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A Contribution to the Design of a Piled Embankment

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ABSTRAK

Penggunaan cerucuk kayu ataupun konkrit merupakan salah satu daripada penyelesaian ke atas masalah ketidakstabilan dan enapan hasil daripada pembinaan benteng jalanraya di atas tanah lembut. Teknik ini memindahkan kebanyakkan daripada beban kenaan (beban benteng) ke grid cerucuk. Untuk menjimatkan perbelanjaan, cerucuk-cerucuk hendaklah dijarakkan jauh-jauh di antara satu dengan lain, dan setiap cerucuk dibekalkan dengan tukup berasingan, bukan papak. Walau bagaimanapun mekanisma pemindahan beban daripada tanah (bumi) ke tukup cerucuk masih belum difahami sepenuhnya. Kaedah-kaedah rekabentuk merupakan kaedah ghalib, berdasarkan kepada ujian-ujian model aras tegasan rendah di atas pasir dan pengalaman luar. Dengan menggunakan ujian-ujian model sentrifiug dan makmal, pengaruh parameter seperti ketinggian timbusan, nisbah luas cerucuk dan sifat-sifat timbusan terhadap pengongsian beban di antara cerucuk dan bumi diselidik dan diperihalkan di dalam rencana ini.

ABSTRACT

The use of timber or concrete piles offers one solution to the problem of stability and settlement posed by construction of road or highway embankments on soft ground. The idea is to transfer most of the applied load on to a grid of piles, and for reasons of economy, the piles should be spaced as widely as possible and capped individually rather than by a continuous slab. However the mechanism of load transfer from ground to the top of the pile cap appears not to be fully understood. Design methods are empirical, based on the results of low stress level model tests on sand, and on field experiences. Using centrifugal and laboratory model tests the influences of parameters such as fill height, pile area ratios and fill properties on the load sharing between the pile and ground are examined and described in the paper.

Keywords: Arching, efficacy, embankment, pile, punching failure

INTRODUCTION

Highway embankments on soft ground pose problems of instability during construction, and long-term and persistent settlement subsequently. This is particularly so in cases where the embankment is high as, for example, at bridge approaches. Movement of a structure such as the bridge abutment will be limited by the piled foundations, whereas the adjacent embankment may settle significantly, causing differential settlement and lateral deformations. One method of solving these problems is to use a grid of piles to support the embankment. In theory, piles driven into soft ground have two effects – they stiffen the soft subsoils and reduce stresses on the upper subsoil by transferring load down to lower elevations, reducing settlement and lateral movement and allowing the possibility of rapid, single-stage construction. Recent examples of piled embankment construction are given by Ooi *et al.* (1987) and Combarieu & Pioline (1991). However, the complexity of the soil-piled structure interaction problem is such that no fully developed theoretical relationship between the characteristics of the soil in the field and that of the pile versus behaviour of the embankment as a whole, appears to have been well established. Uncertainties exist regarding the design of pile caps – their size and spacing, and type of fill. Broms and Hansbo (1981) and Chin (1985) referred specifically to *Fig. 1,* a relationship which was published by the Swedish Road Board (1974), as a general guidance for selection of pile cap size, a, and pile spacing, s. Design methods are empirical, based on past experiences and on the results of low stress level model tests on sand rather than clay.

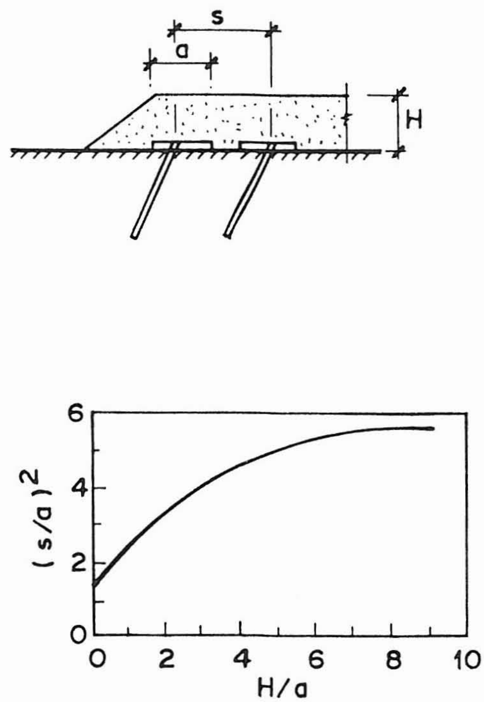


Fig. 1. Empirical design chart (Swedish Road Board 1974)

