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TECHNICAL NOTE

The pressure distribution along stone columns in soft clay under consolidation and foundation loading

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The mechanism whereby foundation loading is transmitted through the column has received little attention from researchers. This paper reports on some interesting findings obtained from a laboratory-based model study in respect of this issue. The model tests were carried out on samples of soft clay, 300 mm in diameter and 400 mm high. The samples were reinforced with fully penetrating stone columns, of three different diameters, made of crushed basalt. Four pressure cells were located along each stone column. The 60 mm diameter footing used in the model was supported on a clay bed reinforced with a stone column and subjected to foundation loading under drained conditions. The results show that the dissipation of excess pore water pressure developed during the initial application of total stresses, when the foundation was subjected to no loading, generated considerable stresses within the column, and that this was directly attributable to the development of negative skin friction. The pressure distributions in the column during foundation loading showed some complex behaviour.

KEYWORDS: footings/foundations; ground improvement; model tests; reinforced soils; settlement; soil/structure interaction

Le mécanisme d'après lequel les charges sur fondations sont transmises à travers la colonne n'a guère été abordé par les chercheurs. Cette communication présente certaines conclusions intéressantes, résultant de l'étude sur maquette en laboratoire concernant cette question. Les essais sur maquette ont été effectués avec des échantillons d'argile tendre de 300 mm de diamètre et 400 mm de haut. Les échantillons ont été renforcés avec trois diamètres différents de colonnes de pierre à pénétration intégrale réalisées en basalte concassé. On a placé quatre cellules de pression le long de la colonne de pierre. La semelle de 60 mm de diamètre, utilisée dans ce modèle, était supportée sur une couche d'argile, renforcée avec une colonne de pierre, et soumise à des charges sur fondations à l'état drainé. Les résultats indiquent que la dissipation d'une pression d'eau interstitielle excessive, qui se produit au cours de l'application initiale de contraintes totales, lorsque les fondations ne sont soumises à aucune charge, produit des contraintes considérables au sein de la colonne, qui sont attribuables directement au développement d'un frottement superficiel « négatif ». Les distributions de pression dans la colonne, au cours des charges sur fondations, présentent un comportement complexe.

INTRODUCTION

The inclusion of stone columns leads to improved load-bearing capacity and overall stiffness, with the resulting benefit of reducing consolidation settlements. Laboratory-based research (Charles & Watts, 1983; Muir Wood *et al.*, 2000; Black *et al.*, 2011), together with analytical modelling (Balaam & Booker, 1981) and field observations (Hughes *et al.*, 1975; Slocombe *et al.*, 2000), has contributed to improving the efficiency and quality of the operation in practice. Whereas many of the studies have focused predominantly on bearing capacity and settlement, there are limited data on the stress transfer mechanism between the stone column and the surrounding clay. This paper represents the first attempt to understand how the vertical pressure along the column varies, and how it is affected by the consolidating surrounding clay and increasing foundation load.

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TESTING PROGRAMME

A large triaxial cell capable of testing samples 300 mm in diameter by 400 mm high was used in the research. Fig. 1 illustrates the key aspects needed in the equipment: the application of independent foundation loading, flexible boundary conditions away from the footing, and measurements of pressure along the column.

The granular columns, on clay samples 400 mm high by 300 mm in diameter, were formed by compacting crushed basalt with particle sizes between 2·5 and 3 mm into a pre-bored hole. Basalt (40 g) was poured into the hole and gently compacted. Once a column length of 90 mm had been achieved, the pressure cell (Fig. 1) was carefully located on the top of the column. Using this procedure, the column was built to the full height. The settlement of the footing and the surrounding clay were measured using linear variable differential transformers (LVDTs) (Fig. 1). In the first stage of testing the sample was allowed to consolidate under 50 kPa of effective pressure, resulting from 300 kPa of confining pressure and 250 kPa of pore water pressure. In the second stage, the foundation was loaded in a ramped fashion at a rate of 1 kPa/h.

RESULTS AND DISCUSSION

Stress transfer mechanism between stone column and surrounding clay during consolidation

Unreinforced sample (Test 4). Figure 2(a) shows the pressures developed under the footing and at the base of the sample during

