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Inextensible reinforcements versus extensible ties – FEM comparative analysis of reinforced or stabilized earth structures

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ABSTRACT : The actual behaviours of vertical earth structures reinforced with inextensible or extensible reinforcements and designed according to current practice are compared on finite element models. Fundamental differences between the observed mechanisms and deformations are highlighted. Important consequences with regards to design principles are identified.

1 INTRODUCTION

While the original Reinforced Earth® technology was developed with steel strip reinforcements, non metallic straps, grids and sheets were later on introduced into that technique. There is an urgent need to identify materials which are in fact suitable for reinforced soil structures with respect non only to durability but also to design implications.

Materials used for reinforcements have different deformabilities and their strains at usual working loads range roughly from 0.1% for steel strips to 7% for oriented polyethylene grids and even more for many geotextiles. This clearly affects the interaction between the soil and the reinforcements, hence the behaviour of the structures and the appropriate design principles.

The University of Manchester (UM) and Terre Armée Internationale (TAI) attempted to directly visualise and compare on finite element models the actual behaviours of the same structure, reinforced with three different types of reinforcements and designed following current practices.

2 MODELLED STRUCTURES

It was found appropriate to study a 7.5m high vertical retaining wall supporting a horizontal embankment, typical of actual road projects. The length of the reinforcements is 6m and their vertical spacing is 0.75m.

The 3 types of reinforcements correspond to products actually supplied to the market place :

1/ High adherence 40 or 60x5mm steel strips (HAS) ; short term strength (STS) : 104 or 158 kN ; Young's modulus : 205.10^3 MPa; stiffness : 40 or 60 MN.

2/ Polyester based belts, 90mm wide (PBB) ; STS : 50 or 100 kN ; stiffness: 4.2 or 6.3 MN.

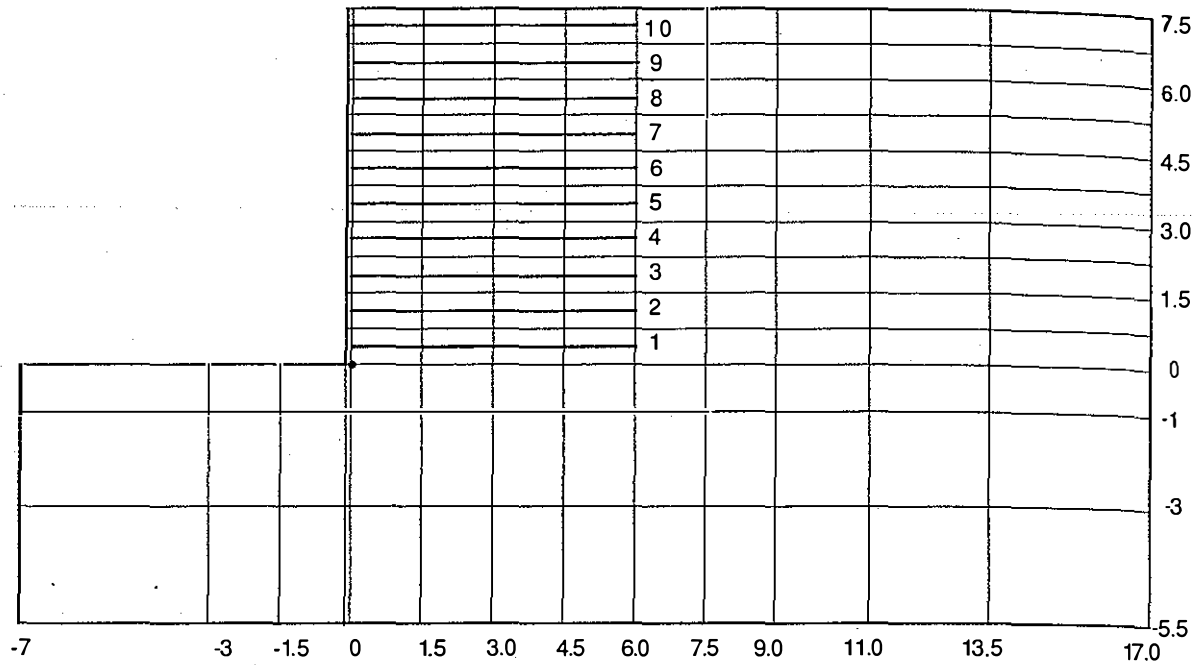
3/ Oriented polyethylene grids, 1m wide (OPG) ; STS : 80 or 110 kN ; stiffness: 0.3 or 0.4 MN.

