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The use of soil reinforcement in highway schemes

Utilisation du renforcement des sols dans les projets routiers

L'utilisation des techniques de renforcement des sols est quelquefois très avantageuse lorsqu'elle intervient dans la phase initiale de la conception d'un ouvrage important. Cette communication montre les modifications qui peuvent être apportées aux projets et l'application des méthodes de calcul classiques de stabilité de pentes au dimensionnement des talus armés.

The development of modern soil reinforcing techniques has been rapid, even so the benefits to be gained from their use have been demonstrated not only in the financial savings achieved but also in their ability to produce novel solutions to construction problems. Even though the principles and benefits have been well researched, few practical applications of reinforced earth systems have been constructed in the United Kingdom although this trend is likely to change following the publication of Memorandum BE 3/78 by the Department of Transport.

Due to the extensive lead times now involved in highway schemes it is probable that the first consideration of soil reinforcing systems by many designers will be as an alternative to a conventional solution. The disadvantages of substitution can be considerable; contractors inexperienced in the technique may tender high, short lead times for material delivery can cause logistical problems and the lack of knowledge relating to specific subsoil conditions may create design problems. The fact that reinforced earth can frequently provide financial benefits when used as a late alternative to a conventional design suggests that greater benefits could be obtained if the use of soil strengthening systems were considered at the conceptual design stage of any scheme.

CONCEPTUAL DESIGN.

Full benefit of soil reinforcing methods can only be obtained if the engineer is aware of the advantages and limitation of the technique and has access to the necessary analytical, testing and estimating procedures required for design. An essential requirement is a comprehensive soil survey which must have been planned with the understanding that soil reinforcing techniques could form part of the design solution. In particular if finite element techniques are to be used in the analysis the conventional soil survey may need to be supplemented to provide information relating to the initial stresses in the subsoil.

A study of the fields of use suggests that the most beneficial highway applications lie in the following areas:

- as retaining walls, bridge abutments or retained embankments,
- as a solution for environmental or special problems,
- as reinforced embankments, either as an aid to construction, or as a means of reducing land requirements.

Walls, Abutments and Retained Embankments.

The design and construction of conventional reinforced earth walls is now established, although the action of the complex mechanisms involved are not properly understood. When viewed at the conceptual design stage of a highway scheme, reinforced earth walls present few problems, although their cost effectiveness may suggest vertical and horizontal alignments which could not be contemplated with conventional structures.

The general motorway or trunk road bridge, if constructed using abutments, will have a significant proportion of the cost of the structure invested in the sub structure. In Yorkshire split costs of decks and abutments have indicated substructure costs rising to 70% of overall cost. Since reinforced earth has been shown to produce economies in abutment costs, significant reductions in total bridge costs are possible. The use of reinforced earth abutments cannot be accomplished without some change to the deck design, the span of which will almost certainly be increased at a cost dependent upon span and skew, Fig. 1.

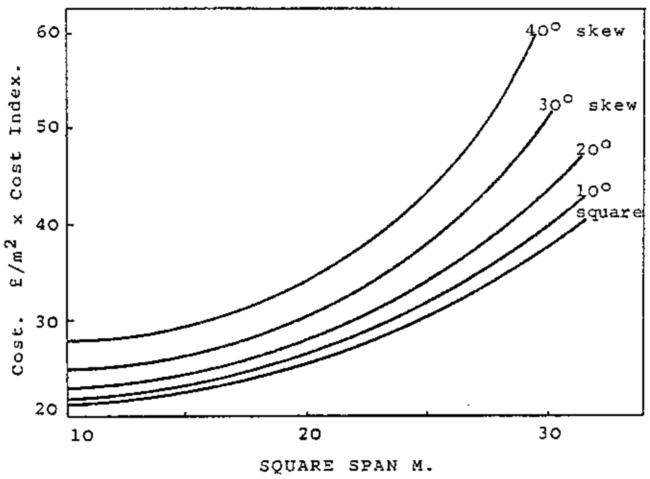

Fig. 1. Deck Costs Relative to Span and Skew.

The possibility of differential settlement with reinforced earth abutments raises concern over potential difficulties in articulation of the deck. However experience with bridges constructed in areas of active mining show that this problem can be resolved with the use of a low torsion beam and slab deck provided the twist does not exceed 1 in 80.* Sims and Bridle (1966).

The use of a low torsion deck does not necessarily introduce a cost penalty since pretensioned beams and an insitu slab deck compares favourably with other forms of deck construction as is shown in Fig. 2 which is based upon Bergg's (1974) costs for bridge decks in Kent.