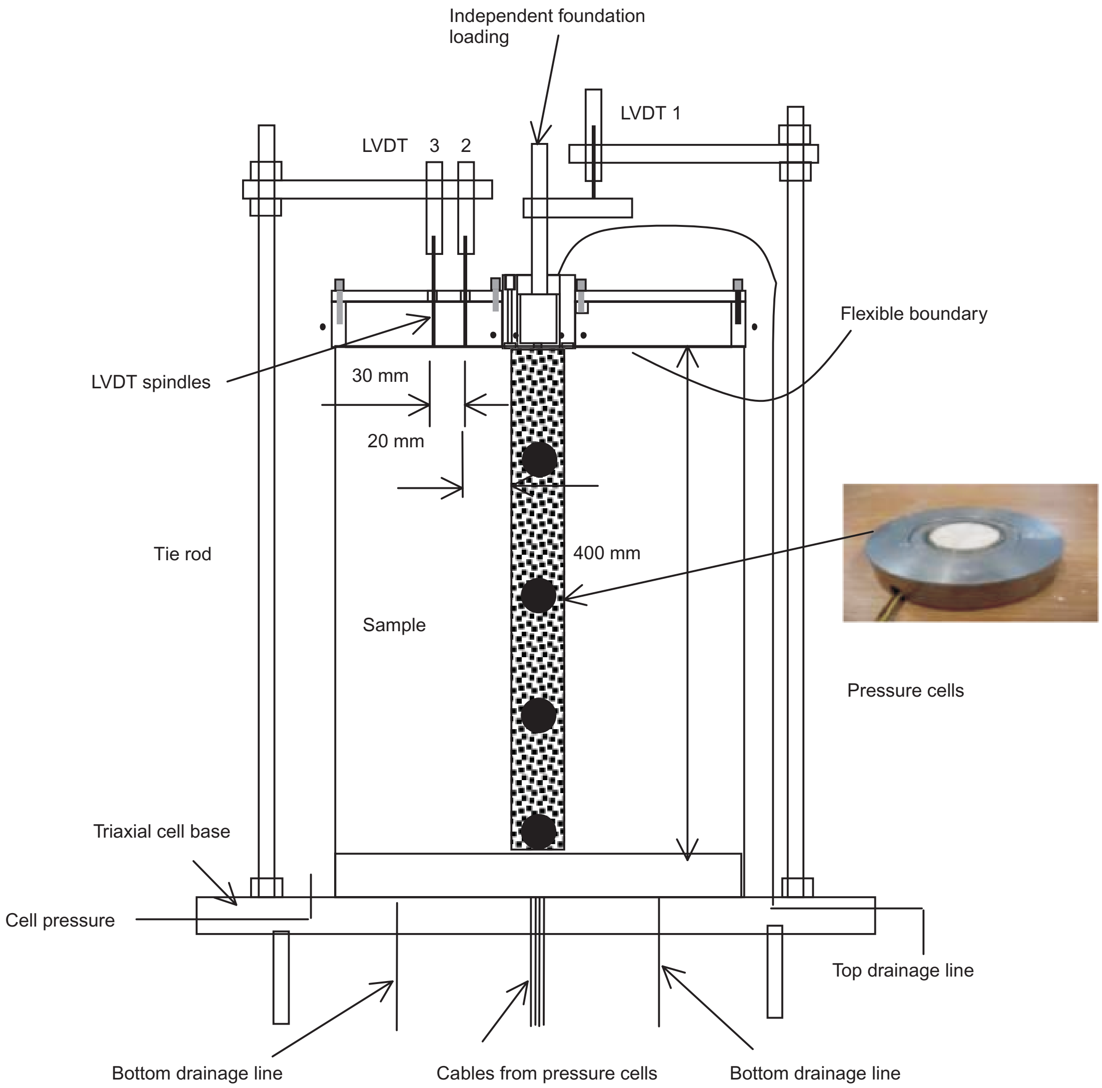

Fig. 1. Assembled sample

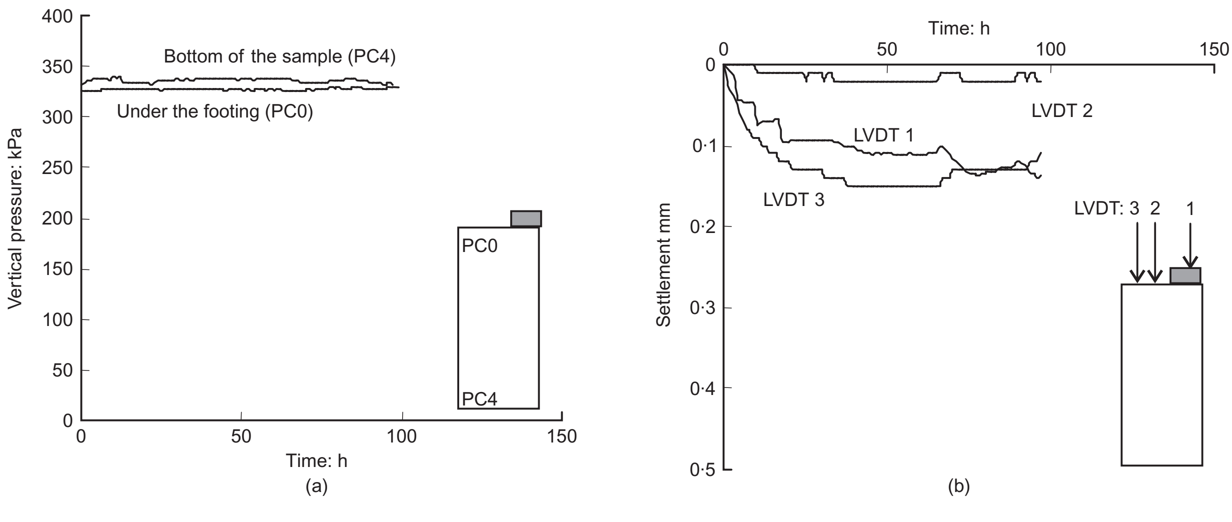

Fig. 2. Performance of sample without column during consolidation: (a) pressure distribution; (b) settlement