Based on the results of centrifugal and laboratory model testing, this paper examines the influence of fill height, area ratios of the pile cap and properties of the fill on the load sharing behaviour between the pile and ground.

METHODS OF STUDY

Centrifuge Model

In many soil mechanics problems a major component of loading and consequently the state of stress is the self weight of the material (Basett & Horner 1979). Under these circumtances, a centrifuge model offers a way of reducing many of the complexities of a model/field scaling. Raising the acceleration of a 1/Nth scale model to N times earth gravity (g) automatically raises all self weight stresses in the model to those in the field, resulting in correct stress distributions and pore water pressure generation within the model.

A series of centrifuge model tests have been performed as outlined in Table 1, all nominally at 1 : 100 scale. *Fig. 2* shows typical cross-sections of the model embankments and their instrumentation.

TABLE 1
Outline of centrifuge test models

	Type of fill	Pile configuration	Construction schedule	Comments
PE1	Mixed fill	As PE3	Bedding run 45 mins @ 100 g. Main run 15 mins to 65 g, 40 mins @ 65 g, 10 mins to 100 g, 2 hrs @ 100 g 10 mins to 134 g	Study effect of stiff fill
PE2	Clay	AS PE3	As PE1, but 1 hr @ 100 g in main run	Study effect of soft fill.
PE3	Mixed	*Fig. 2a*	As PE2	-
PE4	Mixed fill	As PE3, but pile spacing 55 mm	As PE2	Study effect of pile area ratio.
PE5	Mixed fill	*Fig. 2b*	Main run extended to 10 hrs @ 100 g	As PE4 and long term behaviour.
PE6	Mixed fill	As PE5 but pile spacing 35 mm	As PE5	As PE5
PE8	Mixed fill	As PE 3 but pile spacing 65 mm		As PE4

