Retaining walls with curved facings
Technical and aesthetic benefits

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ABSTRACT

Conventionally the facing of retaining walls or steep slopes have been planar, either vertical or inclined. Occasionally, stepped or terraced slopes have been employed. The introduction of modern reinforced soil systems has not changed this conventional approach, which can be related back to Coulomb's principles of design. As a result of the continuation of the use of essentially planar lateral boundaries, the lateral earth pressures to be resisted by reinforcements increase in the reinforced soil in proportion to the height of the wall that can be reinforced. Laboratory testing has been undertaken on walls and steep slopes where the shape of the facing was a variable. In this paper, the laboratory testing that was undertaken is described, the test data presented and the implication for designers and end users are discussed.

1 INTRODUCTION

The use of lateral earth pressure theories for vertical walls or steep-sided slopes is most commonly based on equilibrium conditions within a fill with no lateral boundary deformations (at-rest conditions), or limit equilibrium conditions for either lateral expansion (active conditions) or lateral contraction (passive conditions). The lateral soil-wall boundaries were always taken to be planar, either vertical or inclined with stepped or terraced lateral boundaries used occasionally.

The introduction of Geosynthetic Reinforced Soil Systems (GRSS) has not changed this conventional mode of construction. As a result of the continuation of the use of essentially planar lateral boundaries, the lateral earth pressures to be resisted by geosynthetic reinforcement generally increase in proportion to the height of the structure. This results in rather complicated reinforcement layouts on some occasions, with the spacings, lengths and types of reinforcement varying with depth. In addition, the base bearing pressures are generated with a maximum near the toe of the structure and they increase with the height of the structure.

The above features have proven to impose severe limitations on the maximum height of a GRSS that can be reinforced using specific types of geosynthetic reinforcements. To overcome these difficulties it is suggested that non-planar (curved) lateral soil-wall boundaries can be employed.

Thus, in this paper the overall technical and aesthetic benefits of varying the shape of the lateral soil-wall boundary are described and the design and construction advantages to be derived are presented. Economic benefits from implementation of the Limit State Design approach in combination with optimised lateral soil-wall boundaries and revised material parameters are highlighted.

2 EARTH PRESSURE CONCEPTS

Conventional earth pressure theories employed in the design of GRSSs show that the magnitude and distribution of lateral earth pressures on a lateral soil-wall boundary are dependent upon many factors, including:

- the type of soil used as the reinforced fill,
- the density of the fill,
- the magnitude of the soil-wall friction

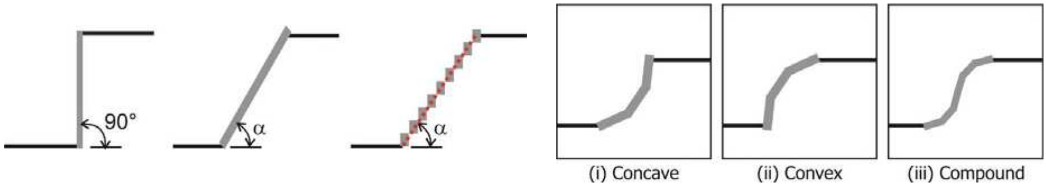
- the nature and magnitude of the soil-wall boundary movements (rotation & translation) and
- system geometry.

Further, it is widely known that as the facing angle of an Earth Structure (α) reduces the lateral earth pressure reduces. Indeed, the earth pressures reduce to zero once the facing angle is less or equal to the operational angle of friction of the soil. By selecting the soil type, the construction process and the nature of the lateral soil-wall boundary, it would thus appear possible to control the magnitude and distribution of lateral earth pressures developed.

Previous research identified several key factors that influence the magnitude and distribution of lateral earth pressures for both, conventional and reinforced soil structures (Yogarajah 1993). The key findings were that the lateral earth pressure distribution is greatly affected by soil-wall boundary movements, and the compressibility (stiffness) of the soil wall boundary.