consolidation. The consolidation lasted about 4 days, during which the total pressures under the footing and on the base of the sample remained unchanged at about 325 kPa, and were approximately equivalent to the confining pressure applied to the sample. Overall the sample compressed vertically (Fig. 2(b)) by about 0·16 mm. Settlement was generally similar under the footing and away from it. The magnitude of the settlement was small, compared with other samples with an included stone column. This was due to the lower excess pore water pressure (Table 1) existing in the sample prior to consolidation, compared with the value of around 20 kPa in all other tests, where the samples included granular columns.

Table 1. Testing configuration

Test no.	Foundation diameter: mm	Column diameter: mm	Pressure cells	Effective consolidation pressures: kPa	Excess pore water pressure dissipated during consolidation: kPa
1	60	60	Yes	50	25
2	60	50	Yes	50	22
3	60	40	Yes	50	22
4	60	No columns	N/A	50	5
5	60	No columns	N/A	50	5
6	60	60	No	50	20

Reinforced sample with 60 mm and 50 mm diameter columns with pressure cells (Tests 1 and 2). Figure 3(a) shows how the vertical pressure changed with time as the excess pore water pressure dissipated over the consolidation period. The pressure under the footing increased by around 18 kPa, but at the bottom of the column the pressure was 90 kPa. Fig. 3(b) shows the pressure distribution along the column at specified times intervals. The observations show moderate to large increases in vertical pressure in the bottom third of the sample, but slightly less increase in the top third of the sample, and a generally small increase in the middle section of the sample. Fig. 3(c) shows the compression of the stone column during the consolidation process. This exhibits a time-dependent behaviour such that the stone column underwent settlement during the entire phase of the consolidation. Observations made with regard to pressure variation along the column and the resulting settlements for the 50 mm diameter column are shown in Fig. 4. The observations are comparable to those for the 60 mm diameter column.

Reinforced sample with 60 mm diameter column without pressure cells (Test 6). Figure 5 shows the performance of the composite sample in relation to the pressure developed under the footing and under the column. At the beginning of the consolidation process the vertical pressure under the footing was approximately 320 kPa. Fig. 5(a) shows how this pressure changed with time as the excess pore water pressure

