</td>
<td>900</td>
<td>200</td>
<td>43</td>
</tr>
<tr>
<td>No of rows of columns</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Row spacing (m)</td>
<td>1.0</td>
<td>NA</td>
<td>3</td>
</tr>
<tr>
<td>Column spacing (m)</td>
<td>5.0</td>
<td>6.5</td>
<td>10-15.0</td>
</tr>
<tr>
<td>Depth of columns (m)</td>
<td>1.0 or 2.0</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>No of columns</td>
<td>105</td>
<td>218</td>
<td>64</td>
</tr>
<tr>
<td>Cement content (% dms)</td>
<td>10</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>Lime content (% dms)</td>
<td>8</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>UCS of column (MN/m²)</td>
<td>3-5</td>
<td>3</td>
<td>3-6</td>
</tr>
</tbody>
</table>

Notes: NA = not available, % dms = percentage by dry mass of soil, UCS = unconfined compressive strength.

The strength of the columns is worth noting, for at 3-6 MN/m² they are in the range of weak to moderately weak rock, and about one-tenth of the strength of good quality concrete. In fact, when carefully excavated, they can be revealed as free-standing columns. The column spacings vary from 1 m x 1 m to 2 m x 2 m.

6 Design
At present there is no proven and accepted method for the analysis and design of installations of lime piles or lime-stabilised soil columns for improving the stability of earthworks slopes. For the design of a pile installation to protect earthworks slopes against slip failure, the reader should therefore consult a textbook on soil mechanics (e.g. Atkinson, 1993) to see the principles involved and the kind of considerations that are required. The following remarks are not intended to constitute a design method, but merely to suggest some considerations that need to be borne in mind and to give a feel for the sort of pile, or column, spacing that might be necessary. In the following account the word ‘pile’ will be taken to cover both piles and columns because the remarks apply equally to both. The design of a pile installation consists of three elements: deciding on the direction and depth of the piles, and calculating their spacing.

6.1 Pile depth and direction
In deciding the direction and depth of the piles, the designer should have a clear idea of how the piles are considered to act. In this account it is considered that the piles perform the simple mechanical function of adding shear strength to the soil in which they are installed. It is considered that if the shear strength of the soil is increased, the stability of the slope will be increased commensurately.

The piles should be deep enough to intercept the potential slip surface and penetrate beyond it into stable ground. For protection against shallow slope failures, say up to 3 m deep, it is suggested that the piles should extend at least as far below the potential slip surface as they extend above (i.e. the potential slip surface is no more than halfway down the pile). For protection against deep circular slips this advice may result in impractically long piles, and some arbitrary solution, such as at least 2 m below the potential slip surface, may have to be adopted.

Therefore, the designer needs to establish the shape and position of the potential slip surface in the slope. Two possibilities are that it is a shallow, more-or-less planar, slope failure (Figures 1a and 1b) confined to the earthworks, or that it is a deep-seated, circular slip which may involve both the earthworks and the underlying stratum (Figures 2a and 2b). But there are other possible shapes of the potential slip surface that need to be considered as well (Skempton and Hutchinson, 1969; Perry, 1994). If there are any existing slope failures at a particular site under consideration for treatment, it is recommended that a careful ground investigation should be made to determine the shape and depth of the slip surface. This information can then be used in the design of the pile installation.

![Potential slip surface](image1)

Figure 1 Pile installations for protection against shallow planar slope failure (diagrammatic)
In Figures 1 and 2, cases (a) show the piles installed normal to the failure planes whilst cases (b) show the piles installed vertically. In terms of the potential gain in shear strength in the region of the failure planes, a marginally increased pile cross-sectional area along the line of an inclined plane will occur with vertical installation. For lime piles, vertical installation is also generally easier in terms of drilling, placing and compacting the lime. A further advantage for shallow slips is that, for piles of the same length, a deeper penetration occurs with vertical piles near the toe of the slope which may enhance short-term drying and strengthening of the ground in this region where control of groundwater is particularly important. If the lime piles are reinforced and able to take tension, cases (a) would then become beneficial as the piles would act partly as soil nails (see Section 6.6).

6.2 Pile spacing

It is assumed that the piles are to be installed in a square grid on the surface of a slope in the direction shown in Figure 1(a) and the problem facing the designer is to determine the pile spacing for the grid. Figure 3 shows a plan view, looking from above, of the potential slip surface in the soil, with the intersection of the piles with the slip surface indicated by the small circles. The pile diameter is $x$ and the pile spacing is $y$. The shear strength of the soil is $S$ and the shear strength of the pile is $P$.

**Figure 2** Pile installations for protection against deep circular slope failure (diagrammatic)

In Figures 1 and 2, cases (a) show the piles installed normal to the failure planes whilst cases (b) show the piles installed vertically. In terms of the potential gain in shear strength in the region of the failure planes, a marginally increased pile cross-sectional area along the line of an inclined plane will occur with vertical installation. For lime piles, vertical installation is also generally easier in terms of drilling, placing and compacting the lime. A further advantage for shallow slips is that, for piles of the same length, a deeper penetration occurs with vertical piles near the toe of the slope which may enhance short-term drying and strengthening of the ground in this region where control of groundwater is particularly important. If the lime piles are reinforced and able to take tension, cases (a) would then become beneficial as the piles would act partly as soil nails (see Section 6.6).