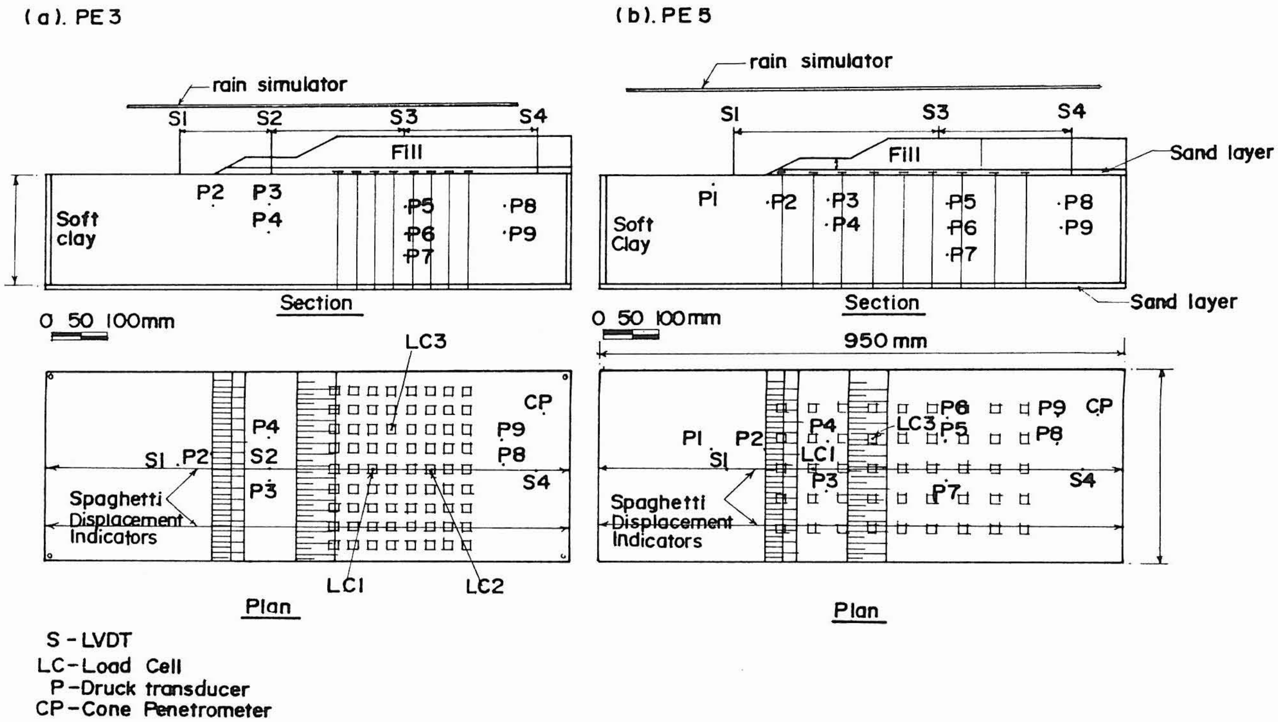


Fig. 2. Typical cross-sections of model embankments

Troll clay with w_L = 60%, w_p = 30 % and c_v = 1 - 3m^2/year was used to simulate a soft clay foundation. This was consolidated from slurry using the hydraulic gradient method (Zelikson 1969) to a graded strength profile, *Fig 3.* Clay and a sand/clay mix were used to simulate cohesive embankment fill. The mixed fill was made by adding kaolin clay to a very sandy soil to obtain a sand:clay ratio of 4:1 by weight. This was compacted at a water content of about 12 %, to give c' = 20 kPa, Ø'= 30 and ρ_b = 2.09 mg/m^3. The model piles were made of aluminium rod, 4.6 mm in diameter, rigidly connected to 18 × 18 × 5 mm aluminium caps. Instrumentation installed was spaghetti displacement indicators, pile load cells, pore pressure transducers and LVDTS. The spaghetti displacement indicators comprised lengths of spaghetti which were installed at regular spacings on particular long sections of the foundation beds to allow visual assessment of deformations and/or rupture in the subsoil on dissection after testing. The models were spun at 100 g for 1 - 10 hours in the centrifuge. Details of the model preparation and test procedures have been described by Bujang *et al.* (1991).