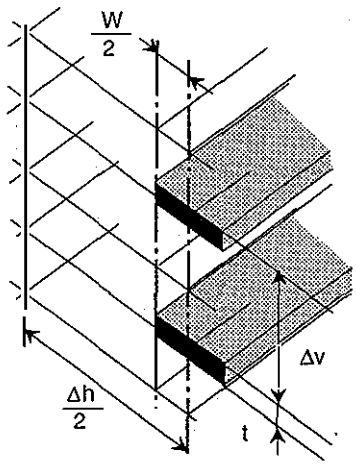
For each type of reinforcement the wall was designed according to the proprietary guidelines in use in a single country, in this case the UK. The resulting arrangement is shown on the table attached to fig.1. Two or three grids had to be superposed towards the bottom of the wall, due to the fixed 0.75m vertical spacing ; this however does not affect the analysis, since friction is over-abundant.

3 FEM DETAILS

3.1 *Mesh*

The analyses were truly three-dimensional, and used "brick" shaped (cuboidal) elements to model fill, foundation, reinforcements and facing. These elements had 14 nodes per element (eight corner and six mid-face). They give a more flexible response than 8-node bricks but are stiffer in bending than 20-node bricks





Reinforcements Horiz.spacing (m)	HAS 0.75	PPB 0.50	OPG 1.25
Layers 10	40	1×"50"	1×"80"
9	40	1×"50"	1×"80"
8	40	1×"50"	1×"80"
7	40	1×"50"	1×"80"
6	40	1×"50"	2×"80"
5	40	1×"50"	2×"80"
4	40	1.25×"50"	2×"110"
3	40	1.25×"50"	2×"110"
2	60	1×"100"	3×"110"
1	60	1×"100"	3×"110"

Fig. 1 : Description of finite elements models.

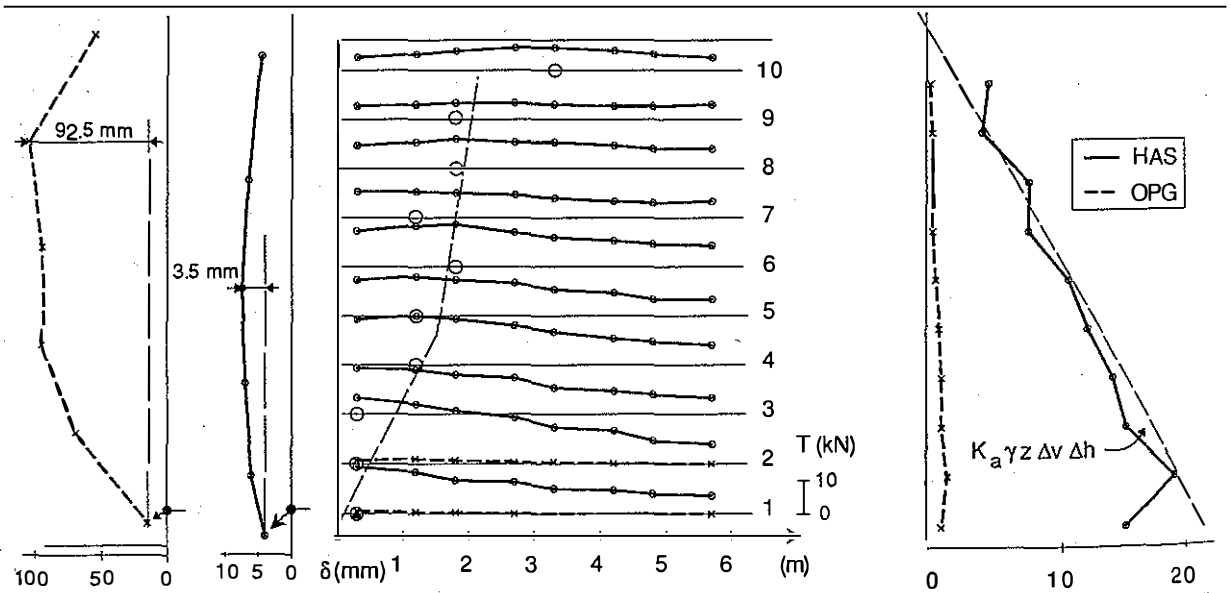


Fig. 2 : Summary of results (deformations, tensile loads, maximum tensile loads) for high adherence strips and polyethylene grids.

