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The discovery of the true nature of compound failure without reinforcement pull-out: The chimeric[1] failure type

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ABSTRACT: The authors have undertaken a series of micro-model failure tests using ultra-weak reinforcements (0.07 kN/m) with high extensibility at failure (30%) and with specifically restricted dimensions in order to try to generate pull-out type failure under internal self-loading gravity-induced conditions. No external surcharges were applied. The actual outcome of the experiments was to observe and directly measure a new mode of failure never previously recorded in either laboratory work or in field observations. The consequences of this mode of failure are fundamental for the theory, design and safety of reinforced soil structures both planned and already constructed. The mode of failure is obvious in retrospect, but unsuspected. It is a mixture of internal tensile failure with a new 'surcharge' wedge-type failure. The authors have labeled it a 'chimeric' failure in recognition of its mixed failure type. Previous concepts of pull-out failure mode must now be revised.

1 INTRODUCTION

The authors have built a laboratory test bench in which they have constructed a number of micro-models of vertical faced reinforced soil structures. These structures have been constructed from clean Leighton Buzzard sand (fine grading) and an ultra-weak tissue paper for reinforcement.

The sand was loose laid from a small, consistent height to give a friction angle of about 36 degrees and a density of about 16 kN/m^3. The reinforcing tissue was used primarily in the machine direction, having an extensibility at failure of about 35% and an ultimate failure strength of about 0.07 kN/m, using the standard 100 mm × 200 mm tensile in-air test (Rankilor et al. 2002). A number of 'calibration' tests were undertaken using the reinforcement in the cross-machine direction, to ensure compatibility with the second author's earlier work (Rankilor 2003). In that direction, the reinforcement had an extensibility at failure of about 5% and an ultimate failure strength of about 0.02 kN/m.

The test bench was narrowed and was left relatively short in terms of the front to back depth of the sand and reinforcement, so that the development of pull-out failure was encouraged. This resulted in all the relevant tests producing a failure mode that had not been suspected previously and yet which, in retrospect, should have been anticipated. It was, however, only with the advent of the use of the ultra-weak reinforcements that multiple test failures under self-loading conditions could be achieved and studied. This work by the authors is based on that technical breakthrough.

2 TEST PROGRAM

The test program comprised an initial series of calibration tests followed by a series of ten tests, each of which was taken to a height of failure. Four of the model tests used the tissue paper reinforcement in the weak, low extension direction. The remaining six test models were constructed with the tissue paper reinforcement used in the stronger and more extensible direction. The test procedure and recording of the position of tensile failure in the reinforcement have been reported previously by Rankilor et al. (2002) and Rankilor (2004a). The latest set of ten model failures have been reported as part of an MSc dissertation by the lead author (Assinder 2004).

[1] A chimera: a mythological animal comprised of a mixture of two or more different animals (pronounced 'kymeera')

3 TEST RESULTS & OUTCOME

The failure tear surfaces of each reinforcement layer were measured and plotted on a CAD package. A summary of the six model failures for the extensible reinforcement models is presented in Figure 1. Reinforced soil structures of all sizes behave according to linear mathematical variables, so in reality these models actually behave the same as full sized reinforced soil structures. They are reinforced soil structures and not models of reinforced soil structures, even though, for convenience, we refer to them as models. In designing them, the same theory is applied as for larger structures.

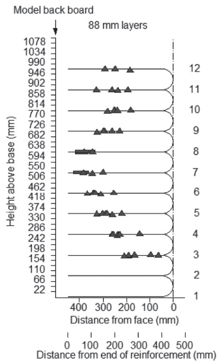

Figure 1. Summary of extensible reinforcement test results.

Each model produced almost exactly the same failure type and pattern. The lower two thirds of the models suffered a 'typical' internal tension-type failure surface (Figure 2 lower lightly shaded area) but the deliberately short reinforcement allowed the primary failure surface to run out of the rear of the reinforced soil block. The primary failure surface would, according to conventional thinking, run either up the back of the reinforcements, or out into the sand at the rear. However, it did neither. It ran back into the upper reinforcements with a defined pattern of failure surfaces (Figure 2 cross hatched area). This is an extremely interesting failure pattern which, to the understanding of the authors, has not been recorded before, either within the laboratory or in the field. The practical outcome was that an upper block of reinforced soil (approximately the upper third) acted as an effective internally reinforced 'surcharge'.

