A new method of soil stabilization

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The paper describes a novel method of soil stabilisation which involves mixing into the soil molecularly oriented mesh elements in the form of squares, rectangles or ribbons. Laboratory compaction, C B R, triaxial and model footing tests are detailed in which 40 mm square mesh elements are mixed into sand in order to identify the important properties of the mesh and the effect of the mesh element content on the behaviour of the stabilised soil. The results indicate that the basic operating mechanism is that each mesh interlocks with the adjacent soil particles to form an aggregation and these aggregations are locked together by the surrounding mesh elements to form a coherent matrix with improved stress resistant properties and increased ductility. These benefits are obtained even when the mesh element content is small.

INTRODUCTION

The stress resistant properties of soils can be improved in a variety of ways. For example, sheets, strips or rods of metal or polymeric materials can be placed in a soil to create a composite material with improved stress resistant properties. This is known as "Reinforced Soil" and can be regarded as soil strengthening at the macro-scale. Alternatively, the matrix of a soil can be modified by physically or chemically binding the particles together in such a way as to increase the overall stress resistant properties of the soil. Binding agents and processes used include lime, cement, bitumen, heating and freezing. All of these are termed "Soil Stabilisation Techniques" and depend on soil strengthening at the micro-scale.

A possible disadvantage of reinforced soil is that strengthening is confined to specific directions or surfaces and with some reinforcing materials, weakening of the soil may occur in some other specific directions or surfaces, McGown et al (1978). Possible disadvantages with the presently available soil stabilisation techniques derive from improvements in stress resistance often being accompanied by reductions in permeability and ductility.

The new soil strengthening technique discussed in this paper involves mixing soil with small squares, rectangles or ribbons of molecularly oriented mesh. These mesh elements interlock with groups of particles and provide tensile resistance to the soil matrix. Their action thus lies somewhere between existing soil reinforcement and soil stabilisation techniques and may thus be described as soil strengthening at the meso-scale. By ensuring that the mesh elements are randomly distributed within the soil matrix, the anisotropy of soil reinforcement is largely overcome. As will be indicated later, no reduction in void ratio occurs when using mesh elements thus no reduction in permeability is likely. Also from tests it is found that soil ductility is not reduced, hence this technique does not suffer the possible disadvantages of available soil stabilisation techniques.

It is envisaged that this innovative method of soil strengthening has the potential of being a most valuable additional means of increasing the stress resistant properties of soils. It is likely that it will be used in its own right in many situations; however, it is also considered possible that it will be employed in conjunction with soil reinforcement or soil stabilisation techniques in other situations. Development and evaluation studies of the technique are still under way and include an intensive laboratory test programme and a study of the practical problems of efficiently mixing the soil and the mesh elements on-site. In this paper, the early development work on the identification of the soil-mesh interaction mechanism, the evaluation of important mesh properties and the laboratory scale testing of soil-mesh mixtures are described.

SOIL-MESH INTERACTION MECHANISM

When a soil mass is subjected to a stress system, it strains. Even when the externally applied stress system is entirely compressive, tensile strains may develop within the soil mass. If tension resistant inclusions are present within the soil in the zones and directions of tensile strains, they will be strained and so develop tensile resistance. This will induce a transfer of stress from the soil to the inclusions, thereby reducing the strains induced by the externally applied stress system, eventually leading to an increase in the overall load carrying capacity of the soil mass.

The mechanism of this load-transfer depends upon the surface characteristics of the

Polymer grid reinforcement. Thomas Telford Limited, London, 1985

reinforcing materials. For the inclusion types currently in use, two main processes can be identified. Where flat sheets, strips or rods are used, the load-transfer depends on the frictional resistance developed at the soil-inclusion interface, but for grids and meshes it depends on their structural elements interlocking with the soil particles. This latter mechanism can be much more efficient than surface friction as it does not require relative movement of the soil and inclusion to mobilise it and it is not limited by the frictional properties of reinforcement material, depending mainly on the number and size of the openings in the grid or mesh and the size and shape of the cross members forming the structure.

It can readily be appreciated that the interlock principle applies to small mesh elements mixed in soil. In fact, it applies at two levels; each mesh element first of all interlocks with a small group of particles to form an aggregation, as in Fig.1(a), then these aggregations are locked together by adjacent mesh elements to form a coherent matrix, as shown in Fig.1(b).