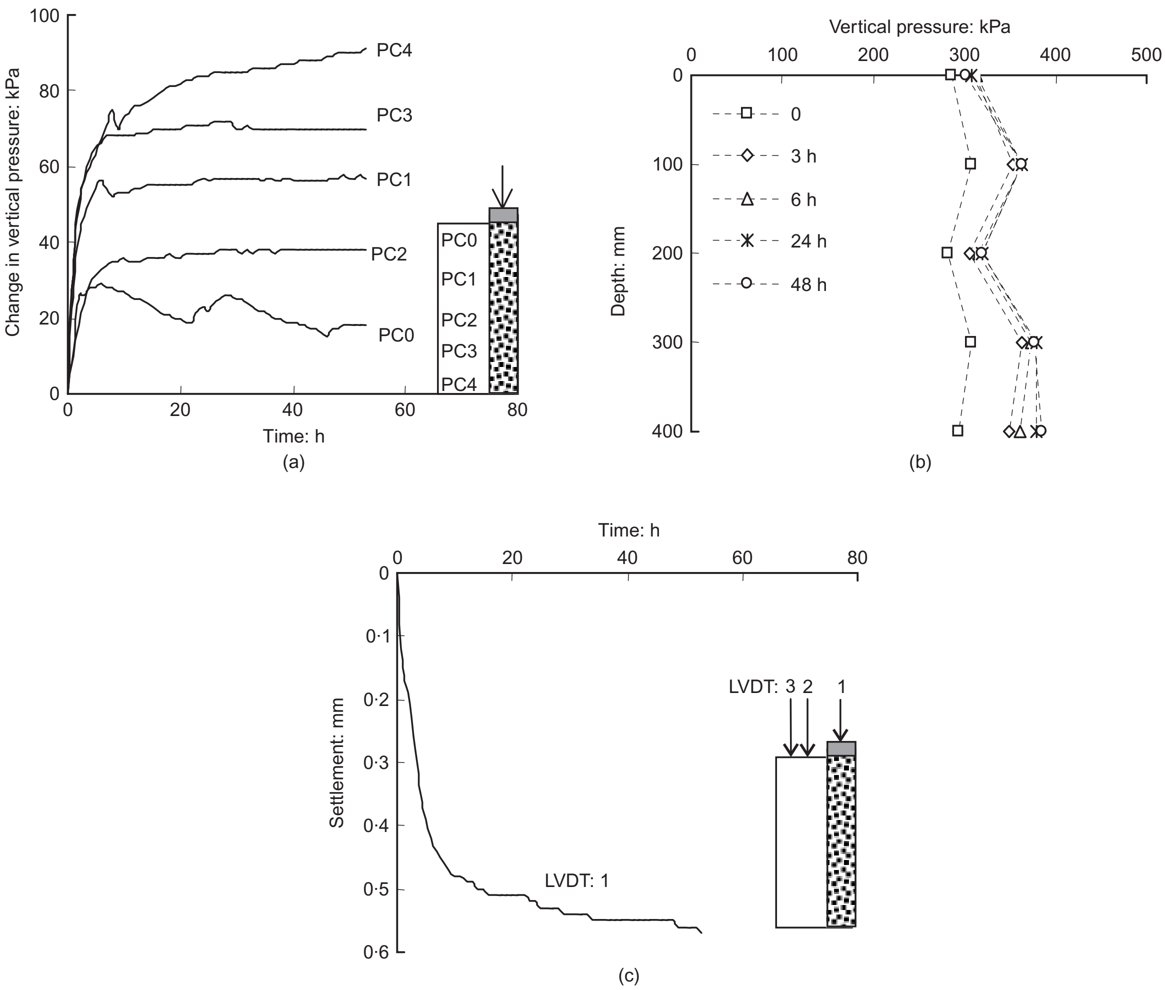

Fig. 3. Performance of sample with 60 mm diameter column during consolidation: (a) vertical pressure; (b) pressure distribution with depth; (c) settlement

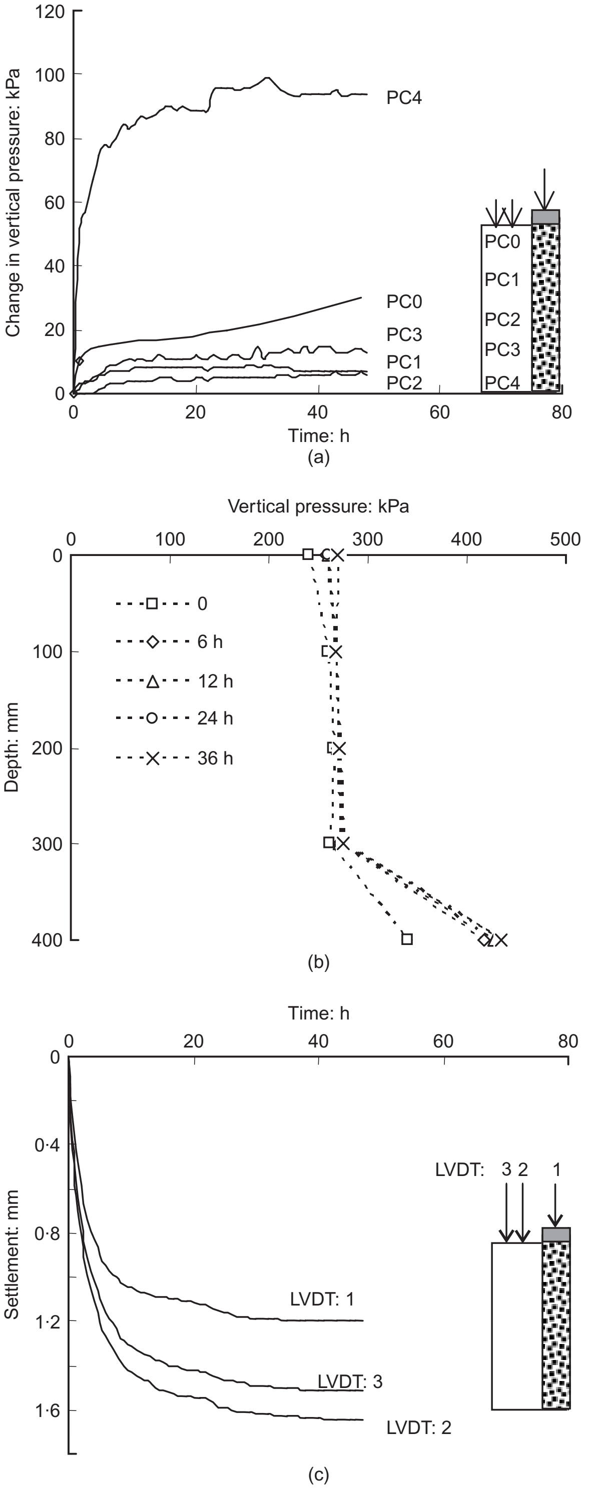

Fig. 4. Performance of sample with 50 mm diameter column during consolidation: (a) vertical pressure; (b) pressure distribution with depth; (c) settlement

dissipated over the consolidation period. The vertical pressure under the footing increased by about 45 kPa, and the change in pressure for the bottom of the column was recorded as 200 kPa (Fig. 5(b)). Fig. 5(c) shows the vertical compression of the stone column and the surrounding clay during the consolidation process: it exhibits a strongly time-dependent behaviour.