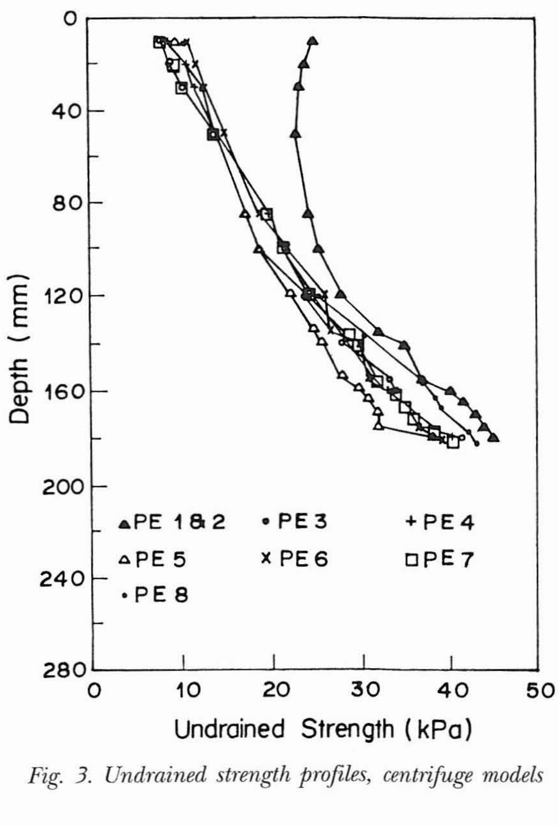


Fig. 3. Undrained strength profiles, centrifuge models

Laboratory Model

In addition to the centrifuge testing, tests were also carried out using a simple laboratory model (*Fig. 4*). The influence of the area ratio of the pile cap, (a^2/s^2), fill thickness, H, and ground settlement on the failure mechanism and load-carrying characteristics of the pile support was studied. The model consists of a square perspex-walled box, with dimensions 910 × 910 × 910 mm. Piles are represented in the tests by blocks of wood (38 mm in diameter) and pile caps are made of square pieces of plywood. The baseboard represents the ground which is settling and transferring load to the piles. First, the piles with caps were inserted through the holes in the baseboard which could be lowered. The walls were greased to minimise friction. Sand was then placed and compacted in layers inside the box. The settlement of the soft ground was simulated by lowering the base board. This was performed slowly and steadily in order to simulate the actual settlement as closely as possible. As the baseboard was lowered, the loads taken by the board and the piles were monitored.

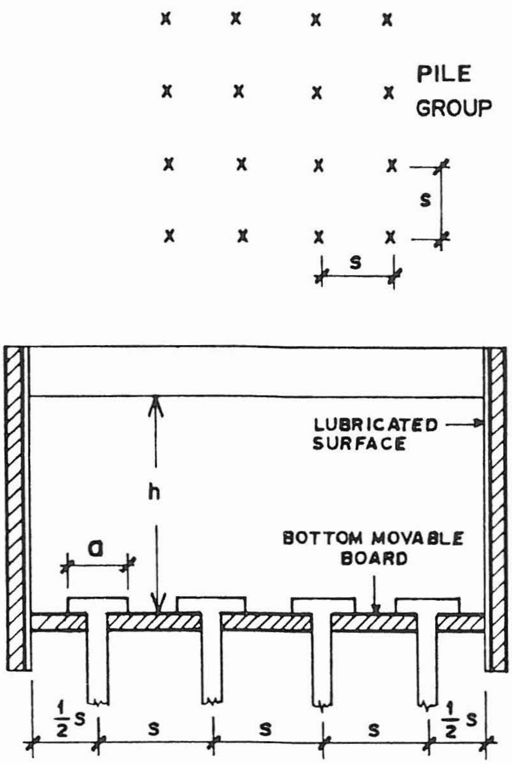


Fig. 4. Cross-section of laboratory model

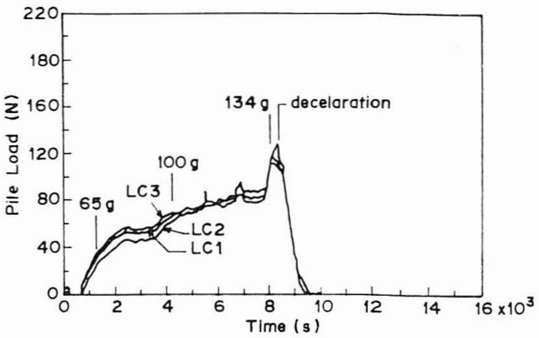


Fig. 5. Pile loads, centrifuge model PE3

RESULTS AND DISCUSSION

Mechanism of Load Transfer

Fig. 5 shows a typical pile load - time relation obtained from the centrifuge model (PE3). During the construction pause period, pile load or efficacy, E (defined as pile load over total available load, γHs^2, where γ is the unit weight of fill, H is the height of fill above the pile head and s is the pile spacing, is observed to increase with time. A similar observation has been reported at field site by Reid and Buchanan (1984) and Ooi *et al.* (1987). This indicated that as the ground between the pile caps settled greater stresses were being transferred from the ground to the top of the pile cap. The mechanism of this may be best explained by referring to Terzaghi's (1943) classic descriptions of a trap door which are stated as follows: If one part of the soil mass yields while the remainder stays in place, the soil