Other researchers addressed the earth pressure distributions within steep slopes. Their findings confirmed that the coefficients of lateral earth pressure (K) are not solely functions of the angle of internal friction, but dependent on other factors (Khan 1999). Numerical analysis and full-scale experimental testing indicated that the lateral earth pressures vary with depth and distance from the soil-wall boundary, as well as, with overburden pressure and other factors. Closed-form solutions, as well as numerical FEM analysis, were used to determine the magnitude and distribution of lateral earth pressures for planar soil-wall boundaries for vertical or near vertical walls and steep slopes (Pradhan 1996).

On this basis it is suggested that, to date, the soil-wall boundary has been considered to be a fixed parameter, either vertical, inclined or stepped, see Figure 1a. However, if the facing slope angle is varied between 90° and ϕ', the earth pressure distribution will not conform to conventional patterns, either in magnitude or distribution. Indeed, by varying the angle and shape of the lateral soil-wall boundary, both the levels and the distribution of the earth pressures may be controlled, see Figure 1b.



(a) Variation of the slope angle

(b) Possible variation of the soil-wall boundary
(multi-linear or curved facings, either smooth or stepped)

Figure 1 Variation in form and shape of the soil-wall boundary for walls and steep slopes

The construction of non-planar lateral soil-wall boundaries may be readily employed in GRSSs by utilising sectional or wrap-around facings already widely used.

3 TEST SETUP

The test programme undertaken was aimed at the determination of the lateral and basal pressure of Earth Structures with planar and non-planar lateral soil-wall boundaries. This work focuses at the at-rest conditions only, i.e. all test walls were rigid and fixed. The test apparatus used for this case consisted of a rigid frame of 500 mm height and 800 mm length, see Figure 2. Load cells were fixed to one side of the frame and along the base, to measure the lateral and vertical pressure, respectively. Load cells and side walls were covered in a layer of PTFE [Polytetrafluoroethylene or Teflon®] to reduce surface friction. Load cell calibration indicated accuracy to ±0.05 N. Due to test setup plane strain conditions were simulated.

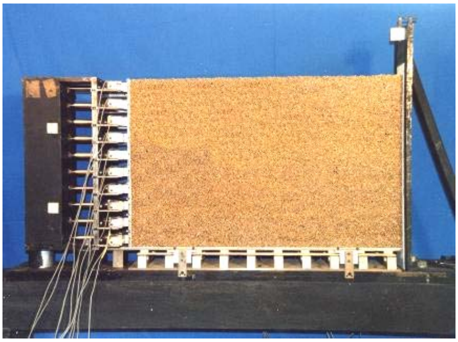
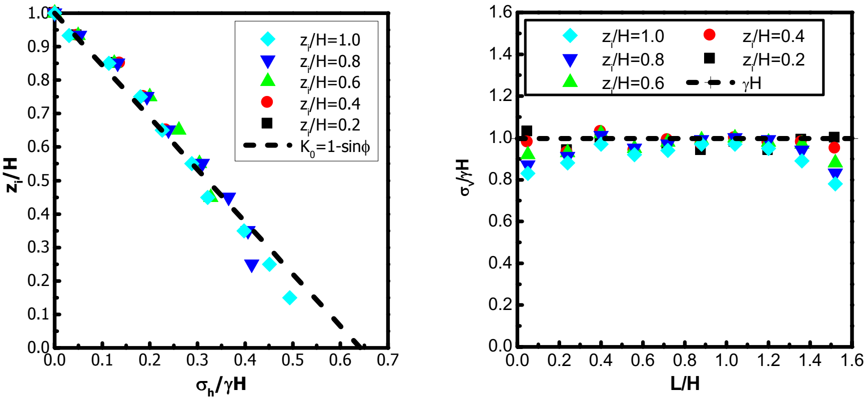