The above observations demonstrate some interesting responses of the composite sample during the initial consolidation. In each case the stone column showed settlement with time. This could be attributed to the gradual increase in

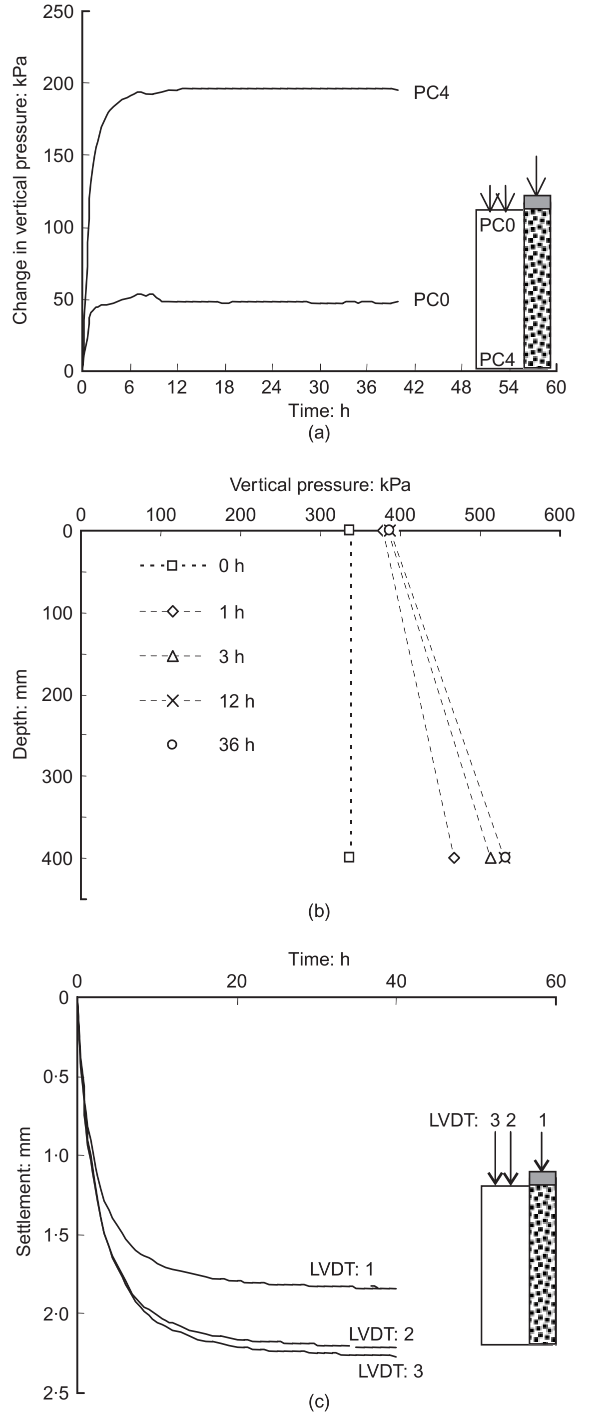

Fig. 5. Performance of sample with 60 mm diameter column during consolidation (control test): (a) vertical pressure; (b) pressure distribution with depth; (c) settlement

vertical stress in the column caused by the consolidation of the clay surrounding the column. The evidence for this is shown in Fig. 4 with reference to the 50 mm diameter column, where the surrounding clay settled more than the column. The consolidation of the clay is a time-dependent process, and therefore its effects on the stone column are also time dependent. The surrounding clay consolidates more than the stone column, resulting in the development of negative skin friction on the stone column.

In all three cases (Tests 1, 2 and 3), the vertical pressure at the base increased by about 100 kPa, except for the case where the stone column did not have included pressure cells (Fig. 5). In this case the vertical pressure increased by about

200 kPa. This effect can be attributed to the additional reinforcement provided by the pressure cells located in the columns. This is clearly demonstrated in Fig. 6, where the column without pressure cells has undergone 1·6 mm of compression, compared with around 0·6 mm for the instrumented column.