(Smith and Kidger, 1992). Deformations of walls modelled with the same number of 20-node and 14-node bricks have been found to be comparable.The 14-node elements are almost exactly integrated using 2x2x2 Gaussian integrating points with no associated spurious zero energy deformation modes. Stresses, strains etc... are computed at the 8 Gauss point locations within each element.

A side view of the first mesh used is shown in fig.1. In later calculations, two columns of elements were moved from the extreme right hand side of the mesh and repositioned within the first mesh spacing behind the wall facing. In either case the mesh contained about 1000 elements.

Because of the repetitive nature of the reinforcements normal to the plane of fig.1 only a thin slice between the vertical plane through the reinforcement centrelines and the vertical plane midway between successive columns of reinforcement was analysed. Indeed there were only two layers of elements, one reinforced and one not, normal to fig.1. Appropriate boundary conditions ensured representation of the repetitiveness.

3.2 *Material Properties*

The soil was modelled as a linearly elastic-cohesionless Mohr Coulomb plastic solid. The Coulomb peak angle of shearing resistance was 36° within the reinforced volume of the wall and 30° in backfill and foundation. Possible softening of the soil due to large strains associated with extensible reinforcements was ignored at that stage. No dilation was attributed to the soil, which everywhere had a density of 20kN/m^3. Fill, within the reinforced volume and in the backfill, had Young's Modulus of 60 MPa while the foundation had twice this value. Poisson's ratio was about 0.3 everywhere.

The wall facing was given the same properties as the soil, implying a "flexible" facing. However, it could not yield.

The reinforcements were treated as linearly elastic solids with a high yield stress (never attained in these analyses). Their Young's Moduli were adjusted to give appropriate stiffnesses in terms of kN/m but in absolute terms were about 130 MPa for the most flexible reinforcement and about 30x10^3 MPa for the stiffest (i.e. 230 times more) at wall mid-height. At the free ends of the reinforcements, separation of reinforcement from surrounding soil was allowed for.

The stress redistribution algorithm was of the viscoplastic type (Smith and Griffiths, 1988).

3.3 *Construction process*

In the calculations, the wall was "constructed" in lifts 1.5m high. The gravitational force of each lift was applied in increments and displacements, stresses and strains were monitored in reinforcement and soil throughout the construction process.

4 COMPARISON WITH PREVIOUS STUDIES

The results of the calculations carried out first with the steel strips were compared with those obtained with the "Rosalie" code (Bastick and Anderson, 1983). This previous study was only a "semi-3D" one, the mesh was different and the actual wall construction was not modelled. The results are however very consistent.

In both cases the maximum tensile loads closely centre on a line corresponding to $K_a\gamma z$, except near to the foundation. The locus of the points of maximum tension is within a distance of 0.25H from the facing over the top half of the wall, forgetting the uppermost layer, of little significance (TAI, 1988).

The variation of tensile load along the different strips has the same aspect in both studies : the strips are under tension over their entire length ; tension decreases evenly up to the end, in other words reinforcement is effective throughout the whole body. The maximum deflection of the facing relative to the toe was found to be about 0.04% or 0.05% of the height, depending on whether the construction is modelled (UM) or not (Rosalie). The displaced wall profile and tensions in the HAS strips from the UM three-dimensional computations are shown in fig.2.

The UM model was consequently validated for the case of inextensible reinforcements.