Figure 2 Test apparatus filled with brass rods

To simulate a granular fill, the frame was sequentially filled with an equal mixture of polished brass rods of different diameters. The compacted fill had a density (ρ) of 7.08 Mg/m^3 and hence a dry unit weight (γ) of 69.5 kN/m^3. The angle of internal friction was determined using shear-box tests under vacuum confinement and shown to be 21° (Fahim 1983). Thus, the coefficient of earth pressure for the at-rest conditions (K_0) was calculated as:

$$K_0 = 1 - \sin\phi = 0.642 \qquad (1)$$

This value was used to check the test data obtained from the apparatus using the rigid vertical wall. The determined properties were similar to those reported in earlier studies (Fahim 1983). The correlation between the calculated and measured at-rest lateral earth pressure is shown in Figure 3a. The correlation between the measured base pressure and the calculated vertical overburden pressure is shown in Figure 3b. The deviation of the measured values from the calculated values was attributed to the residual friction within the brass rods mass and interaction with the PTFE coated sides and base of the test frame (arching effects).

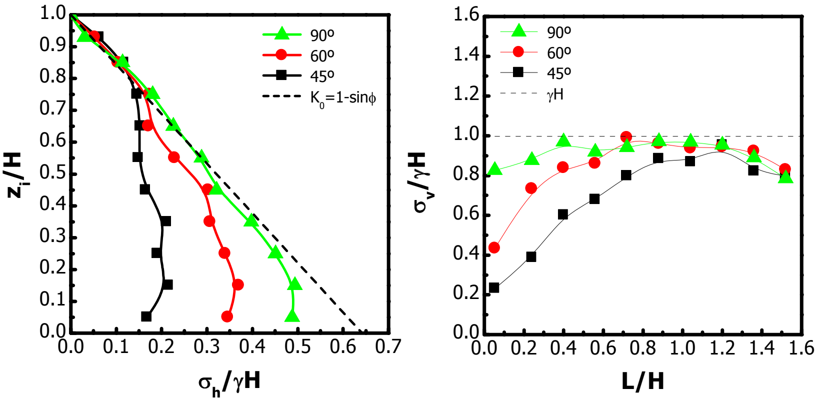


(a) Normalised lateral pressures

(b) Normalised basal pressures

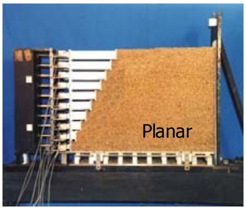
Figure 3 Normalized at-rest lateral earth pressures and base pressures for 90° planar wall (z_i is the construction height)

Various other planar and non-planar lateral boundary shapes were constructed by fixing lightweight tubes of different lengths between the lateral load cells and the PTFE coated facing units. The brass rods were then placed against them. Using this method, lateral boundary shapes were formed as linear slopes with inclinations varying from 45° to 90° and curves with L = z_i^2, 0.5 z_i^2, 0.33 z_i^2, z_i^3, 0.5 z_i^3, 0.33 z_i^3, (where L is the lateral dimension and z_i is the vertical increment measuring from the top of the wall), see Figures 4 to 6.



