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Some considerations on reinforced earth design in the U.K.

Remarques sur le dimensionnement des murs en terre armée au Royaume-Uni

Cet article passe en revue les méthodes de dimensionnement existantes ainsi que certains aspects des matériaux pour armatures et du parement. Jusqu'à présent relativement peu d'ouvrages en terre armée ont été construits au Royaume-Uni, par comparaison avec les nombreuses réalisation faites dans d'autres pays, et cela bien que ce pays possède une gamme étendue de matériaux pour armatures et de nombreux systèmes de murs de soutènement.
L'auteur compare les différents matériaux pour armatures et les différents systèmes de construction qu'il a eu l'occasion de connaître. Il fait ensuite une description et une analyse des différentes méthodes de dimensionnement des ouvrages en terre armée. La forme de la surface de rupture en liaison avec la stabilité du mur constitue un point de désaccord important entre les différentes théories. Ce point doit donc faire l'objet d'une étude approfondie.
L'auteur conclut sur la connaissance actuelle de la surface de rupture et indique que la méthode de dimensionnement britannique, bien qu'applicable sans danger, ne permet pas de prédire le comportement réel des ouvrages en terre armée.

INTRODUCTION

Although the advantages of reinforced earth have led to its use in over 1500 structures throughout the world there has been little use of this technique in the United Kingdom. The first British reinforced earth wall was built near Edinburgh in 1972, and until recently only about five other walls have been constructed. Greater use of this technique appears to have been prevented by uncertainties about design although these have now been resolved by the recent publication of the Department of Environment (DOE) design method (4).

EARLIER DESIGN METHODS

British Engineers generally had a choice of five methods for the internal design of reinforced earth walls before the DOE method was published. In addition to the method used by the Reinforced Earth Company (8) there were the Rankine, Coulomb Force, Coulomb Moment (7) and Banerjee (3) methods. The methods developed by Lee are adaptions of classical retaining wall theories whereas Banerjee's method is based on a finite element analysis. Although these different methods give very similar results for tension design they differ widely for adherence design. Research at Portsmouth Polytechnic (5) has indicated that both the Banerjee and Reinforced Earth Company methods closely predict the behaviour of models. However the reliance on empirical equations in the method used by the Reinforced Earth Company, for example the minimum length of reinforcement being 80 per cent of the height of the wall, may make it unsuitable for some forms of facing and reinforcement. In the Banerjee method use is made of a non-dimensional tension coefficient which is given a maximum value of 0.35. This coefficient is roughly equivalent to the coefficient of earth pressure and the use of a value of 0.35 makes some of Banerjee's equations independant of the angle of internal friction for the fill. Such an assumption makes comparisons with model tests sensitive to the soil and facing units used in the model.

DOE DESIGN METHOD

For tension design there is little difference from previous methods, but for adherence design the difference from some methods is considerable. The first step in the adherence design is to determine the failure plane inclination which would induce the largest tensile forces in the reinforcement. For the simple case of a granular fill supporting a uniform surcharge this is the same as for a conventional retaining wall, namely $(45-0.5\phi)^\circ$ to the vertical. Friction is then calculated assuming only the reinforcement beyond this failure plane is active and that it cannot exceed the tensile strength divided by the factor of safety. By summating this friction on each strip, the overall factor of safety against adherence failure is obtained. Since this calculation is dependent upon the position of the failure plane it is repeated for different failure wedges as shown in figure 1.

The main advantage with this method is that the most critical failure wedge is determined and as any friction within this wedge is ignored the calculations are easily recognised to be safe. This however results in a conservative method which is less economic than most alternative methods. It is interesting to compare the factors of safety predicted in the Edinburgh wall by the different methods. For tension failure the safety factor calculated by both the Reinforced Earth Company and the DOE methods is over 2.0. However due to the differing assumptions for adherence design the Reinforced Earth Company's designed safety factor of 2.45 is reduced to 0.7 when the calculations are checked with the DOE method. Since this structure is still standing it would appear that the DOE method is very conservative for adherence design.

The sacrificial thickness allowed for corrosion of metal reinforcement is an important design factor. With galvanised steel an allowance of 0.5 mm on each face is often used for ordinary soils outside the United Kingdom. However in the DOE Technical Memorandum (4) this is increased to 1.25 mm on each face in slightly cohesive fills, and 0.75 mm in less cohesive fills, which is intended to give the structures a life of at least 120 years.