5 THREE-D F.E.M. ANALYSES FOR EXTENSIBLE REINFORCEMENTS

The following analyses used the mesh shown in fig.1, i.e. without refinement close to the facing. The reinforcement properties were typical of oriented polyethylene grids. The displaced

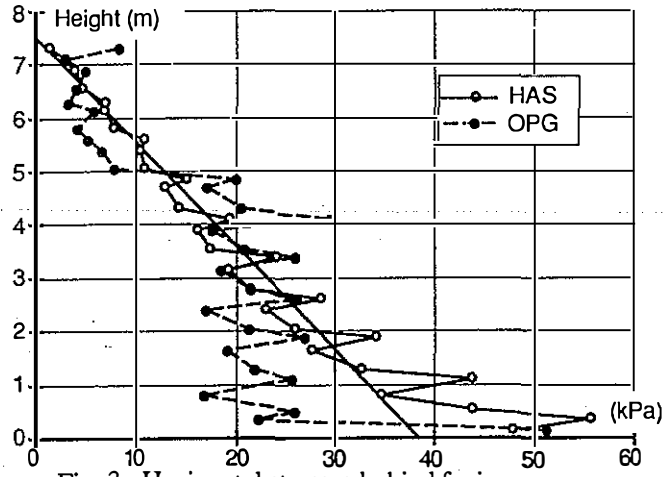


Fig. 3 : Horizontal stresses behind facing.

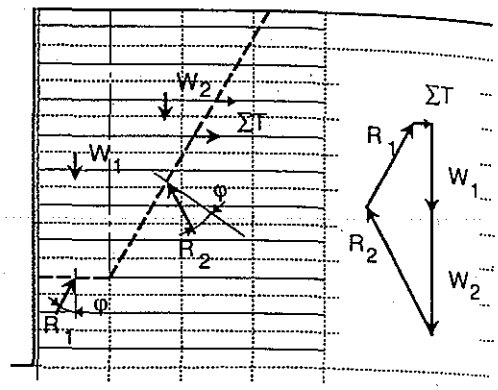
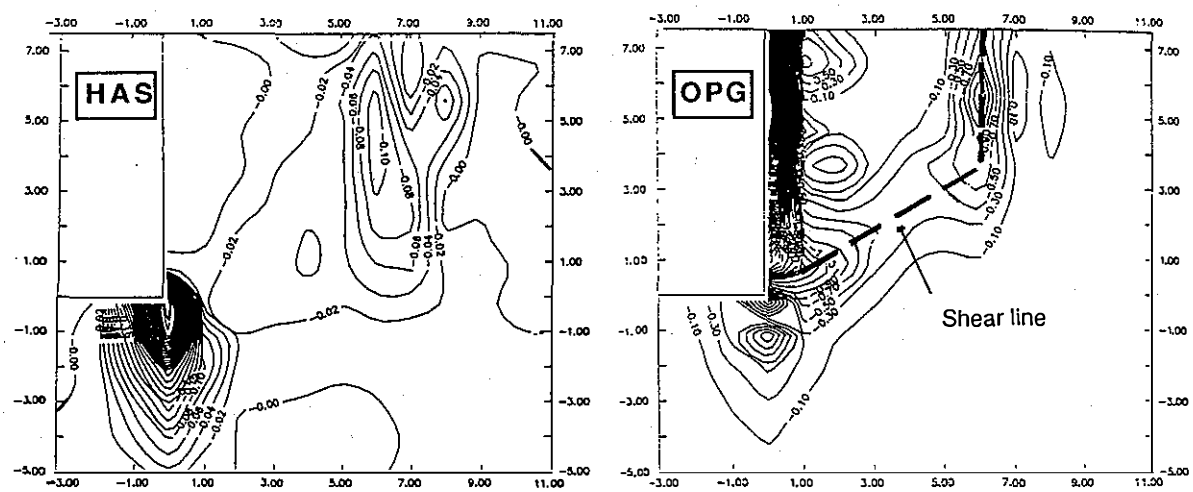
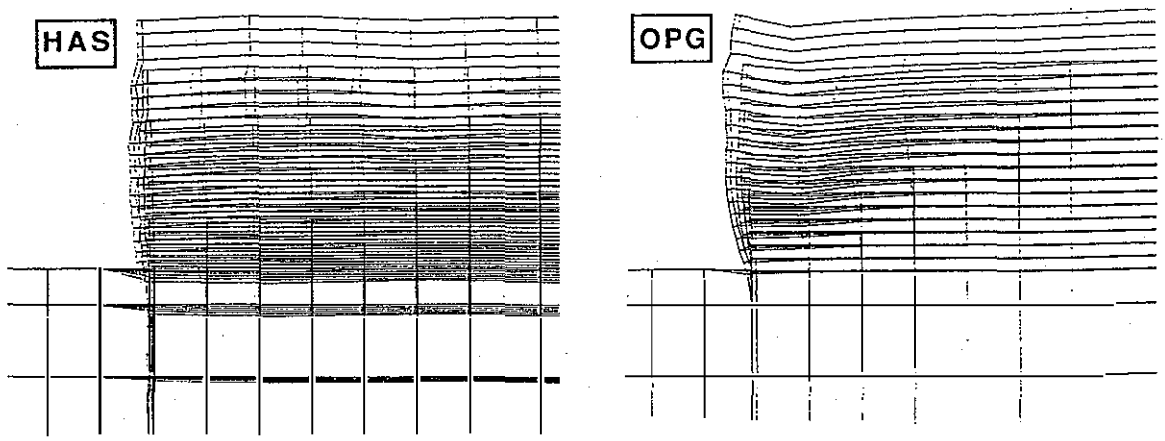