Fig.1(a) Aggregation of mesh element and soil

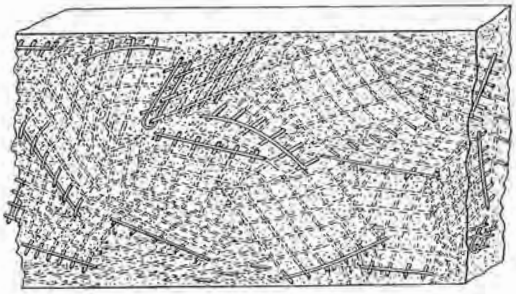

Fig.1(b) Soil - mesh matrix

Attempts have been made to employ staple (short lengths) and continuous filaments to strengthen soil, Andersland & Khattak (1979), Hoare (1979) and Leflaive (1982). The load-transfer mechanism in these cases is essentially surface friction between the fibres and the individual particles. However, where large amounts of continuous filaments are used, the filaments tend to wrap themselves around particles or even small groups of particles and this can give an additional binder effect. It is not, however, directly comparable to the two level interlock mechanism operating with the mesh elements.

IMPORTANT PROPERTIES OF THE MESH

In order to optimise the interlock mechanism, the opening sizes and shapes of the mesh elements are important and must be related to the size of the soil particles in which they are placed. Equally so, the sizes and shapes of the filaments comprising the mesh are important. For best results, the filaments should have a high profile available for containment of the soil particles. In contrast, in order not to weaken the soil, the volume of the void space must not be significantly increased by the mixing of mesh elements into the soil. Equally, the mesh elements must not significantly reduce void space otherwise soil permeability will reduce. Thus restrictions must be placed on the sizes and shape of the filaments in the mesh and on the gross amount of mesh that may be added. Thus the size and shape of the filaments and mesh openings must be balanced for maximum efficiency and the amount of the mesh added to the soil minimised.

As stated previously, the mesh elements interlock with soil particles to form aggregations and these are in turn locked together by adjacent meshes to form a coherent matrix. When this matrix is stressed, tensile strains may develop and the tensile resistance of the mesh mobilised. In order to minimise the amount of mesh required to achieve any specific improvement, the mesh should possess as much tensile strength as possible over the range of operational tensile strains and sustain this throughout the operational lifetime of the structure in which it is placed. Thus the entire load-extension-time behaviour of the mesh elements is important.

Mixing of the mesh elements into the soil must, however, be easily and efficiently achieved. Generally the requirement will be that the mesh elements are evenly distributed and randomly oriented throughout the soil matrix. Preliminary tests using a wide variety of mesh types have shown that the crucial factors in achieving this are the size and shape of the elements and their flexural stiffness and recovery. For different methods of mixing in different end uses, it is likely that the elements will vary in shape from squares to rectangles to continuous ribbons. For ease of mixing and maintenance of their geometrical stability during this stage and during subsequent stressing, the flexural stiffness and recovery of the elements has been found to be absolutely vital. Figure 2 shows the form of some very flexible meshes removed from soil after only hand mixing. It is clear that these would form loose bundles and large voids within the soil and not interlock as intended. At the opposite end of the stiffness range, rigid elements were found to form bridges and so void spaces within the soil, which is highly undesirable. Thus the flexural stiffness and recovery properties of the mesh elements are important and must be carefully selected.

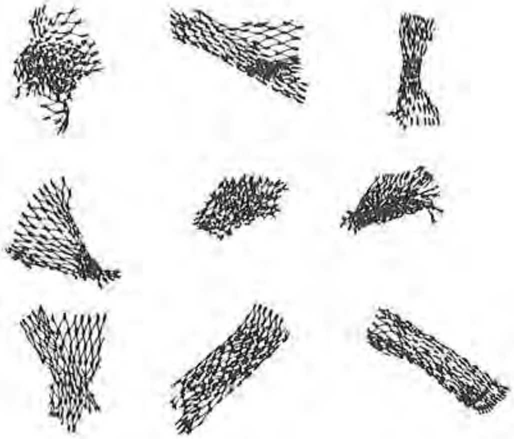

Fig.2 Flexible meshes after mixing

PRELIMINARY LABORATORY TESTING

MATERIALS USED

Prior to testing soil-mesh mixtures, it was necessary to choose a suitable soil and match this with suitable mesh elements.

Soil: The soil chosen was a readily available processed fluvial glacial sand. It has sub-angular particles with the gradation shown in Fig.3 and is known as Mid-Ross sand.