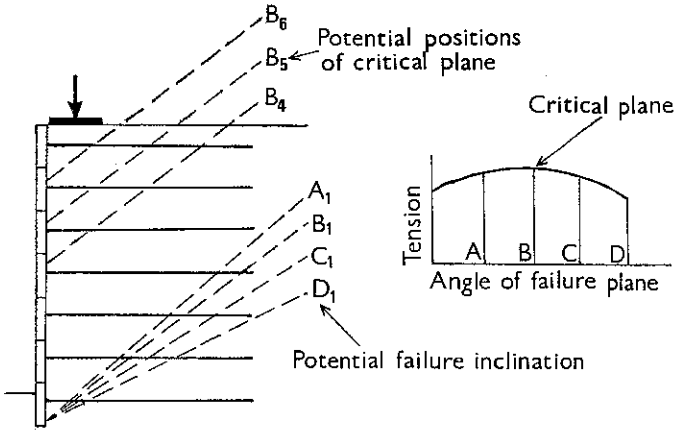


Figure 1 - DOE design method.

The long design life used in the U.K. has helped to stimulate research into alternative reinforcement materials, particularly in the fields of plastic webbing and glass-fibre reinforced plastic. Two of these new materials are so promising that they have recently been used for the construction of several full-size structures (6).

FIBRETAIN

This is the trade name for a glass-fibre reinforced plastic strap which Pilkington Brothers Ltd. have specially developed for reinforced earth. The current form of this reinforcing strip is in the shape of a flat hairpin with the loop being used as the connection to the facing system. Continuous filament E-glass rovings in special Bisphenol Polyester or Vinyl Ester resin are used and in their present form the straps are particularly suited for use with York facing system. A major problem with some glass reinforced resins is their loss of strength with time. Accelerated tests by the manufacturer indicate that the particular resins and curing process they are using result in a useful life of over 100 years for the straps. Since these tests show that deterioration is mainly due to the effect of water, the presence of acids, alkalis, salt or bacteria in solution does not significantly increase the loss of strength. The cost of the straps is generally between galvanised and stainless steel and can therefore be much cheaper than metal where corrosive conditions exist, or a long design life is required.

PARAWEB

This is a linear composite developed by ICI originally for disposable cargo slings. It consists of Terylene cores in Alkathene sheath and a special high strength grade with an embossed surface is produced for reinforced earth applications. The Terylene gives the composite its strength whereas the Alkathene, which is a form of polyethylene gives it a high resistance to environmental attack. Load extension curves for this composite are quite different from metals or glass reinforced plastics. At its ultimate strength, the extension, although low for plastics is about 10 per cent. Such extension would be unacceptable in a reinforced earth wall and is avoided by keeping the working stress well below the ultimate. Creep is another factor which limits the use of plastics for structural components. It has been found that although creep of this composite is initially much higher than for metals, the rate of extension soon reaches a maximum and then rapidly decreases towards zero. Since about two-thirds of the creep occurs in the first 24 hours, it soon falls to a negligable rate.

The extension properties of the composite may sometimes be used to advantage. Where two parallel reinforced earth walls a short distance apart are to be constructed, it is possible to link the walls together with the same reinforcement. If metal reinforcement was used there would probably be insufficient movement to reduce the earth pressures to the active state.

The use of non-metallic reinforcement can lead to additional less obvious benefits. Both these materials can be used in pulverised fuel ash whereas the highly corrosive nature of this fill prevents the use of metal reinforcement. Since reinforced earth is often chosen for use on poor soils, use of this lighter fill could be advantageous.

FACING SYSTEMS

The different reinforcement materials in the United Kingdom have aided the development of further facing systems in addition to those of the Reinforced Earth Company. The York system which uses lightweight hexagonal glass reinforced cement units (2) has now been used for over six years with both metal and glass reinforced plastic for soil reinforcement. Two new systems have recently been developed by A and N Building Components (Anda) Ltd., and Soil Structures Ltd. (6), both of which use plastic webbing for soil reinforcement. The Anda system uses flat hexagonal concrete facing units with the soil reinforcement placed horizontally at 45 degrees to the facing, and Soil Structures uses a T-shaped facing unit.