6.2.1 Worked examples

**Lime piles**

For lime piles we have the following information:

- $x = 0.2$ m
- $P = 4S$ (from Section 4.3.1 above)
- $IF = 1.3$ (assuming the same value, albeit only as a very general guide, as the factor of safety required for slope stability for first-time slides; British Standards Institution, 1981)
Putting these values into equation 9, then

\[ y = 0.56 \text{ m} \]

For steel-reinforced lime piles the designer will need to determine the value of \( P \) for the composite pile.

### Lime columns
For lime columns we have the following information:

\[ x = 0.5 \text{ m} \]
\[ P = 45 \text{ (from Broms and Boman, 1979b)} \]
\[ IF = 1.3 \text{ (as before)} \]

Putting these values into equation 9, we have

\[ y = 1.40 \text{ m} \]

#### 6.3 Circular slip
The same simple method can be applied to a deep-seated, circular slip (Figure 2). An estimation of the mean shear strength along the whole of the potential slip surface, from top to bottom, after installation of the piles is required. The mean shear strength can be given in a simplified form by:

\[ (1 - a)S + aP \quad \ldots(10) \]

where \( a \) is the area ratio, which is the sum of the cross-sectional areas of the piles divided by the total area along the whole of the potential slip surface. The improvement factor is obtained by dividing equation 10 by \( S \), the shear strength of the soil before installation of the piles, to give:

\[ IF = (1 - a) + aP/S \quad \ldots(11) \]

The area ratio, which is the parameter sought, is obtained by re-arranging equation 11 to solve for \( a \):

\[ a = \frac{IF - 1}{P/S - 1} \quad \ldots(12) \]

#### 6.3.1 Worked example
Using the same data as given above for lime piles and lime columns, we have

\[ IF = 1.3 \text{ and } P/S = 4 \]

Putting these values into equation 12 then

\[ a = 0.1 \]

This means that the installation would have to be designed so that the piles occupy 10% of the area of the potential slip surface.

#### 6.4 Colmix process
The design of an installation of Colmix columns can, of course, be made using the simple method given above.

However, a specific design method for installing columns by the Colmix process has been described by Harnan and Iagolnitzer (1992) and is summarised, and interpreted, as follows. Harnan and Iagolnitzer remark that the majority of unstable embankment slopes do not have clearly defined slip surfaces, and they take instead, as a conceptual model for analysis, the situation in which the soil in the embankment moves out horizontally (presumably as a consequence of vertical loading). Their approach is to adopt a model which can be analysed in terms of the modulus of elasticity of the soil (although modulus of deformation would be a better term because the displacements envisaged would seem to be plastic rather than elastic). If \( S_c \) is the column section, \( S_t \) is the grid section, \( E_c \) is the elastic modulus of the column, and \( E_s \) is the elastic modulus of the soil, then the improved embankment modulus \( E_{eq} \) is given by:

\[ E_{eq} = \frac{S_c E_c + (S_t - S_c)E_s}{S_t} \quad \ldots(13) \]

If \( E_i \) is the initial elastic modulus for zero settlement of the embankment, and \( E_r \) is a reference elastic modulus for the soil taking into account the design life of the construction (presumably it can be considered as the long-term value of \( E_s \)), then

\[ E_i = \frac{S_c E_c + (S_t - S_c)E_s}{S_t} \quad \ldots(14) \]

Or re-arranging equation 14:

\[ S_c = \frac{E_i + (S_t - S_c)E_s}{E_c - E_s} \quad \ldots(15) \]

By re-arranging equation 15 to solve for \( S_t \), the grid section for any given column section can be calculated:

\[ S_t = S_c \frac{(E_c - E_s)}{(E_i - E_s)} \quad \ldots(16) \]

The validity of this approach needs to be verified and difficulties may also be encountered in deriving reliable values for the elastic moduli parameters required for the calculations.

#### 6.4.1 Example
It is not possible to give a worked example of the Harnan and Iagolnitzer design method because these authors do not provide values for the elastic moduli parameters, except to remark that “a typical value for \( E_s \) is 2 MN/m², although a variation of \( \pm 1 \text{ MN/m²} \) does not greatly affect the results”. However, they give the cross section and plan of a design for Colmix columns in the slope of an embankment at Tarbes in France for which the following details can be deduced:

\[ S_c = 0.13 \text{ m}^2 \]
\[ S_t = 2.25 \text{ m}^2 \text{ (1.5 m x 1.5 m grid)} \]
6.5 Design implications of pile strength
The worked examples show that for both ordinary lime piles and ordinary lime columns, the pile spacing is small which means that the number of piles needed is large. In order to reduce the number of piles, the pile shear strength would have to be increased. In the case of ordinary lime piles, the maximum strength is limited by the hardened strength of lime which is in turn time dependent. Lime piles can, of course, be strengthened with reinforcement. In the case of ordinary lime columns, the maximum strength is limited by the strength attainable with lime-stabilisation of the soil. However, in the case of Colmix columns, the maximum strength should be greater than that for ordinary lime columns because of the greater strength attainable with lime-cement-stabilisation of the soil.