Stress transfer mechanism between stone column and surrounding clay during foundation loading

Unreinforced sample (Test 4). Figure 7(a) shows the pressure distribution under the footing plotted against the footing settlement of the sample without a stone column. The bearing

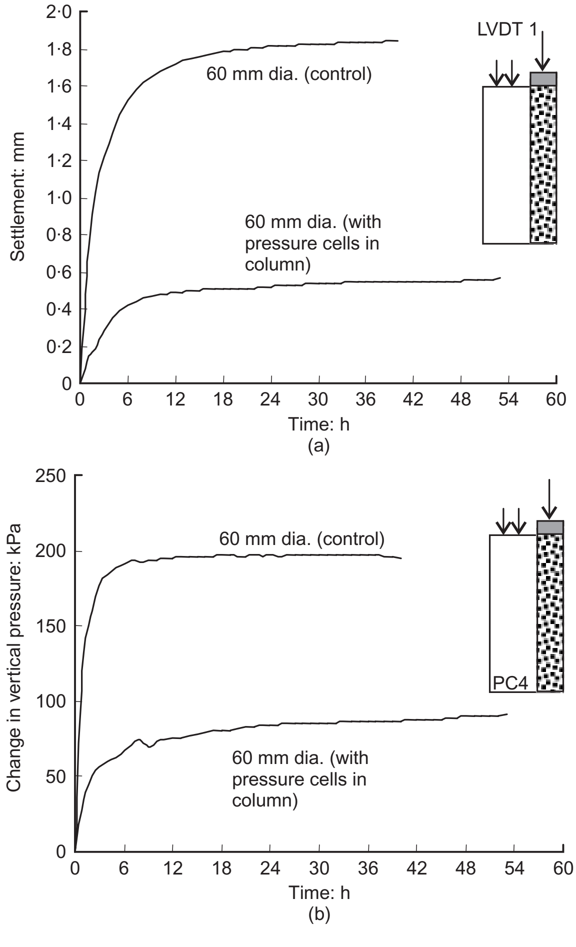

Fig. 6. Effects of pressure cells in column on settlement and pressure variations: (a) settlement of column; (b) change in vertical pressure at base (PC4)

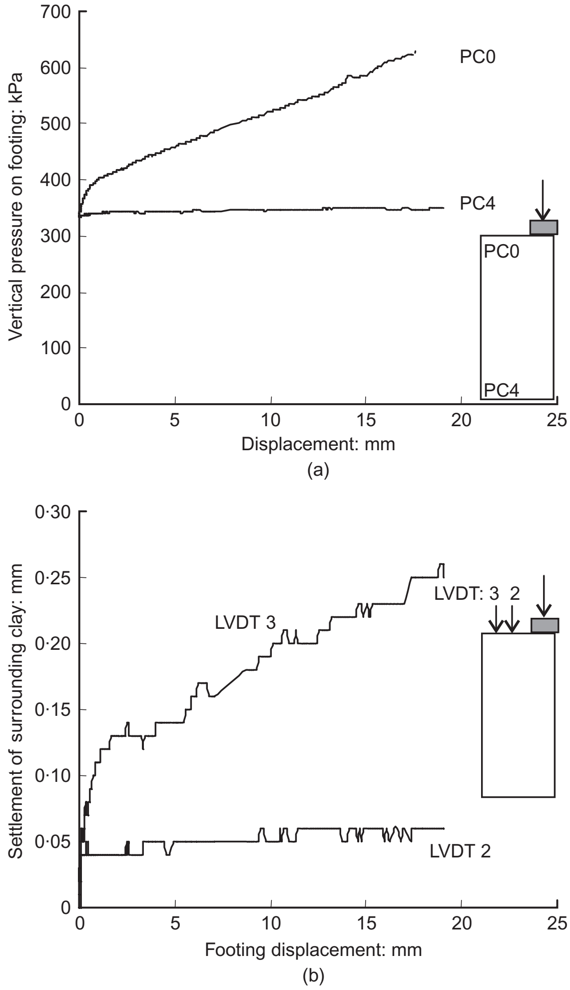

Fig. 7. Performance of sample without column during foundation loading: (a) vertical pressure against footing displacement; (b) settlement of surrounding clay against footing settlement