Care must be taken when applying design equations to any system where the reinforcement is not perpendicular to the facing. Any equation for the minimum reinforcement length should be interpreted as giving the minimum depth of reinforced soil. If a minimum reinforcement length of 5 m was applied to the Anda system without this correction the depth of reinforced soil would only be 3.5 m, which would obviously be less stable than the case where the depth was 5 m.

PROBLEM SOLUTIONS

There are therefore solutions to the problems encountered by British engineers which until recently have prevented full exploitation of this technique in the United Kingdom. The DOE design method is recognised by the authorities and there is little doubt that it is safe. Corrosion can be overcome by using new reinforcing materials or by the use of increased sacrifical thicknesses when metal reinforcement is used. Also there is a wide choice of facing systems, which enables the most appropriate to be chosen for each situation. Nevertheless the economic advantages of reinforced earth in Britain have been reduced since the design method and corrosion precautions are much more cautious than those abroad.

RESEARCH

Since the DOE design method differs considerably from some other methods, research at Portsmouth Polytechnic, England, has concentrated on the main points of disagreement between the different theories. Adherence is the area of most dispute, as some design methods consider the full length of reinforcement to be active whereas others only take the friction developed beyond the failure wedge as contributing to stability. In order to examine adherence failure, and in particular the failure wedge, a series of model tests was commenced. These were carried out in a 2 m high tank with plate glass sides. Timber strips 25 mm high and 4 mm thick were used as the facing and card used as reinforcement. The fill was loose, dry sand and horizontal layers of black sand were placed at 25 mm intervals to detect the failure wedge. Model walls were built a short distance from the front of the tank so that the failure pattern could develop before the wall came to rest in contact with the front of the tank. Although this series of model tests has not yet been completed the preliminary results reveal several interesting points which are detailed below.

FAILURE WEDGE

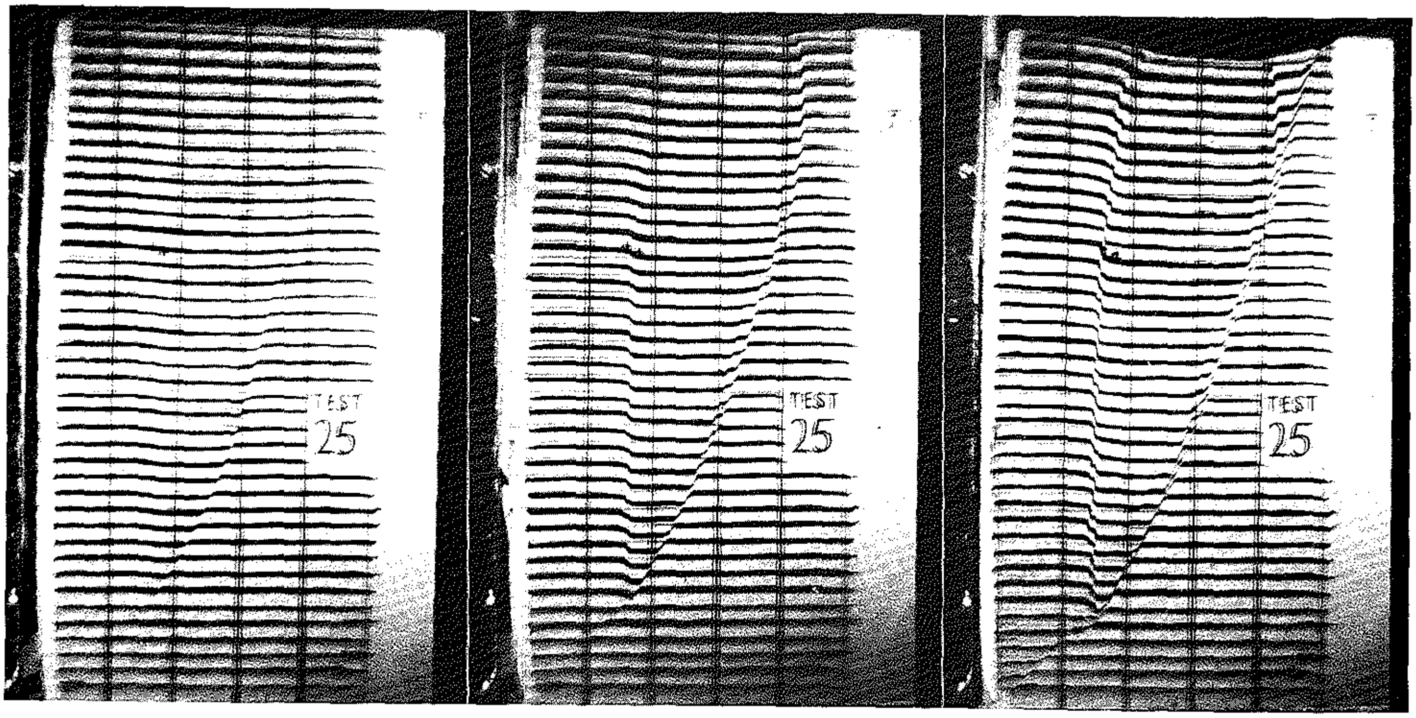
In the short models the failure plane appeared to be a straight line at $(45-0.5\phi)^\circ$ to the vertical but there were insufficient layers of black sand to clearly define the plane. As the height of the models was increased, it became apparent that the walls were rotating about their upper edge and the failure plane was curved. Usually there was more than one failure plane at the top of the models, and in a few cases more than one plane at the foot of the model. In those models with short reinforcement, the failure planes although curved could be approximated to two straight lines with an abrupt change of direction at the back of the reinforced zone. For these models the results appeared similar to those obtained at Cambridge University using radiographs ( ).