The use of reinforced earth abutments in areas of low bearing capacity in which piled foundations would normally be used provides additional benefits, as the average cost of piling under abutments is high, 29% of total cost according to Bergg. The design con-

* *This represents a differential settlement of 300mm across the abutment of a typical two lane over bridge.*

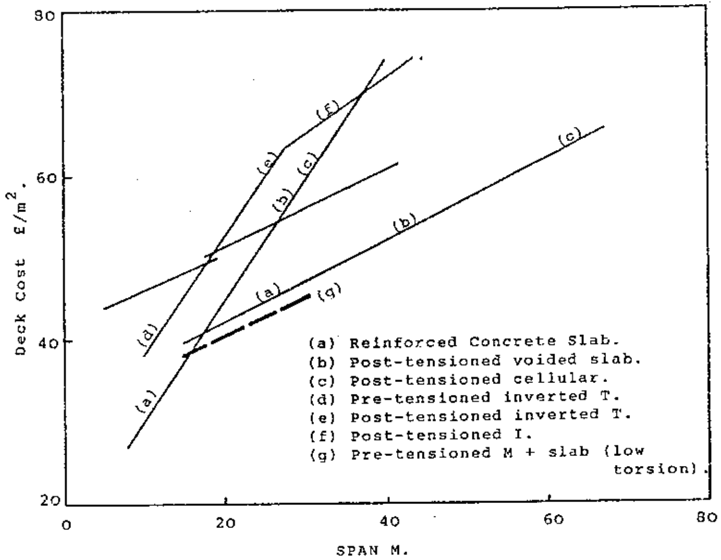

Fig. 2. Deck Cost Comparisons.

cept in these circumstances is similar to the procedure adopted in mining areas where piled foundations cannot be used due to the problem of differentail subsoil strain caused by a moving subsidence wave or where past mining activities have resulted in the presence of migrating lense cavities.* In the Yorkshire coalfield one solution is to provide a substantial bearing pad, up to 7m thick, of compacted granular material under the abutment and to accept any residual differential settlement. The use of a thinner reinforced slab formed as an integral part of the reinforced approach embankment is a practical alternative which has the advantage of minimising the incident of differential settlement which frequently occurs behind conventional abutments, Walkinshaw (1975). The same concept can be used under central piers of a two span structure, although a degree of sophistication may be required in the analysis to permit the settlements of the abutments and the pier to be of the same order.

Sutherland (1973) has shown that the use of retained embankments in place of viaducts offers considerable financial benefits, although in an urban environment the local severence caused by such structures may cause problems of access, Fig. 3.

In rural conditions the use of viaducts is synonymous with bad ground conditions on which a conventional embankment cannot be constructed. In these conditions the use of earth reinforcing systems to improve the bearing capacity coupled with a reinforced earth retained embankment warrants special consideration. A design procedure for reinforced embankments forms the second part of this paper.

* *Cavities which over a period of many years move to the surface - hence the term migrate.*

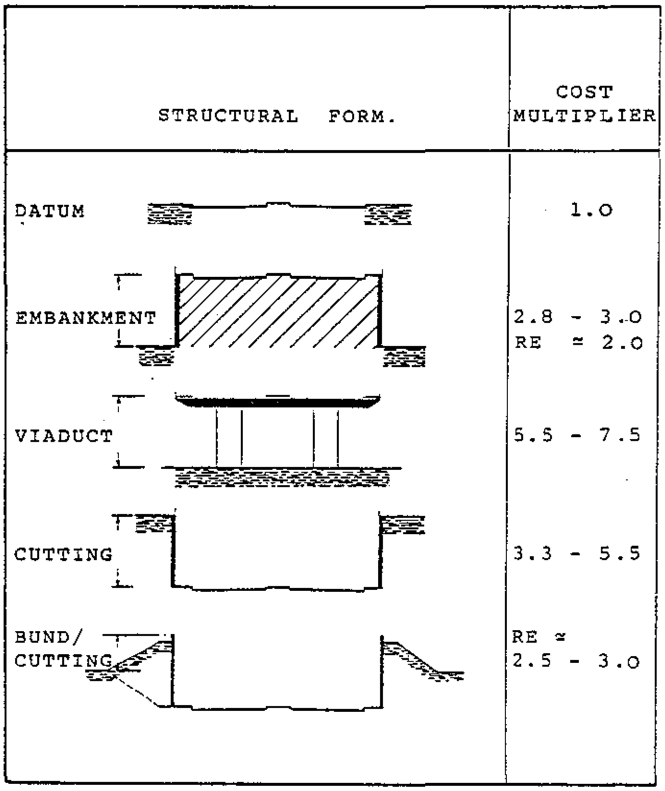

Fig. 3. Cost Alternatives of Structural Forms.