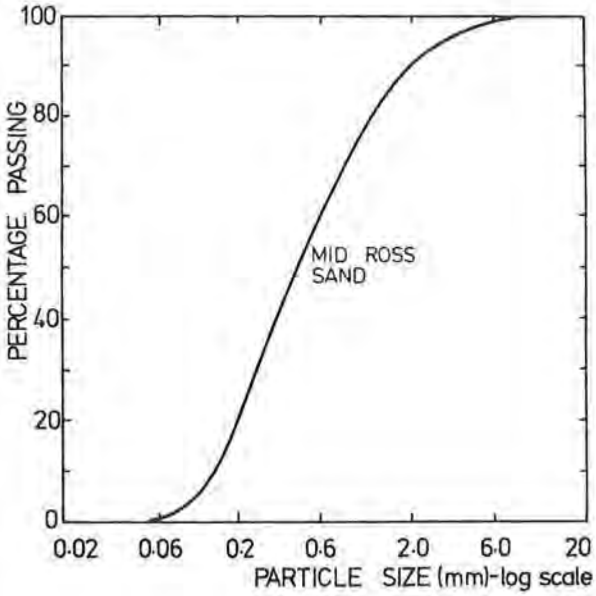

Fig.3 Particle size distribution of Mid-Ross sand

Mesh Elements: Many possible mesh types and element shapes were subjected to some exploratory tests and from these 40 mm square elements of Netlon Mesh Type 7 constructed with filaments of the shape shown in Fig.4, were chosen as the most suitable.

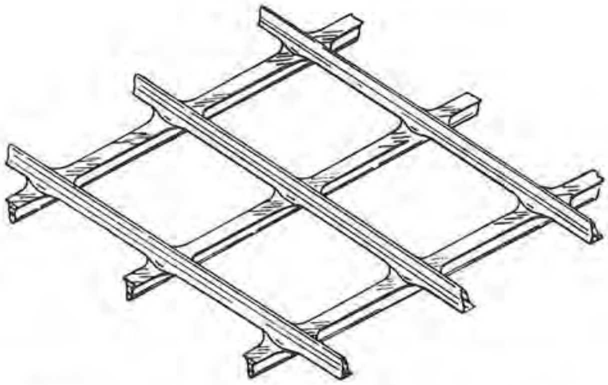

Fig.4 Structure of mesh used in tests

The physical properties of the mesh are given in Table 1 together with the tensile strength obtained from tests conducted on samples 200 mm wide by 100 mm long at 2% per minute constant rate of strain and temperature of 20°C.

TABLE 1 PROPERTIES OF MESH ELEMENTS TESTED

Production process	Netlon
Type	7
Polymer	Polypropylene
Overall size	40 mm x 40 mm
Mass/Unit area	52 g/m^2
Opening size	6.1 x 7.1 mm
Filament thickness	0.5 mm M.D. 0.48 mm X.M.D.
Maximum Tensile Strength (2%/min. at 20°C)	3.5 kN/m M.D. 3.80 kN/m X.M.D.

TESTING UNDERTAKEN

Four sets of laboratory tests were undertaken during the preliminary test programme using the Mid-Ross sand and the 40 mm square Netlon Type 7 mesh elements.

Compaction Tests: The tests were carried out in a standard CBR mould. This is 6" (152 mm) diameter and 7" (177 mm) high. The soil-mesh mixture is placed into this in three equal layers and each layer is then subjected to 55 blows using a 5.5 lb (2.5 kg) hammer dropping through a height of 12" (300 mm) onto the soil. First of all several tests were conducted on the soil alone using different water contents to establish the relationship between dry density and water content for this particular soil. As shown in Fig.5, the optimum moisture content for the Mid-Ross sand was 7.5% and the maximum dry density was 1818 kg/m^3 for this

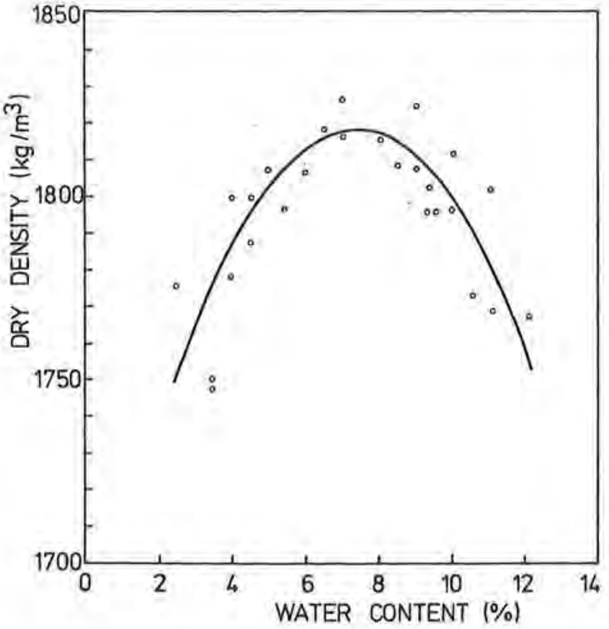

Fig.5 Compaction curve for Mid-Ross sand

level and method of compaction.