Fig. 4 : Image of possible effect of model rigidity.



(HAS : Contour every 0.02%) (OPG : Contour every 0.20%)

Fig. 5 : Plastic shear strain contours.



(HAS : Deformations × 80) (OPG : Deformations × 8)

Fig. 6 : Superimposed deformation patterns during wall construction.

wall profile and tensions in the sheets are also shown in fig.2. The maximum relative deflection of the facing is now of the order of 1,2% of the height i.e. 30 times that of the inextensibly reinforced wall. However the sheet tensions are found to be small, of the order of I kN compared with about 10 kN for the steel strips.

In order to explain these differences or anomalies, it is necessary to examine the mechanisms which develop during deformation of the two systems - inextensibly and extensibly reinforced.

5.1 *Stresses*

The horizontal soil stresses which develop behind the facing -in the vertical plane containing reinforcements- in shown on fig.3 for the two systems. Also shown is the line of active soil pressure for a Coulomb angle of friction of 36°. It can be seen that although the horizontal stresses are somewhat lower for the extensibly reinforced case (possibly due to the fact that the extensible reinforcement almost extends over the full width) the difference is nothing like enough to explain the difference in reinforcement tensions. In the case of inextensible reinforcement, the active soil stresses are opposed at all depths by the tensions in the strips, as expected, whereas in the case of extensible reinforcements, according to this analysis, they are not...this may result from the resistance of the flexible but unyelding facing, or -since the unbalanced active earth pressure seems to be opposed by shearing of the backfill over some width behind the facing- to an excessive size or rigidity of the "bricks" at the front, as suggested by the graph in fig.4.

5.2 *Plastic shear strain*

This interpretation is aided by fig.5 which shows contours of plastic shear strain at full wall height for the two systems (bearing in mind that the interval between two contours is equal to 0.02% in the case of the HAS, while it is 0.20% for the OPG). The inextensibly reinforced system develops essentially no shear strains within the reinforced volume, although there is a very localised plastic zone at the toe. The extensibly reinforced system endures a great deal of plastic straining immediately behind the facing. It also suffers large plastic deformations in a wedge containing the reinforcement and there is evidence of a shear line developing from the toe into the reinforced soil, as shown on the figure.

In order to understand these two mechanisms better, fig.6 contrasts the deformation patterns computed during wall construction. What are shown are the deformed meshes at all 5 construction stages superimposed one on top of the other. This creates an illusion of an animated sequence of pictures and shows the monolithic block of reinforced soil produced by inextensible reinforcement contrasted with the wedge of deformation which spreads through the extensibly reinforced soil. In effect, for the latter case, the reinforcement "floats" along with the soil.

Although we must acknowledge that the numeric results may be subject to mesh effects, the model undoubtedly shows that the extensibly stabilised structure necessarily endures significant movement and shearing deformations even before effectively bringing the extensible reinforcements into play.

5.3 *Additional information*

As a further piece of information it can be mentioned that, after a first refinement of the mesh immediately behind the facing, the finite element calculations showed that the sheet tensions did in fact increase by about 70%.