Environmental or Special Problems

U.K. road desgin standards cater not only for the road user but also for the community and the environment. In particular the problem of noise pollution is taken very seriously, and following the introduction of the Land Compensation Act 1973 and the Noise Insulation Regulations 1973, highway designers are obliged to consider noise in the environment at the initial design stage of any scheme. Noise barriers have to be introduced, and noise insulation installed on adjacent buildings if noise levels exceed 68dB(a). Dropping the highway into a cutting is one way of reducing noise pollution. The relative cost of a highway in cutting aginst that at datum can be high and a compromise solution is the use of reinforced earth environmental bunding in conjunction with a partially sunken road. With this solution not only is the noise pollution eased but the severence problem is less acute as bridge crossings of the sunken highway require relatively short climbs for elderly pedestrians, Fig. 3.

The potential for using reinforced earth as a method of solving particular technical problems is extensive. The following example illustrates a unique quality with regard to bridge abutments in areas of mining subsidence. Bridges and other structures in an active mining area are subjected to both compressive and tensile ground strains. Designing bridges to resist these strains is usually uneconomic, the solution is to permit the abutments to move together during the compressive phase of the subsidence wave, Sims & Bridle (1966). Confirmation of this action has been obtained during active mining, Jones and Bellamy (1973). Designing the abutments to accommodate the lateral pressures needed to cause this movement can add 25% to the cost. Reinforced earth structures can tolerate compressive strains and hence stresses without any major change in design, although care must be taken to ensure that the tension phase of the mining wave does not cause tension failure of reinforcement.

Reinforced Embankments.

Reinforcement in an embankment can take several forms depending upon the nature of the problem to be solved. In Japan reinforcing the edge of railway embankments, using nets to combat the acute climatic conditions, has been reported by Iwasaki and Wakanabe (1978). The use of reinforcement close to the face permits the operation of heavy compaction plant near the shoulder of the slope and encourages uniform compaction throughout the embankment. Adoption of this construction technique on highway schemes could ensure the stability of the edge of the hard shoulder which is known to cause some problems, Fig. 4.

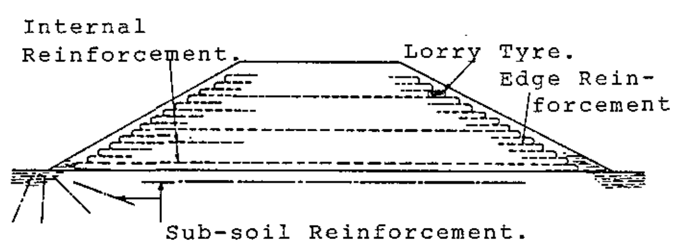

Fig. 4. Reinforced Earth Embankment.

Similarly the use of nets throughout the embankment permits higher compaction to be obtained. The latter has been demonstrated on the Uetsu Railway line where Iwasaki and Wakanabe have recorded the stiffness of an unreinforced earth embankment as having Standard Penetration Values (N values) averaging N4 with a peak of N 7.5. The equivalent readings for a reinforced earth embankment of N 30 with a peak of N 60 permits the reduction of the embankment spread by steepening the slopes. The benefit of reducing the spread can be substantial.*

**Savings of £1,000 per m. excluding land can be demonstrated for a 10m high embankment steepened from 1:2 to 1:1 situated in a semi-urban environment.*

A further use for earth reinforcement is beneath embankments situated on weak subsoils. The objective in this application being either to permit construction to take place by the creation of an artificial subsoil crust (the alternative being a viaduct tructure) or to enable the erection to proceed at a faster pace than the dissipation of the pore water pressures would normally allow, to this end the use of subsoil reinforcement may be used as an alternative or adjunct to expensive subsoil drainage.

PRACTICAL DESIGN METHOD FOR REINFORCED EARTH EMBANKMENTS.

The design of local edge stiffening is heavily dependent upon the development of suitable construction details, in particular there is a need to provide a self supporting edge around which the reinforcement can be wrapped. The use of waste materials such as lorry tyres or redundant kerb stones can provide this function, Dalton (1977). The analysis of the edge stiffening condition can be undertaken using empirical methods based upon the stability of wedges loaded by compaction plant, Iwasaki and Wakanabe (1978) or against localised modified Rankine lateral earth pressures, Broms (1978).