Further to establishing these data, a soil moisture content of 9.3% was chosen for use in all subsequent compaction and CBR tests on soil alone and soil-mesh mixtures. This was chosen as it ensured that the air void space available for occupation by the mesh filaments, without causing increase in void space, was at a minimum. Thus tests at this moisture content provided a "worst case" condition.

Following this, various percentages of mesh (by dry weight of soil) were mixed into the soil at a water content of 9.3% and subjected to exactly the same compaction test as the soil alone. The data obtained are presented in Fig.6 and indicate that up to a mesh content of 0.6%, the dry density of the mixture is the same or slightly greater than that for the soil alone. Therefore the mesh elements are not causing an increase in void space in the soil. At percentages of mesh content in excess of 0.6%, the dry density of the mixture rapidly decreased, indicating that the meshes were forming additional void space in the soil, which is not desirable.

<u>C.B.R. Tests</u>: The compacted soil and soil-mesh mixtures were all subjected to CBR tests. In this test, the soil in the compaction mould is placed in a testing machine, an annular surcharge load of 5 lb (2.27 kg) is placed on the trimmed top surface of the soil and a 2" (50 mm) diameter plunger is pushed into the soil at a constant rate of 1.25 mm/min. The test specimen is then turned upside down, the base of the mould removed, the annular ring

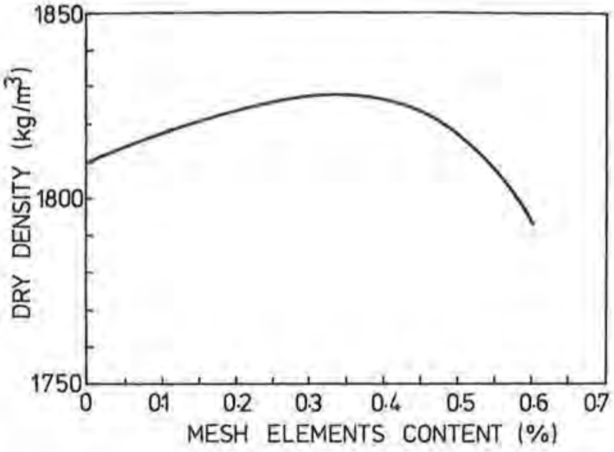

Fig.6 Effect of mesh element content on the dry density of compacted samples

positioned and the test repeated as before on the bottom of the specimen. The relationships between penetration and load applied are plotted and corrected where necessary for bedding errors, and the CBR values calculated for both top and bottom of the specimen as follows:

For 0.1" (2.5 mm) penetration $\quad \text{CBR} = \dfrac{\text{Test Load}}{\substack{3000\ (\text{lb}) \\ (13.3\ \text{kN})}} \times 100\%$

and

For 0.2" (5.0 mm) penetration $\quad \text{CBR} = \dfrac{\text{Test Load}}{\substack{4500\ (\text{lb}) \\ (20\ \text{kN})}} \times 100\%$

Figure 7 shows the effect of mixing various percentages of mesh, by dry weight of soil, into the Mid-Ross sand, in terms of CBR values at both 0.1" and 0.2" penetration. It also shows data from both the top and bottom of the test specimens but it must be pointed out that the results obtained using the top of the specimen should be discounted due to unavoidable disturbance of the specimen during trimming of the surface of the soil-mesh mixture. The results from the bottom of the test specimen were undisturbed and are therefore more indicative of the CBR value of the soil-mesh mixtures. These bottom values show that there is a steady improvement in CBR values as the percentage of mesh is increased up to almost 0.6% where some 400% improvement over soil alone is evidenced. It is envisaged that smaller mesh contents would be used in practice; however, it is clearly demonstrated in this test that such smaller mesh contents would still provide substantial improvement in soil properties.