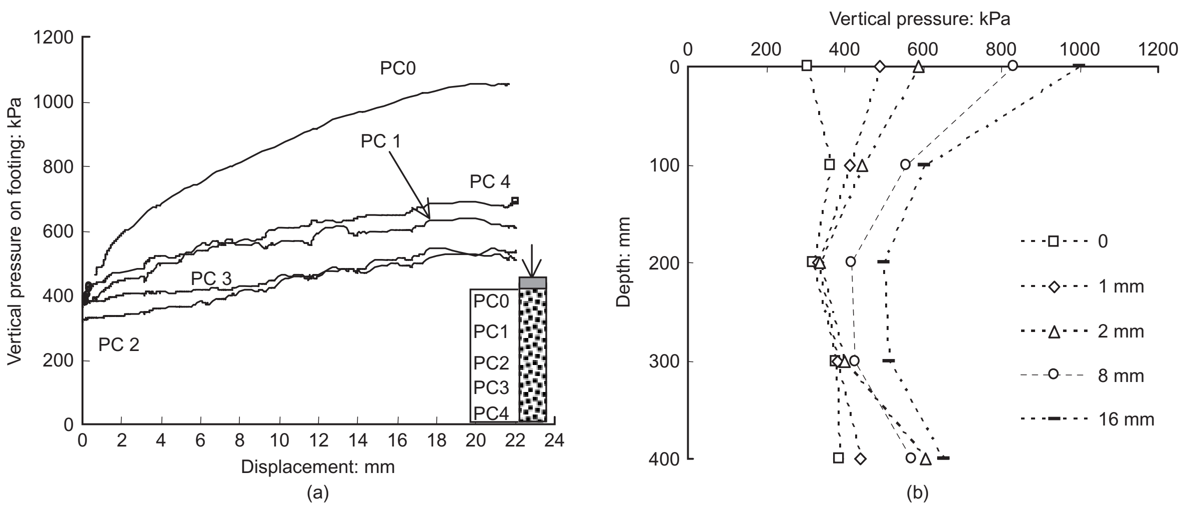

Fig. 8. Performance of sample with 60 mm diameter column during foundation loading: (a) vertical pressure against footing displacement; (b) pressure distribution with depth

pressure under the footing continued to increase, and the increase was about 300 kPa when the footing penetration was 15 mm. The relevant increase of vertical pressure at the base of the sample at this displacement was about 10 kPa, and this compares favourably with the estimated increase using a 2:1 spread. Fig. 7(b) shows the settlement of the surrounding clay, which was about 0·25 mm.

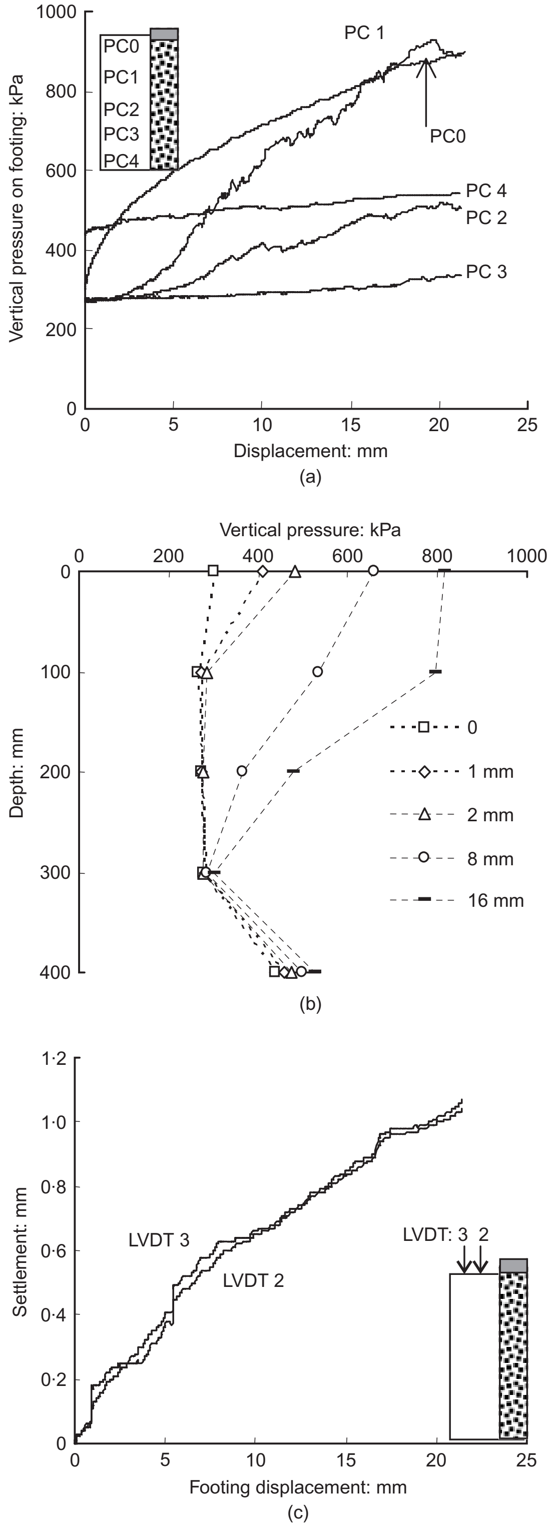

Fig. 9. Performance of sample with 50 mm diameter column during foundation loading: (a) vertical pressure against footing displacement; (b) pressure distribution with depth; (c) settlement of surrounding clay against footing settlement

Reinforced sample with 60 mm diameter column with pressure cells (Test 1). Referring to Fig. 8, the pressure under the footing was about 320 kPa at the beginning of the foundation loading, but increased to 1000 kPa at a footing displacement of 21 mm. Fig. 8(b), in which the relevant pressures are plotted against depth, shows how this varied at specified footing displacements. The changes in the vertical pressure reduced along the column length up to a depth of about 300 mm before it began to increase along the bottom quarter of the column. Similar observations are made for the column diameters of 50 mm (Fig. 9). The minimum increase in the vertical stress took place about 300 mm below the footing for the 60 mm and 50 mm diameter columns; for the 40 mm diameter column it was 200 mm.