TABLE 2
Summary of pile H/s & area rations (centrifuge models)

Model	Pile cap size, a	Spacing s	(a^2/s^2)	H/s Berm	H/s Main Setion
PE1	18 mm	35 mm	0.26	-	1.64
PE2	18 mm	35 mm	0.26	-	3.50
PE3	18 mm	35 mm	0.26	-	1.64
PE4	18 mm	55 mm	0.11	-	1.05
PE5	18 mm	55 mm	0.11	0.41	1.05
PE6	18 mm	35 mm	0.26	0.64	1.64
PE8	18 mm	65 mm	0.08	-	1.04

adjoining the yielding part moves out of its original position between the adjacent stationary masses. This relative movement within the soil is opposed by shearing resistance within the zone of contact, between the yielding and stationary masses. Since the shearing resistance tends to keep the yielding mass in the original position, it reduces pressure on the yielding parts and increases pressure on the adjoining stationary part. In a piled embankment problem, the fill in between the pile caps, as in the trap door, can be visualised as moving downwards due to yield and/or consolidation of the ground underneath, while the pile caps provide a stationary support.

In the centrifuge test (PE3) mentioned above the area ratio of the pile cap [a^2/s^2] was 0.26, and the final embankment height at the main section was greater than the pile spacing (Table 2). No punching failure was observed at the fill surface of the model, apart from local punching or bedding-in seen at the model base, indicating that the mechanism of load transfer from ground to the top of the pile cap was due to arching.

Fig. 6 shows the results of the laboratory model. The figure shows the changes in proportion of fill weight taken by the piles as the baseboard is lowered (to simulate ground settlement) for pile caps occupying 25% of the baseboard area. Three different fill heights were considered, i. e. 1.0s, 1.5s and 2.0s where s is the pile spacing. Generally, as in the above, the proportion of fill weight taken by the piles increases with increase in ground settlement until peak. The figure also shows a slight drop in E to constant residual values after the peak. Both the peak and residual values of E are dependent on the fill height. Table 1 shows the development of crack which separates the fill material carried by the piles from that