It is furthermore interesting to know that an analysis of similar models, based this time on

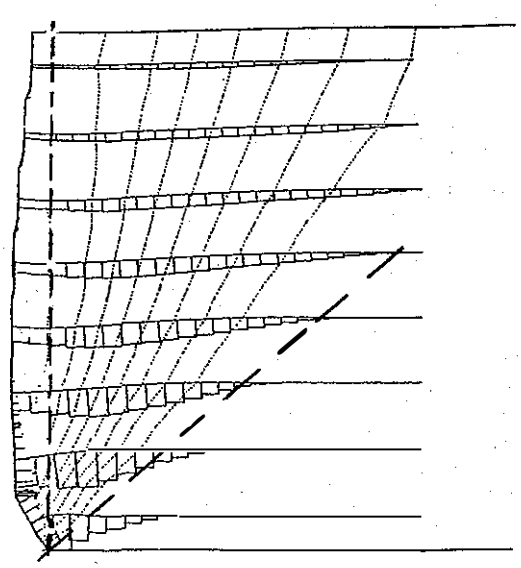


Fig. 7 : Finite differences model (extensible reinf.). Tensile loads and deformations (not exaggerated).

"finite differences" (fig.7), was also separately carried out for TAI by ITASCA Consultants. This study indicated that reinforcing strips 10^3 more extensible than steel, finally balanced the active earth pressure at the expense of a bulging of the facing of 7.5%, the strips being under tension only above practically the same shear line (Billaux and Cundall, 1992).

6 DESIGN IMPLICATIONS

The above findings, although incomplete, lead to a number of remarks with regards to the design principles or to the applicability of the different techniques.

1/ It is clear that while an inextensibly reinforced structure does behave as a monolithic block, or a coherent gravity body, an extensibly stabilised embankment simply behaves as a tied back mass of soil at failure. This means that in no case the "coherent gravity" (or Reinforced Earth) design method should be used for structures where extensible materials are to be utilised.

2/ Whereas local internal stability is insured by the "floating" reinforcements, a shearing movement necessarily develops through the stabilised embankment, should overall stability require it. This movement and puts some of the reinforcements into further action.

Hence the arrangement of the reinforcing layers may depend more on the shearing resistance of the foundation soil at the toe of the wall than on the characteristics of the backfill material itself. This means that internal and external stability are totally inter-related ; it ensues that one should be cautious about typical designs or standard charts.

3/ Matters are more risky in cases such as the one of an extensibly stabilised structure built on a slope (fig 8). While a "coherent gravity" reinforced body will usually shift the potential failure line into the slope, the former will not. Moreover its overall stability implies actual displacement along failure line. This may generate a weakness in the foundation, through potential reduction in shearing resistance of cohesive soil strata for example.

4/ The amount of deformations, whether it is bulging of the facing or subsidence at the top, is clearly a key point of the design in many applications. In addition to the elongation of "floating" reinforcements (possibly attenuated owing to good quality of compacted backfill),

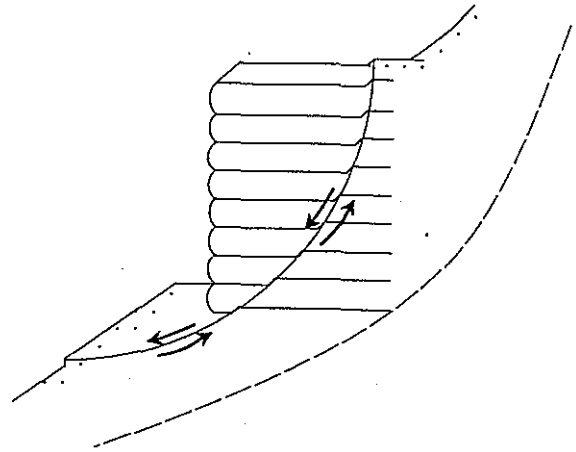


Fig. 8 : Stability of an "extensibly reinforced" structure built on a slope.

post-construction movements associated with "activation" of the shear line may appear later on, following for example: backfill saturation, vibrations, earthquakes.

7 CONCLUSION

Although it is difficult, time consuming and costly, such comparative studies are certainly worth being pursued, in order to better understand the actual behaviour -and in some cases, the effectiveness- of extensible ties in stabilised earth structures.

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