An experimental study to determine the location of the critical height in piled embankments

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ABSTRACT: Geosynthetic reinforced piled embankments (GRPE's) have become an increasingly popular means of constructing on unsuitable foundation soils. However the design of GRPE's is extremely complex and relies on determining the magnitude of arching in the embankment fill and the tension in a geosynthetic reinforcement layer at the base of the embankment. Several design methods are available for estimating the magnitude of arching and the tension in the geosynthetic reinforcement. Naughton (2007) showed that the magnitude of arching and therefore the tension in the geosynthetic reinforcement can be estimated based on the concept of critical height. The critical height is a function of the frictional characteristics of the embankment fill and pile-pile cap spacing at the base of the embankment. An instrumented laboratory 1:3 scaled model of typical piled embankment geometries was used to investigate the influence of the embankment fill material properties on the location of the plane of equal settlement and therefore the influence of the critical height in the design of GRPE's. Three sand types with different strength and gradation characteristics were examined. The model was used to quantify the unrestrained arching in the model embankment. The influence of the angle of internal friction on the location of the critical height was investigated and the critical height was found to increase as the angle of internal friction increased. It was observed that when the peak angle of friction was used in the method suggested by Naughton (2007) that good agreement was found with the experimental data.

1 INTRODUCTION

Soil arching is a natural phenomenon which occurs in all granular soils as a result of stress redistribution. In a piled embankment the soft soil between the pile caps settles under the weight of the embankment while the soil block above the pile cap does not thus shear stresses develop in the fill material between the yielding and unyielding zones (Terzaghi, 1936).

Essentially for soil arching or stress redistribution to occur the depth of fill has to be sufficient for the full arch to develop. Embankment height is critical to the development of soil arching (Naughton, 2007). At low embankment heights the shear stresses mobilised during yielding extend to the surface of the embankment, thus full arching is not achieved. With an increase in embankment height the shear stresses terminate within the body of the fill and full arching, with enhanced load transfer is achieved (Naughton, 2007). The critical height can be defined as the minimum embankment height required to achieve full arching in the embankment fill.

2 MATERIAL PROPERTIES

The three sands examined in the experimental model came from three different quarries in Ireland. The sand properties, shear strength and dilatancy characteristics, Table 1, were determined in accordance with BS1377 (1990).

Table 1. Unit Characteristics for three sands examined

Sand	A	B	C
Classification	Well graded, sub-rounded	Uniformly graded, rounded	Well graded, angular
C_u	4.53	1.33	6.21
C_c	0.966	1.02	0.689
ϕ'_{peak}	45°	42°	50°
ϕ'_{cv}	39°	36°	41°
ψ'_{max}	9.8° ± 0.58	10° ± 1.4	11.1° ± 0.73
(ρ_s)	2.688	2.660	2.717
(e_{max})	0.58±0.04	0.84±0.01	0.61±0.03
(e_{min})	0.22±0.01	0.39±0.006	0.16±0.009

The shear strength and dilatancy characteristics of the sands were obtained using direct shear tests under normal stresses ranging from 123kPa to 368kPa.

3 EXPERIMENTAL MODEL

A 1:3 laboratory model of a piled embankment unit cell was developed to investigate the arching mechanism (Britton & Naughton, 2008). Sand samples were formed using an air pluviation technique similar to that described by Schnaid (1991). The model was filled in a series of lifts and the densities measured at each lift to check homogeneity of the samples. The recorded maximum, minimum and mean densities achieved using the air pluviator are presented in Table 2, together with the mean sample density index achieved for the sands. The distribution of load within the model due to arching was discussed in Britton & Naughton (2008).

Table 2. Sample deposition densities, (Mg/m^3)

Sand	A	B	C
Maximum density	1.72	1.60	1.77
Minimum density	1.69	1.56	1.74
Mean density	1.707	1.58	1.762
Standard deviation	0.011	0.016	0.0108
Density Index	0.824	0.81	0.797

4 CURRENT DESIGN METHODS AND EXPERIMENTAL INVESTIGATIONS

Several design methods are available for estimating the magnitude of arching within GRPE's such as Terzaghi (1943), Hewlett & Randolph (1988), BS8006 (1995), Collin (2004), Kempfert (2004) & Naughton (2007). These methods employ, either directly or indirectly, the critical height of the embankment when calculating the load transfer and hence the tension in the geosynthetic reinforcement. Also the critical height has been shown experimentally by Horgan and Sarsby (2002) and Aslam and Ellis (2008). The Collin (2004) and Aslam and Ellis (2008) methods are discussed here, while Naughton (2007) and Britton & Naughton (2009) discuss the other methods in detail. The critical height associated with the different design methods and experimental investigation are summarised in Table 3.