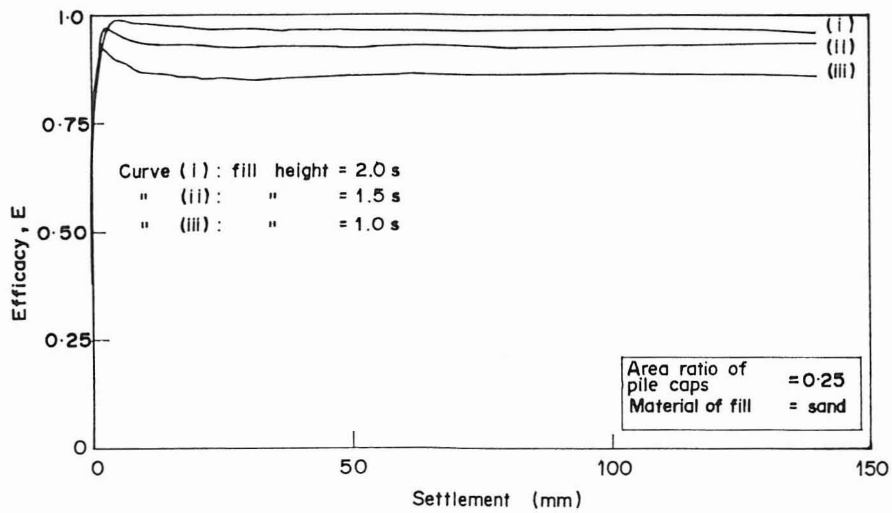


Fig. 6. Efficacy vs. settlement, laboratory model

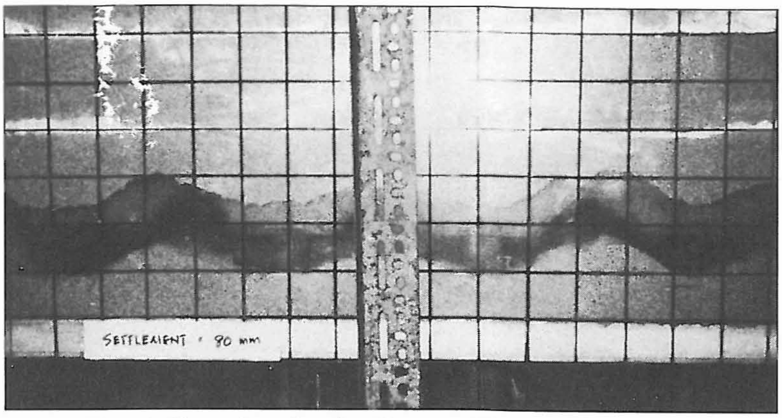


Plate 1. Formation of arches (for case $H/s > 1$, $a^2/s^2 = 0.25$), laboratory model

carried by the baseboard. The formation of arches can be clearly seen from the figure. The surface of the fill remained fairly even, and the weight of fill above the arches was transferred to the pile caps which remain stationary during test.

The maximum load that a pile can take depends on the bearing capacity of the pile cap. This is shown in the piled load measurements of centrifuge model PE5 in *Fig. 7.* Settlement of the foundation increased the load transfer or efficacy initially until the shear strength of the fill local to the pile caps was again transferred to the clay foundation. Ultimately however, stable arches formed above the pile head.

In cases where the final embankment height is low relative to the pile spacing, or the pile spacing is too large (too much load is available to be relieved), a near vertical rupture occurs throughout the whole depth of fill above the pile head. This is shown at the supported berms of centrifuge

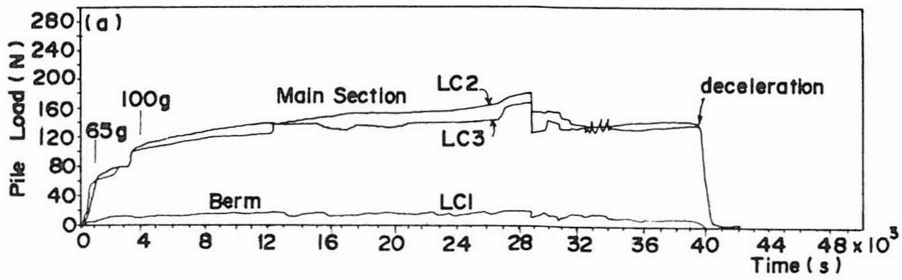


Fig. 7. Pile load measurement of model PE5

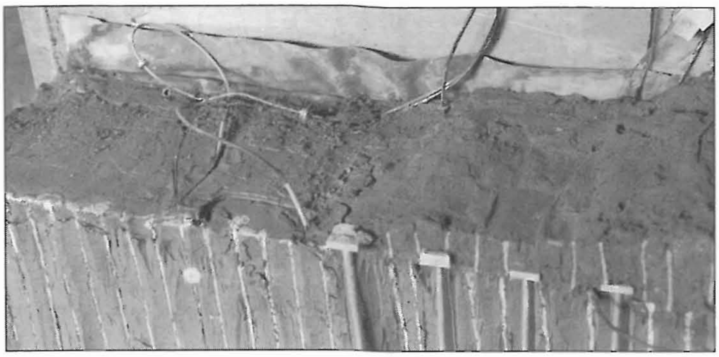


Plate 2. Punching failure, centrifuge model PE5

model PF5 and PE6. The berm section failed by punching shear resulting in uneven surfaces with zone between piles settling relative to the pile caps with star-formed cracking immediately above the piles as shown in Plate 2. The H/s and area ratios of the pile cap of the supported berm of model PE5 (and PE6) were respectively equal to 0.11 and 0.41 (and 0.64 and 0.26).