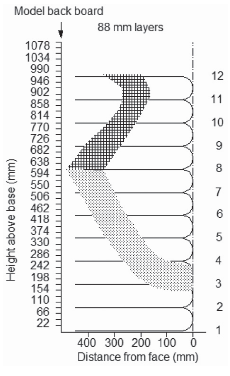

Figure 2. Simplistic representation of failure pattern of extensible reinforcement models.

The shape and angle of failure surfaces were very similar to previously reported models which failed under their own self-weight with a single failure surface staying within the reinforcement. The upper recursive tear surfaces within the surcharge zone were not random, but conformed to a curved wedge-like pattern.

To understand the process of how such failures have occurred one must consider how such reinforced soil structures are constructed. It is clear and really quite straightforward that such structures comprise a staged/phased construction pattern which let stresses build up as the structure height is increased to completion. What has not been previously clear is how such stresses are accepted within the structure as it is built. Rankilor (2004b) has produced the basis of a new theory on how and where such stresses develop in a reinforced soil structure. It is this new theory which helps shed light on why such failure patterns were encountered as part of this research.

As each reinforcement layer is constructed the critical internal failure surface gradually moves backwards towards the rear of the reinforcement as stresses develop. There was limited front-to-back depth since the reinforcement in the model was kept particularly short relative to earlier-published reinforcement models. Consequently, when the critical internal failure surface reaches the back of the reinforcement, it no longer intersects the reinforcement layers above. Therefore, in effect the layers above are really no longer providing a reinforcement benefit. However, the in-soil strength of the reinforcement below remains strong enough to keep the structure stable for some time as construction continues. This is a novel concept that has not been recorded before. The reinforced soil layers above are now acting as an internally reinforced surcharge block, which provides increasing stresses to the reinforced block below as more layers are added. The critical point, which induces failure, is when the stresses reach a level which creates a tension-type failure in the lower block. As this block fails in tension, the reinforced block above immediately drops due to gravity and the block below fails outwards. This type of failure is believed to be the reason why the failure shapes shown in Figures 1 and 2 are developed.

The development of the tear pattern in the upper reinforced block is probably due to the rapid removal of support below it as the lower reinforced soil block fails out in a small fraction of a second. As support is removed from the upper block, it moves out fractionally and thus restraint is removed from the rear and it effectively becomes a reversed reinforced soil wall constrained by wraparound at the outside, but not on the inside. As the upper block drops due to gravity, it strikes the failing active wedge beneath, which creates the energy to tear the reinforcement in the upper block. As the least resistance within the surcharge zone is toward the rear (the front is probably stronger due to the wraparound), the tear develops as a 'reverse' failure surface.

4 CURRENT THEORY

Previous design procedures, including the current British Standard code of practice for reinforced soil (BS8006 1995) assume two different modes of internal failure within a reinforced soil structure; tension-type failure or pull-out failure. It is worth noting that the BS8006 representation of pull-out failure indicates that all of the reinforcement layers, from top to bottom are pulling out (this is actually shown happening for the BS8006 section on slopes). Such a scenario is calculated on the basis of wedges travelling from the face of the structure at varying intervals and angles (although the 'worst case' scenario is assumed to be the wedge that travels through the toe of the structure at approximately $45°\text{-}\phi'/2$).

In reality the development of such a wedge is unable to happen, due to the process of the potential failure surfaces developing and gradually migrating backwards as each reinforced soil layer is placed. Conventional pull-out theory is based on the premise that the reinforced block of soil is constructed 'instantaneously'. Under such theoretical conditions the reinforced block is subjected to stresses imposed via Rankine's stress distribution theory (i.e. maximum lateral stress at the base, reducing linearly to the top).

A simplistic comparison between forces exerted on a geotextile and the available grip on that geotextile shows it to be very unlikely that pull-out failure can occur. To generate pull-out failure you obviously need a greater amount of force than grip behind the failure surface. As the tension in the geotextile is directly proportional to the depth (under current theory) you get a straight line which falls to zero at the top of the wall and the grip on the geotextile is largest at the base. As the grip area reduces (as the failure surface moves back from the face) so do the outward forces. Force can be considered as $H\,\gamma K$, and grip as $H\,\gamma\mu$ ($\times$ 2 for each side of the geotextile). The lateral earth pressure coefficient and coefficient of friction between the geotextiles and fill can be considered to be similar (in reality μ is likely to be higher). The grip is additionally increased by the length of the geotextile and the fact that there is likely to be 3 or 4 layers typically installed within every 1 m^2 of face. A further interesting fact is that it is impossible to pull out a geotextile when the grip exceeds the ultimate strength of the geotextile (the geotextile would tear before it pulled out).