4.1 *The Collin (2004) design method.*

The Collin method was based on the results of plate loading tests on samples of geogrid reinforced sand in a confined rigid box carried out by Guido et al. (1987). It suggests the use of multi layers of geogrid to enhance the transfer of vertical loading. A critical height equating to at least one times the clear span between supports was suggested.

4.2 *The Aslam and Ellis (2008) experimental study.*

Aslam and Ellis conducted centrifuge tests examining the performance of unreinforced piled embankments constructed on soft soil. The tests were carried out at 30 and 60g and the results showed that as depth/span ratio increased to 2 the surface deformation reduced to zero, which is taken here to correspond to the location of the critical height.

Table 3. Summary of critical heights for various design methods/experimental investigations.

Design Method / Experimental investigation	Critical Height (H_C)
Terzaghi (1943)	2.5 (s-a)
Hewlett & Randolph (1988)	1.4 (s-a)
BS8006 (1995)	1.4 (s-a)
Collin (2004)	1.0 (s-a)
Kempfert (2004)	s/2
Naughton (2007)	1.25(s-a) - 2.4(s-a)
Horgan & Sarsby (2002)	1.545(s-a) - 1.92(s-a)
Aslam & Ellis (2008)	2.0(s-a)

5 EXPERIMENTAL TESTING

The movable cruciform base at the bottom of the model has a plan area of 0.36m^2 while the four pile caps had individual surface areas of 0.16m^2 for all the tests reported in this study. Samples of various heights were formed using the air pluviator described earlier. Density indexes for the three sands were found to be within the range of 0.797 to 0.824, which classifies all samples to be dense (Lambe and Whitman, 1979). A more detailed description of the air pluviator and sample repeatability is given in Britton and Naughton (2009). After placement of the sand samples the movable cruciform base was lowered and the sand allowed yield. Displacement of the movable base and the top of the sand sample, together with load changes on the pile caps were recorded at 1 second intervals using a DAQ system.

6 ANALYSIS OF RESULTS

When the desired test sample height was achieved the LVDT's were set up at the base of the model and the surface of the sample and set to their maximum stroke. The movable cruciform base was then lowered slowly and readings from the LVDT's were recorded. An example (H=480mm, Sand A) of the base versus surface displacement, which is approximately linear is presented in Figure 1.

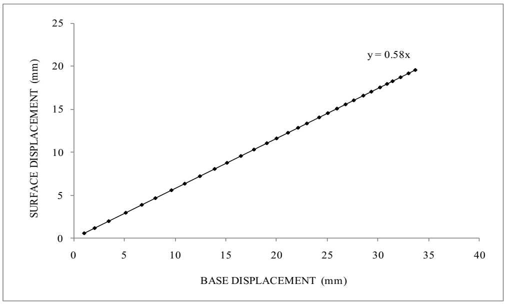

Figure 1. Base to surface displacement ratio (H=480mm, Sand A)

It was noticed for all three sands that as the sample height increased the ratio of base to surface displacement decreased significantly. Above a particular sample height the surface deformation tended to remain constant, suggesting that full arching was achieved. It was assumed in this study that the height at which this occurred was the critical height for the sand. The variation of base to surface displacement was entirely due to arching as no geosynthetic was incorporated in the experimental model for this test series.

The ratios of surface to base displacements against sample height are presented in Figures 2, 3 and 4 for Sand A, B and C, respectively.

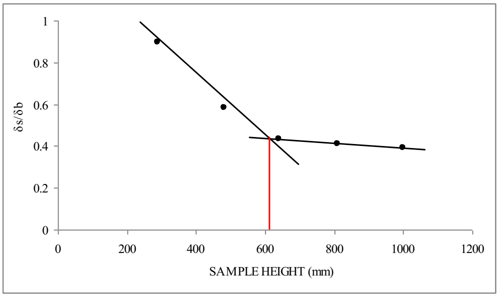

Figure 2. Base to surface ratios v Sample Height. (Sand A)

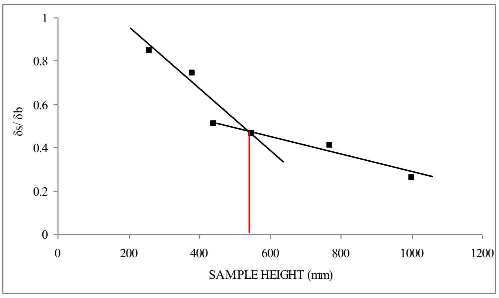

Figure 3. Base to surface ratios v Sample Height. (Sand B)