6.6 Soil nailing analogy
It will be recalled that a reinforced lime pile is one with a steel reinforcing bar fitted axially along the length of the lime pile. If the lime hardens satisfactorily along its full length and there is good adhesion between bar and lime, and between lime and soil, then the reinforced lime pile should be able to take tension in the direction of its length. This consideration has prompted the idea that reinforced lime piles could be used to improve earthworks slope stability by acting as soil nails. To be used effectively in this way they would, preferably, need to be installed at an angle of inclination typically 10° to 15° below the horizontal. There are some obvious severe operational difficulties in doing this in drilling, placing and compacting the lime around the rebar, although it has been done at the London Underground site (see Section 4.3.2).

The design of reinforced lime piles used as soil nails would be to treat them similarly to bored-and-grouted soil nails as covered by HA68 (DMRB 4.1.4). For this purpose the characteristic strengths of the lime and the bar, as well as the bar-lime and the lime-soil bond resistances are required. Also required are the appropriate effective soil strength parameters \( c' \) and \( \phi' \) for the earthworks into which the nails are to be installed. In short, the design method in HA68 (DMRB 4.1.4) adopts a limit equilibrium approach based on a twin-wedge failure model of the earthworks slope. However, it is currently considered that the use of reinforced lime piles as soil nails should fall outside the scope of this review, until more data become available.

The analogy with soil nails is subject to confirmation and will depend on the activation of the lime. It may be that at this stage of development designers would prefer either a simple design using lime piles, and keeping costs down, or a switch to grouted soil nails with their added surety of a confident solution. Using soil nail design for lime piles may just complicate a simple and practical technique.

7 Conclusions
A review of the available literature on lime piles and lime-stabilised soil columns has been undertaken and the following conclusions reached:

1. All the clays most at risk from slope instability on highways in England and Wales are likely to respond to treatment with lime.

Lime piles

2. The major short-term stability is derived from a reduction in pore water pressure and dehydration of the clay surrounding the pile due to the hydration of the quicklime. However, beneficial effects will slowly dissipate with time, so that in the long term the clay will return to its original moisture content and pore water pressure.

3. Available evidence on the migration of lime into the surrounding clay suggests that the lime penetrates only to a small distance. Therefore, the beneficial effect of pozzolanic reaction between lime and clay will be restricted to a skin around the pile.

4. Because of these reasons, ordinary lime piles (i.e. non-reinforced lime piles) would primarily contribute to slope stability in the long term by virtue of the shear strength of the pile being greater than the shear strength of the ground in which it is installed. Research is needed to establish this quantitatively, but indications are that the shear strength of a lime pile could be of the order of 400 kN/m².

5. Reinforced lime piles (i.e. lime piles containing a steel reinforcing bar down the centre) would contribute more to slope stability than ordinary lime piles because of the additional shear strength of the reinforcing bar. Also, the lime surrounding the bar would perform the useful function of offering it some protection from corrosion.

6. It might be possible to use reinforced lime piles as soil nails carrying some tensile load, subject to overcoming installation difficulties and proving the bonding.

Lime-stabilised soil columns

7. Lime-stabilised soil columns were developed specifically to improve the bearing capacity and reduce the settlement of soft clay. However, because the columns also have a greater shear strength than the ground they are installed in, they could be used to improve slope stability in a broadly similar way as proposed for lime piles.

8. To be successfully used in this way, the auger would need to be powerful enough, and robust enough, to drill through, and mix, stiff clays.

9. Lime-stabilised soil columns are said not to give rise to spoil, in contrast to lime piles which do. This may be an important consideration if lorry movements are to be restricted.
The Colmix process offers the advantage of a proven method of installing stabilised soil columns in embankment slopes of in-service earthworks. It has the facility to formulate the lime and cement content of the binder to suit the soil to be treated, and to produce columns that are stronger than if lime alone were used as the binder. The Colmix process is said not to give rise to spoil, but this would have to be verified for stiff overconsolidated British clays.

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9 References


Volume 4 Geotechnics and drainage, Section 1 Earthworks, Part 6: HA 74 Design and construction of lime stabilised capping. (DMRB 4.1.6).


Abstract

Lime piles and lime-stabilised soil columns, including the proprietary Colmix process, are reviewed in order to assess if they would be suitable treatments for improving slope stability on the ageing, clay earthworks of Britain’s motorways. Lime and the effects of lime on clay soils are also reviewed. All the clays most at risk from slope instability would respond to lime treatment. It is concluded that, because they can increase the shear strength of the ground, both piles and columns have possibilities. A simple design method is given which indicates the direction, depth and spacing of piles or columns that would be required.

Related publications

TRL306 Laboratory trial mixes for lime-stabilised soil columns and lime piles by A H Brookes, G West and D R Carder. 1997. (price code E, £20)
CT69 Embankments - design and construction (1991-1994) (price £20)

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