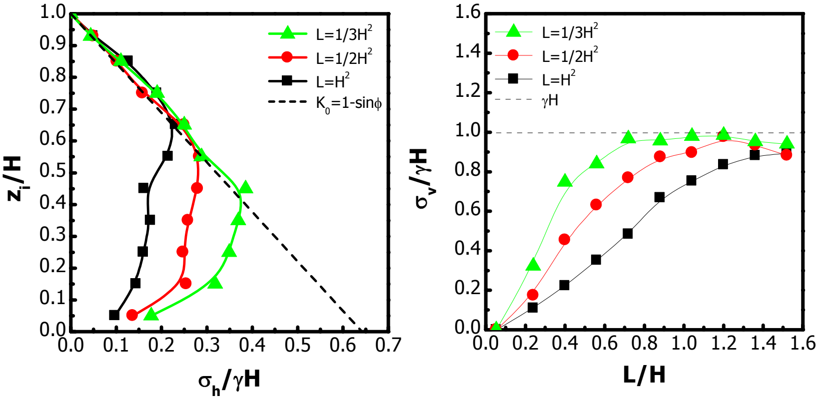
(a) Lateral pressures

(b) Basal pressures



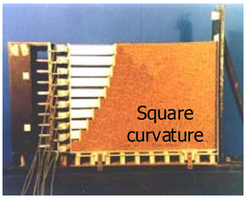
Planar boundary -
60° steep slope

Figure 4 Normalised test results – Planar soil-wall boundaries



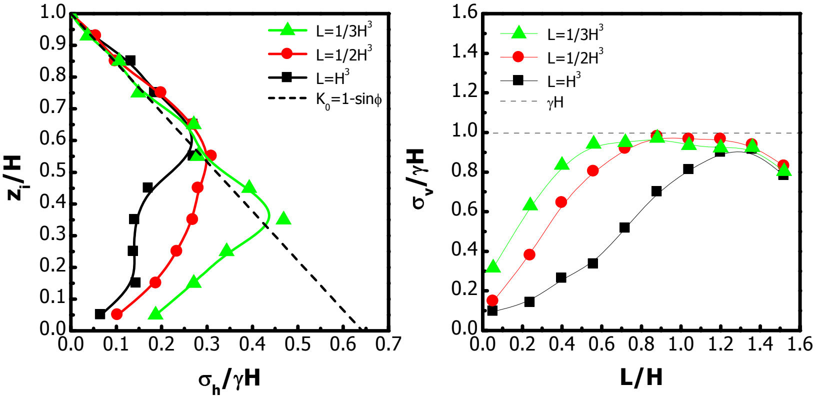
(a) Lateral pressures

(b) Basal pressures



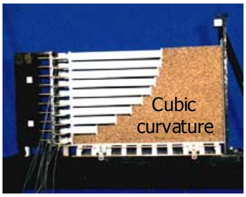
Non planar boundary -
L=0.5H²

Figure 5 Normalised test results – Square curved soil-wall boundaries



(a) Lateral pressures

(b) Basal pressures



Non planar boundary -
L=H³

Figure 6 Normalised test results – Cubic curved soil-wall boundaries

4 TEST RESULTS

The test results from small-scale testing indicate that the effects of non-planar soil-wall boundaries on the lateral and basal earth pressure distribution may be significant. Leonards (1962) has developed closed-form solutions to determine the pressure distribution on deformed soil-wall boundaries, e.g. a section of a deformed sheet pile wall or braced cuts. On the basis of field measurements Terzaghi & Peck (1948) and Tschebotarioff (1951) suggested that trapezoidal pressure distributions may be used as approximations in such cases. However, these simplified assumptions have not been widely employed in the design of retaining structures and do not in any case deal with the general condition of a curved soil-wall boundary.

The measured lateral pressure distributions for the planar lateral boundaries at different slope angles exhibited a progressive reduction in lateral pressures with reducing inclination, see Figure 4a. They also exhibited a significant reduction in base bearing pressures near the toe of the wall, see Figure 4b. Thus the measured benefit of reducing the inclination of planar lateral boundaries was two-fold and in line with existing knowledge.

The measured lateral pressures exhibited by square and cubic curved (non-planar) boundaries are shown in Figures 5a and 6a. The base bearing pressures for these curved boundaries are shown in Figures 5b and 6b. Such curved boundaries provide both the possibility of reduced lateral pressures and reduced base pressures near the toe when compared to the vertical wall condition or similar slopes. Of particular note, are the curved boundaries $L = k \times H^2$. These lateral boundary conditions provide relatively uniform pressure distributions with depth and significant reductions in the base bearing pressures near the toe.

Thus, based on the above results an optimisation of the lateral and basal earth pressures may be accomplished by varying the shape and form of the lateral soil-wall boundary to either achieve a uniform distribution of lateral earth pressures with depth or reduce base bearing pressures at the toe.