The models in which two failure planes were observed near the toe were generally those which collapsed very suddenly and struck the front of the tank with a loud bang. It was concluded that the additional plane was caused by the sudden collision with the tank front and this was confirmed by photographing some collapses with a motorised camera. One of these collapse sequences is shown in figure 2.

These photographs also revealed further information about the failure planes. The small movement of 25 mm, about 2 to 3 per cent of the walls height, was sufficient to distort the failure pattern. At the instant of collapse the failure was a clearly defined curve, near to a logarithmic spiral, and passing smoothly from the reinforced to the unreinforced zones. The failure appeared to initially be much closer to the face of the wall (figure 2a), and as the planes became vertical it initiated a less steep failure, a small distance further back from the face, which when it became vertical initiated yet another plane so that three superimposed arcs can be observed in figure 2b. As the model continued to collapse the large vertical movement near the top induced a secondary straight line failure. A plane parallel with the walls face also developed at the end of the reinforcement. Due to the rigidity of the reinforced zone there was also a significant downward movement of the failure wedge behind the reinforcement. This wedge acted as a solid body and penetrated the undisturbed sand beneath the wedge to a depth of about 50 mm, considerably distorting the failure pattern where the plane passed out of the reinforced zone.

It was concluded from the photographs obtained with the motorised camera that previously reported failure planes were inaccurate since they were not observed at the instant of collapse but at a short time afterwards, when the model had come to rest. The true failure plane appeared to be a logarithmic spiral with no abrupt change at the back of the reinforced zone.

The test shown in figure 2 was repeated using longer reinforcement to determine the effect of a true adherence failure instead of the combination of overturning and adherence failure obtained in test 25. Figure 3 shows the resulting collapse pattern. The longer reinforcement was inserted every ninth layer and its position indicated by the letter L drawn on the glass side of the tank. Collapse was a much slower and more gradual process than before with the wall initially bulging, causing the central failure plane, but not collapsing. Then as the height of the wall was increased the wall bulged further, causing the lowest failure plane, but still not collapsing. The height of the wall was further increased, causing the uppermost plane and the ultimate collapse of the wall. The first failure plane to develop originated where the lowest long reinforcement



2a 2b 2c

Figure 2 - Collapse of Model Number 25

enters the heavily reinforced zone. The second plane developed at the end of the short reinforcement at the foot of the wall, and the third place originated from the second layer of long reinforcement. All these planes are curved with small steps away from the face of the wall where the failure planes cross the long reinforcement. It can be shown that the three curved failure planes in test 26 are almost exactly the same curve since a tracing of any plane can be overlaid over the other two planes. For the earlier models with one main curved failure, the collapse patterns were reproduced at different scales so that although the height of the models differed the scale drawings were of the same height. Despite the differences in model reinforcement and height, when these drawings are overlaid the failure planes closely coincided.

From these tests it appears that the construction process of building a reinforced earth wall in layers, significantly restricts any yielding of the upper part of the wall. The pressure at the top of the wall remains close to that when the facing unit was placed, and the friction developed on the reinforcement effectvely anchors the top of the wall. As a result of this, the walls rotated about their upper edge, contradicting the assumptions in Coulombs wedge theory and producing a logarithmic spiral failure as predicted by Terzaghi (11).