In the design of more extensive reinforced earth systems, such as where the embankment is to be stepped or where reinforcement is required beneath a major embankment, more detailed design procedures may be required based upon the predicted behaviour of the embankment and its supporting subsoil. The action of reinforcement embedded in soils in an area of tensile strain is to anisotropically suppress the natural dilation, Bassett & Last (1978). This conclusion has followed from extensive studies into the fundamental behaviour of simple soils and in particular their stress-strain characteristics as described by Roscoe (1970). Many of the findings of this work have implications to the designer of reinforced earth embankments. In particular the finding that for monotonically increasing stress the principle axes of strain rate (increment) and of principal total stress coincide, together with the concept that slip planes or ruptured surfaces (velocity discontinuities) coincide with the directions of zero extension, (the α and β trajectories), can be used as the basis for a design method for embankment reinforcement. In an embankment structure the major principle stress (σ_1) and (σ_3) are both usually compressive. However due to the dilation characteristics of a compacted embankment the minor principal strain rate ($\dot{\varepsilon}_3$) is tensile and the area of this tensile strain is bound by the arc formed by the α and β directions. Tensile reinforcement embedded in the soil contained in this arc will be effective.

The problem facing the designer is one of determining or predicting the directions of the compression strain trajections and the α and β zero extension lines. Failure to do this could mean placing tensile reinforcment in a position of compressive strain. This is not only ineffective but could result in a decrease in the overall strength of the system if the surface friction and adhesion of the soil - reinforcement was less than the soil itself and if the reinforcement was aligned close to a slip plane, Andrawes et al (1977). The directions of the compressive strain trajectories and the α and β zero extension lines are readily obtained from model tests in which internal strains can be measured, Roscoe (1970), while Bassett & Horner (1977) have demonstrated that accurate predictions can be obtained from centrifuge tests. Model tests are not applicable to the embankment design problem in which gravitational stresses are dominant and although centrifuge tests meet all requirements their use is restricted due to the special nature of the facility.

The answer lies in the use of mathematical soil models based upon the finite element method. These have been shown to produce accurate predictions of the behaviour of full scale structures, Jones and Edwards (1975), Wroth (1975). In practice only two models appear generally available for use, but between them reflect the two extremes of approach to this form of mathematical modelling. CHRISTINA* is an elasto-plastic stress/strain model based upon the concept of critical state soil mechanics which includes realistic volumetric and shear behaviour for the soil. It can conduct analyses in terms of effective stress (it can model pore pressures) and covers the effects of stage by stage construction. Being based upon the modified Cam-Clay model, it is technically restricted to problems of normally or lightly overconsolidated cohesive soils, although linear elastic behaviour can be specified for any part of the problem.

The other available soil model is FELSTA‡ which is based upon the non-linear elastic model proposed by Duncan and Chang (1970). This uses a hyperbolic curve to represent the results of triaxial tests of representative samples of soil. The tangent of the hyperbola is used to provide an expression for an incremental deformation modulus, the increments giving an excellent representation of step by step construction. The hyperbolic model does not allow for dilatancy and is sensitive to criticism regarding the rate of volume change. However a tangent modulus can be obtained to simulate

* *CHRISTINA - Critical State Finite Element Program developed by the Soil Mechanics Group of Cambridge University.*

‡ *FELSTA - Finite Element Stability Analysis developed by West Yorkshire Metropolitan County Council for and on behalf of the Department of Transport, (Edwards (1978)).*

changes in Poisson's ratio and this is included in FELSTA, Kulhanny and Duncan (1972). The FELSTA program was evolved from a range of structural finite element programs and includes linear elastic elements, elastic perfectly plastic elements and truss elements, the latter are capable of passing through an element without adversely affecting the idealisation of the shear strain properties of the system. As a result it can be used to simulate the interesting condition in which prestressed reinforcement is used. Since the action of correctly orientated tensile reinforcement is to supress the dilation of the soil, one of the main objections to the use of the hyperbolic model is removed and this model is used in the following design example.

The form of the analysis is analogus to the finite element analysis used with many bridge decks in which the analysis is used to determine shears, bending moments and reactions from which the necessary reinforcement is derived using Wood-Armer equations. In the case of reinforced embankments the analysis has to be taken to a second iteration:

(i) an initial finite element analysis using incremental procedures (step by step construction) is used to derive the direction of principal total stress for each increment, together with the α and β zero-extension lines. Fig. 5.