Fig. 8 shows the behaviour obtained from the laboratory model for pile caps occupying 12.5 % of base board area. It can be seen that the proportion of fill weight taken by the piles continuously drops after peak. No stable arches seem to form during test. When the test was stopped the pile almost punched through to the surface. At this stage humps were observed directly above the pile caps as shown in Plate 3.

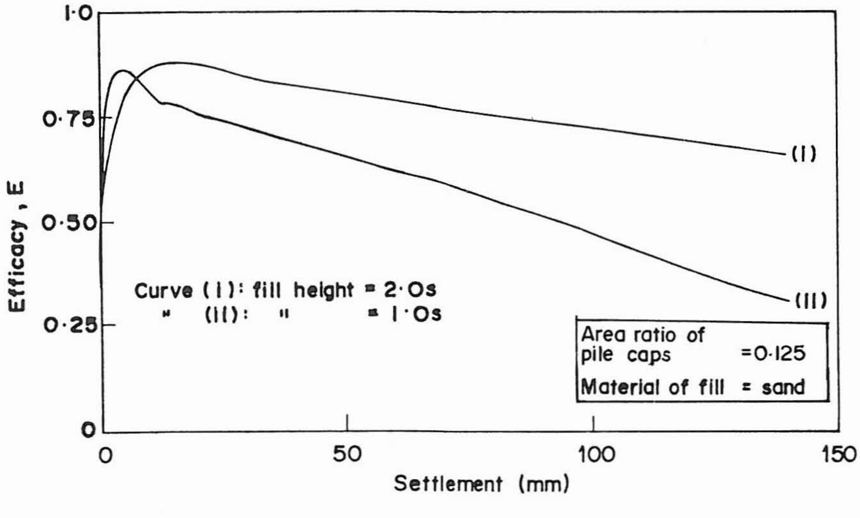


Fig. 8. Efficacy vs. settlement, laboratory models

Plate 3. Punching failure (for case of $H/s = 1$, $a^2/s^2 = 0.125$), laboratory model

It is apparent that in a piled embankment design in order to prevent failure by punching and to encourage arching or high efficacy of the pile support, the fill thickness, depending on the area ratio of the pile cap, needs to be at least equal to, or greater than, the pile spacing.

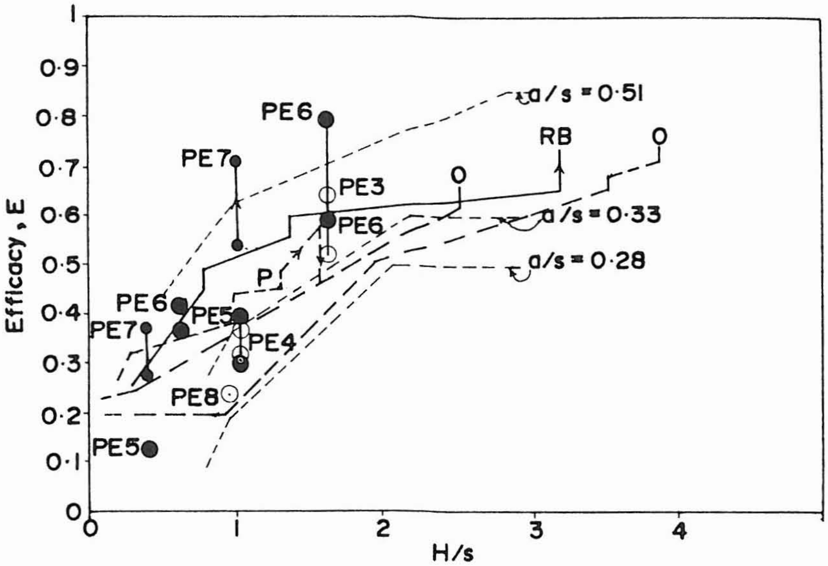
Effect of the Area Ratio of the Pile Cap

Reducing the area ratio of the pile may lead to higher load on individual piles but naturally reduces the value of E and throws more load onto the subsoils. This is shown in the values if E of the centrifuge models of different area ratios in *Fig. 9*. Plotted also on *Fig. 9* are the values of E from the field sites, and that of a closed form solution based on limiting equilibrium of forces required to sustain an arch suggested by Hewlett and Randolph (1988). The agreement between the experiments, field data and calculations appears to be reasonable.