5 TECHNICAL AND AESTHETIC BENEFITS

The method of constructing GRSSs is to place successive layers of compacted fill and reinforcement, with the latter connected to facing units or formed into a wrap-around facing. For construction simplicity it is desirable to keep the thickness of the compacted fill layers the same and employ only one type reinforcement, or at the most two, over the height of the structure. To do this, the pressures to be resisted at the lateral boundary require to be as uniform as possible. This will have the effect that the loads carried by the various layers of geogrid reinforcement are very similar over the full height of the structure. As a direct result, the lateral soil-wall boundary (or facing) deformations will be very uniform and the required geogrid stiffness very similar over the full height of the structure.

On the basis of the experimental work described above, it may also be possible to reduce base bearing pressures near the toe of the structure and modify the shape of the soil-wall boundary to rapidly reduce lateral earth pressures. A further advantage may be that for GRSSs subject to shock or earthquake loading, non-planar lateral soil-wall boundaries may be more likely to provide higher resistance than vertical or steep planar boundary conditions due to the uniform lateral earth pressure distribution and reduced toe bearing pressures. Thus, the optimum shape of the lateral soil-wall boundary will be different for each application.

By standardising the types, layout and lengths of the reinforcements, considerable economic benefits may be gained. Another benefit is achieved by keeping the spacings between individual layers constant, define constant anchorage lengths and employ only one or very few geogrid types within the structure. Another, benefit is that the design concept is simplified for structures with different elevations, i.e. the top 5 m of a 15 m high wall will be identical to the top 5 m of a 5 m high wall. Thus, it is suggested that nomograms may be employed in the design of GRSSs with non-planar soil-wall boundaries. Furthermore, lengthwise construction of GRSSs with anisotropic uniaxial geogrids is suggested (anisotropic uniaxial geogrids posses the principal strength in cross-machine direction instead of in the machine direction). Lengthwise construction may significantly increase construction rates. Additionally, end users and designers have the possibility to specify or create

GRSSs with non-planar lateral soil-wall boundaries which may have many aesthetic advantages over conventional structures, i.e. retaining walls or steep slopes may be designed to be less intrusive and ‘blend in’, especially if vegetated facings being used.

6 DISCUSSION AND CONCLUSIONS

The influence of the shape of the lateral soil-wall boundary on the performance of steep slopes or walls has been identified on the basis of small-scale laboratory testing.

Tests were conducted on a brass rod model with rigid lateral planar and non-planar boundaries. The benefits from the use of particular forms of non-planar lateral soil-wall boundaries were deemed to be two-fold, i.e. the possibility of more uniform lateral earth pressures with depth and reduced toe bearing pressures.

To date increasing lateral earth pressures with depth and large toe bearing pressures associated with planar lateral soil-wall boundary conditions, have greatly limited the application of GRSSs in practice. The possibility of controlling these factors by adopting non-planar lateral soil-wall boundaries appears to have considerable potential. McGown (2000) estimated that by employing the Limit State Design approach for GRSSs the costs associated with design, construction and materials may be reduced by up to 75%. By including the benefits that may be achieved by optimising the shape of the soil-wall boundary, standardising the design and construction of GRSSs, the project costs may reduce even further.

To date, the use of Computer Aided Design [CAD] programs for the design of GRSSs is common practice and numerous software packages for conventional and reinforced earth structures are readily available. The changes to current design programs to include non-planar soil-wall boundaries, as discussed in the above sections, are deemed to be minor. The underlying design philosophy suggested is to determine the maximum long-term strength that can be resisted by the geogrid reinforcement and then changing the shape of the lateral soil-wall boundary to such an extent that the maximum allowable strength is not exceed in any part of the structure.

Due to uniform lateral earth pressure distribution with depth the soil-geogrid interaction is likely to be influenced by the increasing confining pressure with depth only and pull-out test results at different confining pressures may be directly applied to the analysis. The internal stability and external stability analysis of the optimised structure is likely to follow the established patterns, with Factors of Safety or Partial Factors likely to be significantly higher compared to conventional earth structures due to decreased toe bearing pressures increasing significantly the external stability for applications over soft bearing strata.

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