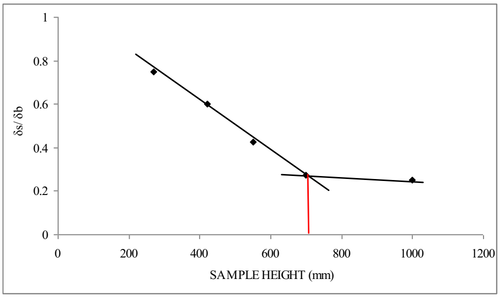

Figure 4. Base to surface ratios v Sample Height. (Sand C)

As the model base and pile cap size had a constant area for all the tests carried out the clear spacing was therefore constant at 283mm. For Sand A the critical height was approximately 610mm, Figure 2, for sand B approximately 550mm, Figure 3 and for Sand C approximately 730mm, Figure 4. This is the equivalent to 2.2(s-a), 1.94(s-a) and 3.1(s-a) for sand A, B and C, respectively.

Good agreement was found between the experimental critical heights and those associated with the design methods, Figure 5.

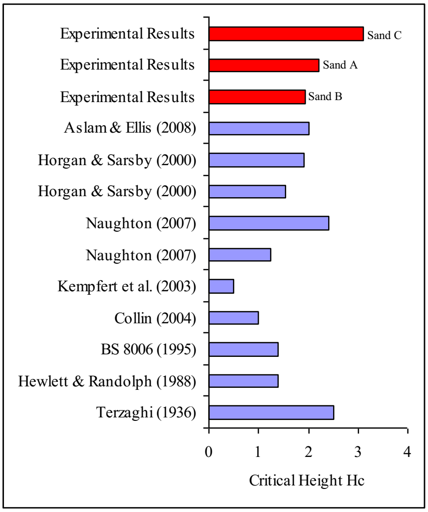

Figure 5. Critical height recommendations from literature.

The values recorded from the laboratory investigations for the critical height within a piled embankment was found to be within the range of suggested by Naughton (2007). The value obtained for Sand B was in close agreement with those suggested by Horgan and Sarsby (2000) and Aslam and Ellis (2008) however the value for sands A and C were slightly higher. The values predicted by the Russell et al. (2003), Terzaghi (1943) and Kempfert (2003) design methods seem to over predict the critical height thus making them overly conservative while the values obtained from BS8006 (1995) and Hewlett and Randolph (1988) are under conservative therefore underestimating the load on the reinforcement and thus the tension in the reinforcement.

Naughton (2007) assumed the shear planes in the fill, generated during load transfer, were log-spiral in shape. By applying the boundary conditions to the general equation for a log-spiral Naughton (2007) generated the following expression, as a function of the clear spacing between the pile caps (s-a), for the critical height:

$$H_C = C(s-a)$$

Where,

$$C = 0.5e^{\frac{\pi}{2}\tan\phi}$$

The effect of ϕ on the critical height suggested by Naughton (2007) is shown in Figure 6, together with the results of the experimental test programme for the critical and peak angles of internal friction of the three sands. Both Naughton's model and the experimental data suggest that the critical height increases as the angle of internal friction (constant value and peak) increases.

The model suggested by Naughton was in excellent agreement with the experimental data based on peak angle of internal friction.

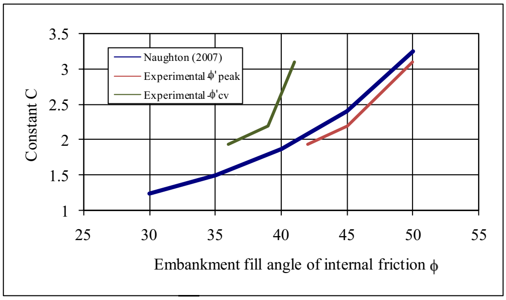

Figure 6. Influence of ϕ on the critical height H_C of the embankment

7 CONCLUSIONS & RECOMMENDATIONS

A series of model tests were carried out using three sands to investigate the location of the plane of equal settlement and hence the critical height in a piled embankment. The results obtained were compared to current design methods and past experimental investigations. Close agreement was found between the model test results and suggestions for critical height from Naughton (2007), Aslam & Ellis (2008) and Horgan and Sarsby (2000).

The influence of the angle of internal friction on the location of the critical height was also investigated. The critical height was found to increase as the angle of internal friction increased. Excellent agreement was found between the experimental data based on peak angle of internal friction and the model suggested by Naughton (2007). The experimental work discussed in this paper is currently ongoing and samples will be tested to investigate whether density affects the location of the plane of equal settlement and hence the location of the critical height.

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