<u>Triaxial Tests</u>: Dry samples of sand alone and sand mixed with various percentages (by weight) of mesh elements were subjected to drained triaxial tests. The specimens were 6" (152 mm)

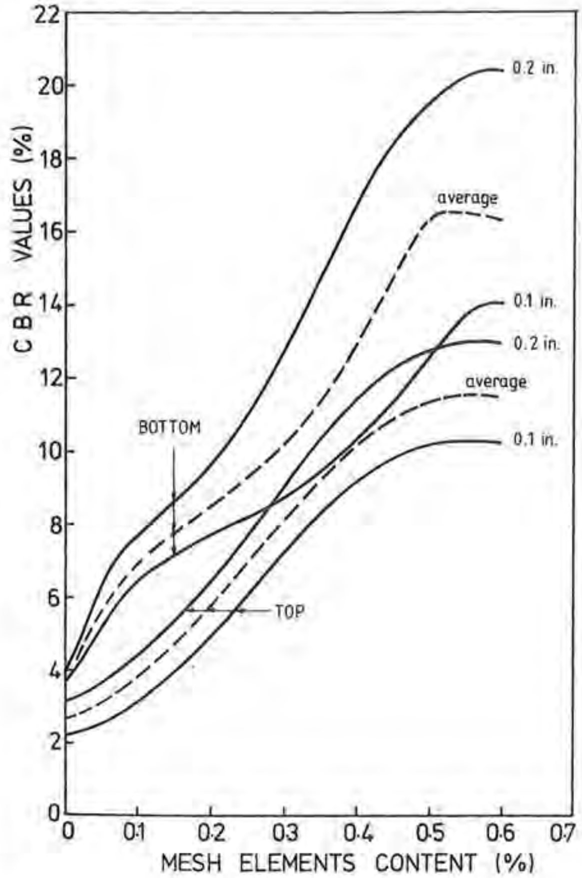

Fig.7 Effect of mesh element content on CBR values

diameter and 7" (177 mm) high, the same size as the CBR specimens. Indeed they were prepared by the same compaction procedure in split CBR moulds, the only difference being that the soil was dry. The samples were then placed in the triaxial test apparatus using lubricated end platens and subjected to cell pressures in the range 50 to 300 kN/m^2, after which they were sheared under a constant rate of strain of 5.6×10^{-4}%/min. Figure 8 shows the results of tests on the sand with and without 0.19% by weight of mesh elements at cell pressures of 50 and 150 kN/m^2. These data show that the peak deviator stresses, at these cell pressures, increased by 60% and 25% respectively, which confirms the ability of the mesh elements to strengthen soils. The data also indicate that soil improvements can be generated at low strains and low stress levels using these mesh elements and that the strength of the soil-mesh mixture is maintained over a larger strain range than with the soil alone. Thus the soil-mesh mixture is more ductile than the soil alone.

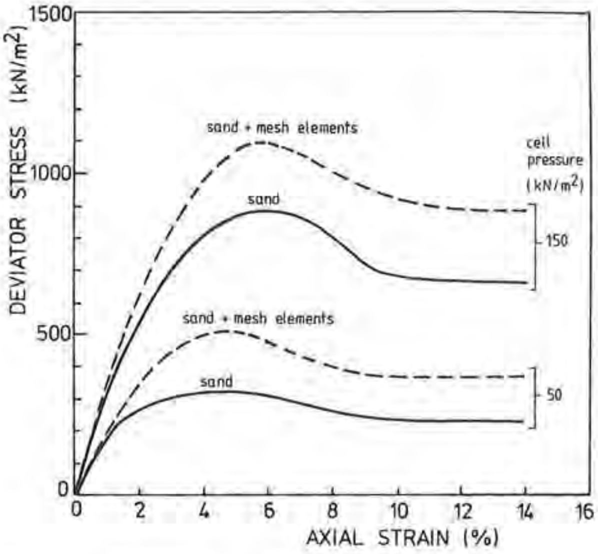

Fig.8 Triaxial test results for sand and sand containing 0.19% by weight of mesh elements

Footing Tests: In order to ensure that the previously described improvements in soil strength were not limited to these tests, plane strain model footing tests were undertaken. The test apparatus consisted of a rigid glass sided tank 640 mm long x 300 mm deep x 75 mm wide. The tank was filled with dense, dry Mid-Ross sand with and without mesh elements and a smooth metal footing 75 x 75 mm pushed down into it at a constant rate of penetration of 1 mm/min. The average data obtained from five tests conducted on the sand alone is shown in Fig. 9 which is typical of the load-settlement behaviour of this type of soil. A series of tests were then conducted with a layer containing 0.19% (by weight) of mesh elements over the dense sand. The depth of the soil-mesh layer (D) was varied from 0.5 to 4 times the breadth of the footing (B). Each test was repeated at least twice and the data from these are presented in Figs. 9 and 10.