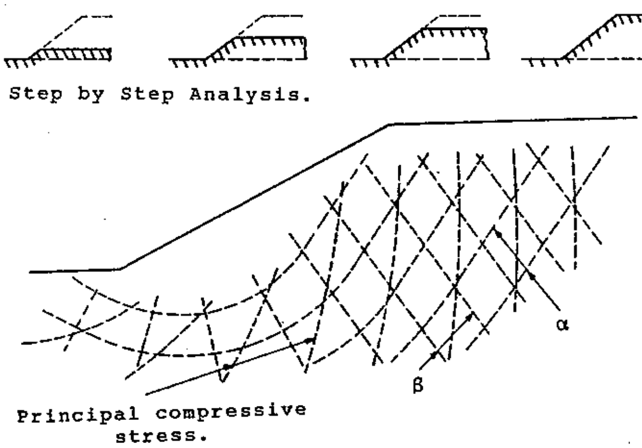

Fig. 5.

(ii) Additional elements are added to the idealisation to represent the reinforcement and the analysis is repeated. Fig. 6. (In view of the uncertainty in the use of any soil model it seems prudent to restrict the position of the reinforcement to the middle third of the tensile strain arc, practical considerations permitting).

The second analysis is required to check that the reinforcement stresses do not exceed limiting values based on stress levels or adhesion characteristics derived from laboratory tests. The second analysis can also be used to demonstrate the re-

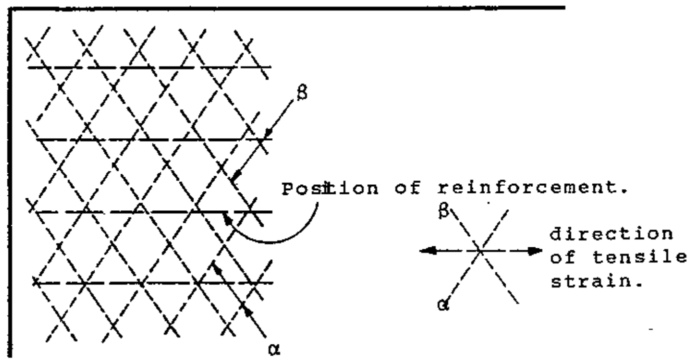

Fig. 6.

alignment of the zero extension characteristic described by Bassett and Last (1978).

In a cohesiveless soil the zero extension characteristic cannot be plotted directly, since the FELSTA analysis ignores volumetric strains. However tests at Cambridge have shown that a value for volumentric strain $\nu = 20^{o}$ for dense sands holds over a wide stress range (covering the internal stresses generated in embankments up to a height of 30 m.), Roscoe (1970). Using this the zero extension lines can be derived from

$$\frac{dy}{dx} = \tan\left(\xi \pm \left\{\frac{\pi}{4} - \frac{\nu}{2}\right\}\right)$$

where ξ = direction of the major principal strain rate $\dot{\varepsilon}$.

In the subsequent analysis in which reinforcement is included a value of $\nu = 0$ seems more appropriate.

In the case of reinforcement beneath an embankment cohesive soils are usually present and an analysis based upon undrained conditions is appropriate. Fig. 7 shows the α and β trajectories and the preferred positioning of the reinforcment. The distribution of the rupture surfaces show a pattern similar to that obtained from centrifuge tests.

If reinforcement is applied across the compressive strain arc, Fig. 5, the other form of reinforced earth, namely a reticulated structure is obtained. Reinforcement for this form of structure must be capable of resisting compressive strains and is traditionally formed from small diameter concrete piles.

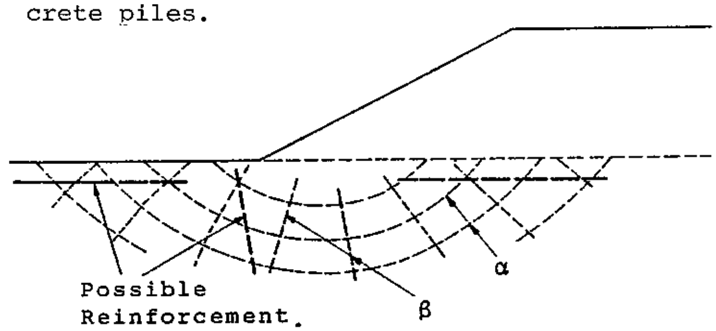

Fig. 7.

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