It is of interest to note that as shown on *Fig. 9*, for a given type of fill there is no further significant increase in E once the fill thickness exceeds 1 - 2 times the pile spacing, depending on the area ratio of the pile cap. Although arching that occurred between adjacent piles necessarily meant that all overburden beyond certain elevation will be transferred to the piles, the limiting condition in this case is the bearing capacity of the pile cap. The efficacy of the pile support for a given type of fill, however, can be increased by increasing the area ratio of the pile support, either by enlarging the pile cap or reducing the pile spacing.

Effect of Fill Properties

Since the transfer of fill load from ground to the top of the pile cap relies on the shearing resistance of the fill, type or quality of fill can be expected



------ Calculation

Field Studies

— — —P-Field Trial (ave. E), a/s = 0.51 } Free standing vertical piles

— — —O-Ooi *et al.* (1987), a/s = 0.52

——— RB-Reid & Buxhanan (1984), a/s = 0.37

Centrifuge Models (ave.E @ 100g)

⊙ PE3, a/s = 0.51 } Free standing vertical piles

⊙ PE4, a/s = 0.33

⊙ PE8, a/s = 0.28

● PE5, a/s = 0.33

● PE6, a/s = 0.51

• PE7, a/s = 0.33 - Vertical piles with tie beams

Fig. 9. Comparison of pile support efficacy, E

to affect the efficacy of the pile support. Better quality fill of high strength and stiffness would facilitate more efficient transfer of fill load to the piles. This is shown in the values of E of the centrifuge models with equal area ratio but of different fill types summarised in Table 3. It may be suggested that rock fill which has higher strength and stiffness – hence high bearing capacity and low strain required to mobilise large shearing resistance, as used in Sweden (examples Broms and Hansbo 1981) would allow more efficient transfer of fill load to the pile than the materials (cohesive fill and sand) dealt with in this study. Layers of stiff geomembrane placed immediately on top of the pile head may also help to improve local bearing capacity of the pile support (Reid and Buchanan 1984).

It is also of interest to note that as mentioned earlier, there is no significant increase in rate of efficacy E once the fill height exceeds 1 to

TABLE 3.
Efficacies of centrifuge models PE1, PE2 and PE3

Model	Fill	at 100 g	Efficacy, after	E hrs at 100 g
			0.7 hr (0.8 yr)	1 hr (1.1 yr)
PE1	Mixed	0.52	0.57	0.68
PE2	Clay	0.40	0.44	-
PE3	Mixed	0.51	0.59	0.65

2 times the pile spacing. It may therefore be advocated that a high quality fill (such as rock fill) need not be higher than 1 to 2 times the pile spacing above the pile heads. A lower grade of fill may be placed above this elevation, the overburden of which will be transferred to the piles via arching of the lower layer.

CONCLUSIONS

The mechanism of load transfer from ground to the top of the pile cap is a complex relationship between the strength and stiffness, and height of fill above the pile head, geometry of the pile support, and consolidation characteristics of the foundation clay.

Settlement of the foundation increased the efficacy initially due to transfer of stresses from ground to the top of the pile cap, until the shear strength of the fill was exceeded local to the pile caps when load was again transferred to the clay foundation. Ultimately however, stable arches formed above the pile head.

For low fill thickness relative to the pile spacing, punching shear failure was in evidence resulting in low efficacy, but for high fill relative to the pile spacing, only local failure occurred just above the pile head with the fill surface remaining fairly even, resulting in high efficacy.

Reducing the area ratio of the pile cap increases the proportion of load carried by the ground in between the pile caps, increasing the possibility of punching failure and reducing the efficacy.

High quality fill of high strength and stiffness resulted in more efficient transfer of load from ground to the piles, giving high efficacy.

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