The data from the tests illustrate that the bearing pressure increases, for any given settlement, when the soil-mesh layer is present. Also from these figures it can be seen that for a soil-mesh layer depth of 1.5B or greater no significant further increase in load at any given settlement is achieved. This implies that deep treatment of soils in such a situation is not required. Further, as the load bearing capacity at any settlement increases with increase in settlement, the soil-mesh layer has increased the ductility of the soil system, a factor previously noted in the triaxial test data.

CONCLUSIONS

The early development work on the use of small amounts of molecularly oriented mesh elements to increase the stress resistant properties of

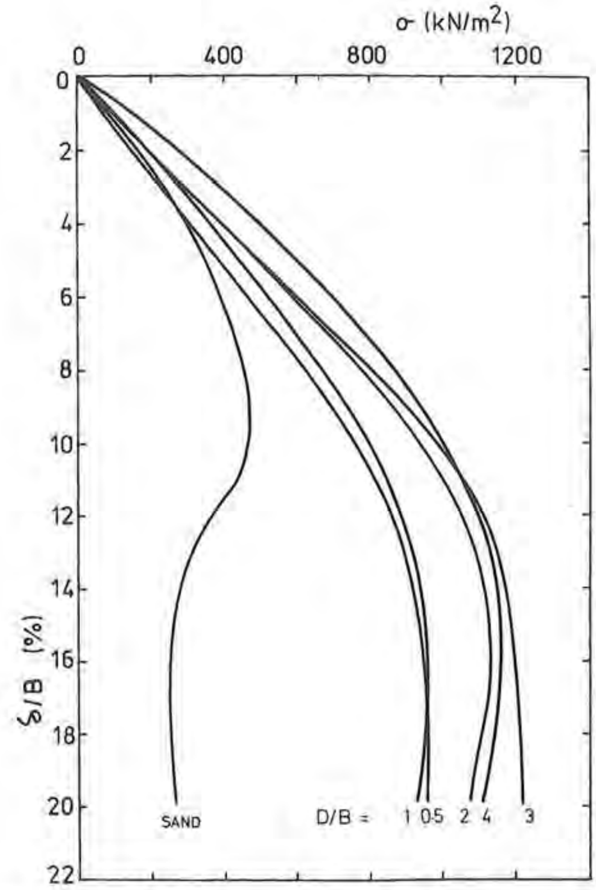

Fig.9 Footing tests - effect of the depth of the stabilised layer on the load-settlement behaviour; mesh element content = 0.19%

soils has shown that improvements can be achieved with this method without any reduction in soil density or ductility. Indeed increased ductility was a feature of the mixture identified in both triaxial and model testing. The basic responses of the mixture in the various tests were also essentially similar to those of the soil alone, thus a new design technology will not need to be developed for this technique to be employed; conventional designs using modified (improved) soil parameters should be adequate.

Further laboratory testing is now under way to further identify and optimise the important properties of the mesh elements and to relate these to different soil types. In parallel to this, field mixing equipment is being developed and mixing trials are planned. Numerous end uses for this new method of soil strengthening are also being identified and it is envisaged that the rapid development of this new concept into a practical soil improvement will be possible before very long.

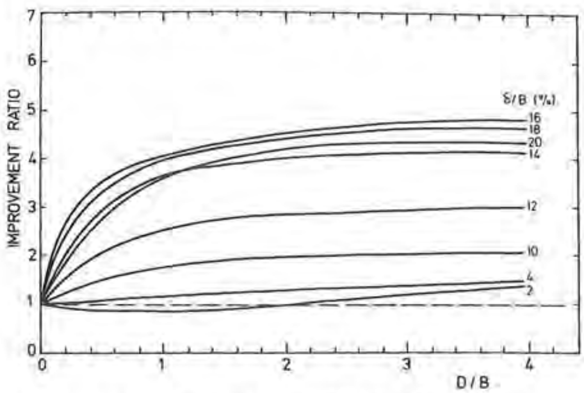

Fig.10 Footing tests - effect of the depth of the stabilised layer on the load carrying capacity at different settlements; mesh element content = 0.19%

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Patent applications have been filed in a large number of countries.

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