Rather than a pull-out type failure occurring, it is considered more likely that structures fail either as purely internal tension-type failures or as chimeric failures – the chimeric failure comprises an internal tension-type failure which is initiated following additional stress build up from an independent reinforced soil zone above. Internally reinforced surcharge zones may develop when the in-soil strength of the reinforcement is in reality much higher than that suggested by the in-air tensile strength, which is presently typically used for design purposes and where the reinforcement length becomes less than 0.5H.

The implication of such chimeric type failure requires consideration with respect to not only future design procedures but also issues of health and safety. The commonly accepted failure pattern in reinforced soil structures is that the base is supposed to be stressed the most (which has proven to be incorrect: Rankilor 2004b). The existing theory assumes that as the area of highest stress is typically associated with the basal layers which are expected to fail out first. The many laboratory test structures undertaken to date have all failed from a purely internal tension-type failure or from a tension-type failure under an internal surcharge zone. Additionally, all have failed first near the centre of the internally reinforced zone. Therefore all have bulged out at this central point and, at failure, all have thrust out at this central point. Those models that displayed a chimeric failure type not only thrust out in the centre of the internally reinforced zone but also comprised a falling block of surcharge as shown in Figures 3 and 4.

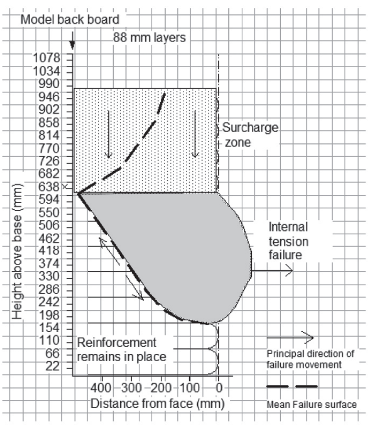

Figure 3. Chimeric failure pattern.

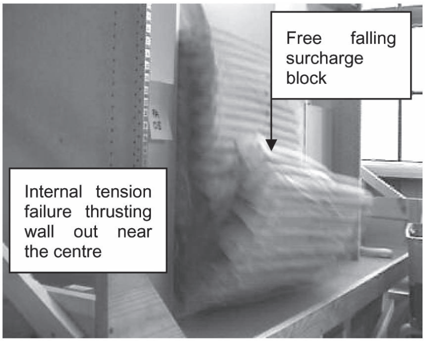

Figure 4. Video still capture of a Chimeric failure.

5 IMPLICATIONS FOR CURRENT STRUCTURES, FUTURE DESIGN & REMEDIAL WORKS

With regard to current structures there is now a strong possibility that there are reinforced soil structures that are standing, with reinforced surcharges, that are only marginally safe with respect to the structure's design life (even though the structure may have been designed with a factor of safety of say 4). This is because the lower reinforced block (a) potentially has too short or too weak reinforcement layers in the central height zone of the wall, where the highest stresses are believed to be present and (b) because the reinforcement is too short, the upper layers are not providing any reinforcement benefit. Consequently, there may be structures with free standing, 'loose' blocks of surcharge that contain reinforcement layers that are overstressing the underlying reinforced soil block.

Future designs should recognise that there is no such failure mode as pull-out. Instead, designers must, in future, be aware of the potential for chimeric failure to develop. Consequently, under current design procedures, designers must ensure that adequate lengths of reinforcement are provided. Using current design procedures greater lengths of reinforcement would stop the upper reinforced block acting as a surcharge which is not functioning as part of the overall reinforced block. Additionally, stronger and more frequent layers of geotextiles should be provided in the central section of future structures. The second author is presently developing a new reinforced soil design theory which overcomes these problems. This will be reported subsequently when fully developed.

Remedial works sometimes have to be undertaken to repair, for example, modular block wall systems which have moved out in the middle. Previously the reason for the movement has not, in the authors view, been properly explained. Typically such movement has been attributed to soft spots in the construction, localised poor construction technique and/or localised pockets of perched groundwater: all of which apparently created weak spots. However, the author's believe that it is too great a coincidence that the construction workers always 'cut corners' on the build quality of the middle part of the structure or that geotechnical problems always appear just there. Following the research undertaken by the authors, it is no longer a surprise that reinforced soil failures appear to move out at the central wall height. The authors believe that in the case of failures, initial design had not taken account of the central maximum stress zone within the structure. Therefore, in the case of a design where the overall safety factor is inadvertently low, it will be the central height zone that will be under-reinforced and will fail first. Following current theory, remedial works would be aimed at reinforcing the lower zones, which would not be correct and would lead to a further inaccurate expectation of safety factor in the remediated structure.

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