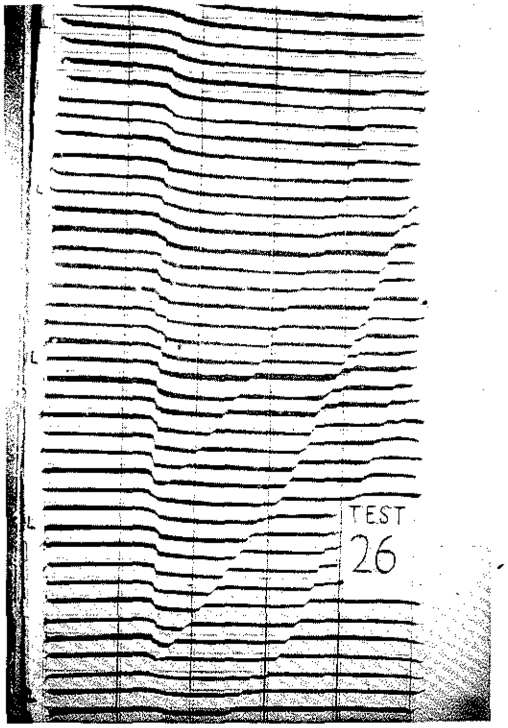
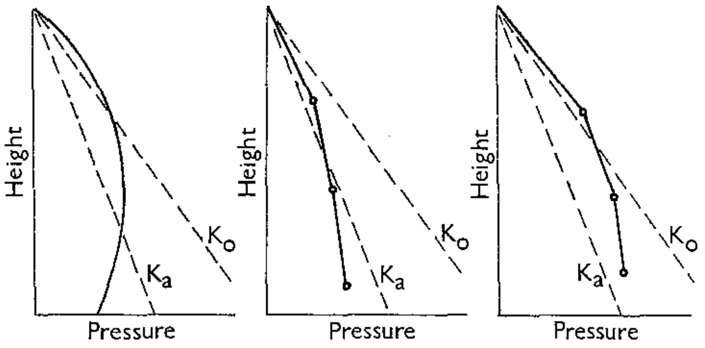


Figure 3 - Collapse of Model Number 26

EARTH PRESSURE

It is apparent from the rotation of the model walls and the shape of the failure planes that a reinforced earth wall behaves nearer to braced trench sheeting than other forms of retaining structure. The pressure distribution would therefore be as shown in figure 4a and not a simple triangular active pressure distribution. Field measurements of the lateral pressure in the Edinburgh wall (10) and a full scale experimental wall (1) are shown in figures 4b and 4c. These readings show a pressure distribution very similar to that predicted by Terzaghi for a wall rotating about its uppermost edge.



4a Theoretical (Terzaghi) *4b Measured (Al-Hussaini)* *4c Measured (Sutherland)*

Figure 4 - Lateral Earth Pressure Distribution

A pressure distribution of the form suggested above would explain the strange behaviour of test 26. The initial bulging and partial collapse causes the upper part of the wall to yield further, reducing the pressures nearer to the active state and making the wall stable. As the height of the model wall was increased this process repeated causing two further partial failures before the wall finally collapsed.
It is interesting to note that the location of the critical failure plane changed as the earth pressure distribution altered, but its shape remained constant. This appears to verify the basic concept in the DOE design method, of determining the critical failure plane first, and then determining its most critical location.

CONCLUSIONS

The construction process for a reinforced earth wall prevents the development of fully active earth pressure for the full height of the wall. Therefore the upper part of the wall should be designed for at-rest lateral earth pressure (K state). Existing walls designed on active earth pressure assumptions are probably safe because adherence is generally more critical than tension at the top of the wall.

The failure plane in a reinforced earth wall approximates to a logarithmic spiral and this applies to all walls, whether their reinforcement is long or short. The assumption that the failure plane in walls with short reinforcement is two straight lines is therefore only an approximation.

Failure patterns observed in models are distorted by the collapse of the model. Support should be placed as near as practicable to the front of the model, in order to keep the movement when the wall collapses to a minimum.

The existing British design method, although safe does not truly predict the behaviour of reinforced earth. Further refinements could be made for the shape of the failure plane, lateral earth pressure distribution, and the strength of the facing units.

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