Reinforced sample with 60 mm diameter column without pressure cells in column (Test 6). Figure 10 shows the vertical pressure under the footing and the vertical pressure at the base of the column in the control test, where the column was not instrumented with pressure cells. The vertical pressure under the footing increased by 500 kPa, and at the base of the column was 60 kPa.

The minimum vertical pressure was observed around 200 mm below the footing for the 40 mm diameter stone column and around 300 mm for the 50 mm and 60 mm diameter columns. This suggests that the critical length of the column is about five times the diameter, similar to the estimates made by many previous researchers (McKelvey *et*

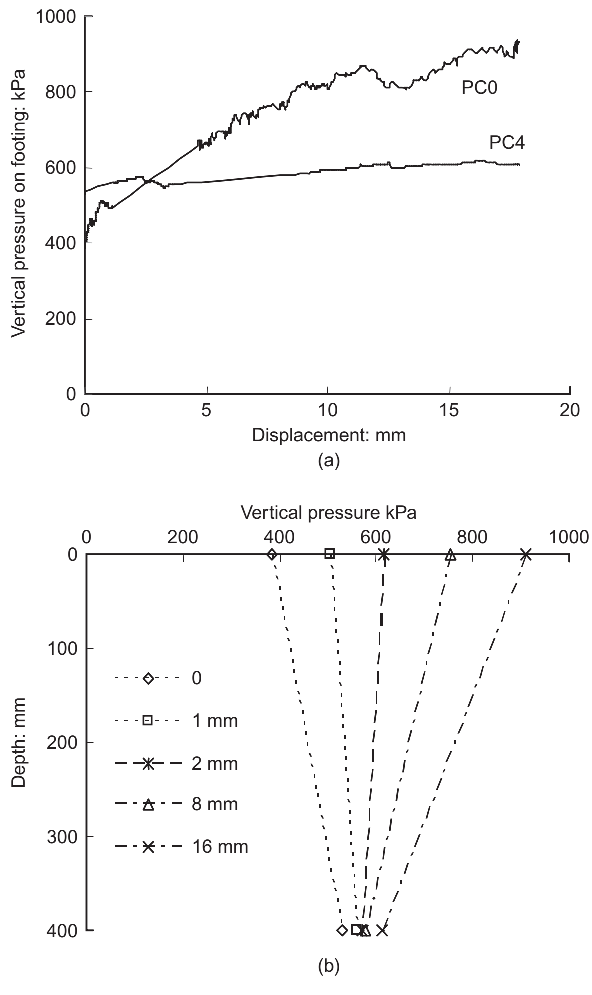

Fig. 10. Bearing pressure–settlement characteristics (control test): (a) vertical pressure against footing displacement; (b) pressure distribution with depth

al., 2004). The reduction in vertical pressure in the column with depth is caused by the load transfer mechanism between the column and the surrounding clay. The load in the column is transferred to the surrounding clay as increased lateral pressures, caused by bulging and side friction. The crucial question remains, however, as to why the vertical pressure begins to rise again after the critical length.

Unlike rigid piles, any load that is applied to the stone column has to be supported by the surrounding clay, particularly at shallow depths. The bulging generates enhanced lateral pressures and shear stresses in the upper region, which in turn leads to settlement of the surrounding clay. The negative skin friction will develop only when the settlement of the pile is less than that of the surrounding clay. It is possible that the overall compression of the stone column below the critical length is not significant compared with the compression of the surrounding clay below this depth, thereby leading to the development of negative skin friction. Interaction between the stone column and the surrounding clay is highlighted in Fig. 11, where the early part of the stress–settlement curve up to a bearing pressure of 150 kPa is shown, together with the settlement of the surrounding clay bed for columns with diameters of 50 mm and 60 mm (Tests 2 and 6), and for the case without a stone column. The settlement of the footing generally reduced as the column diameter increased. However, there was a remarkable increase in the settlement of the surrounding soil when the stone column was 60 mm in diameter, where the settlement of the surrounding clay was about 60% of the foundation settlement. This reinforces the argument that the stone column in soft clay acts as a load transfer unit, whereby the loading applied on the column is transferred to the surrounding soil as enhanced lateral stress and shear stress. However, for unreinforced clay, the loading is more concentrated just under the footing, and no significant changes in the stress occur away from the footing.

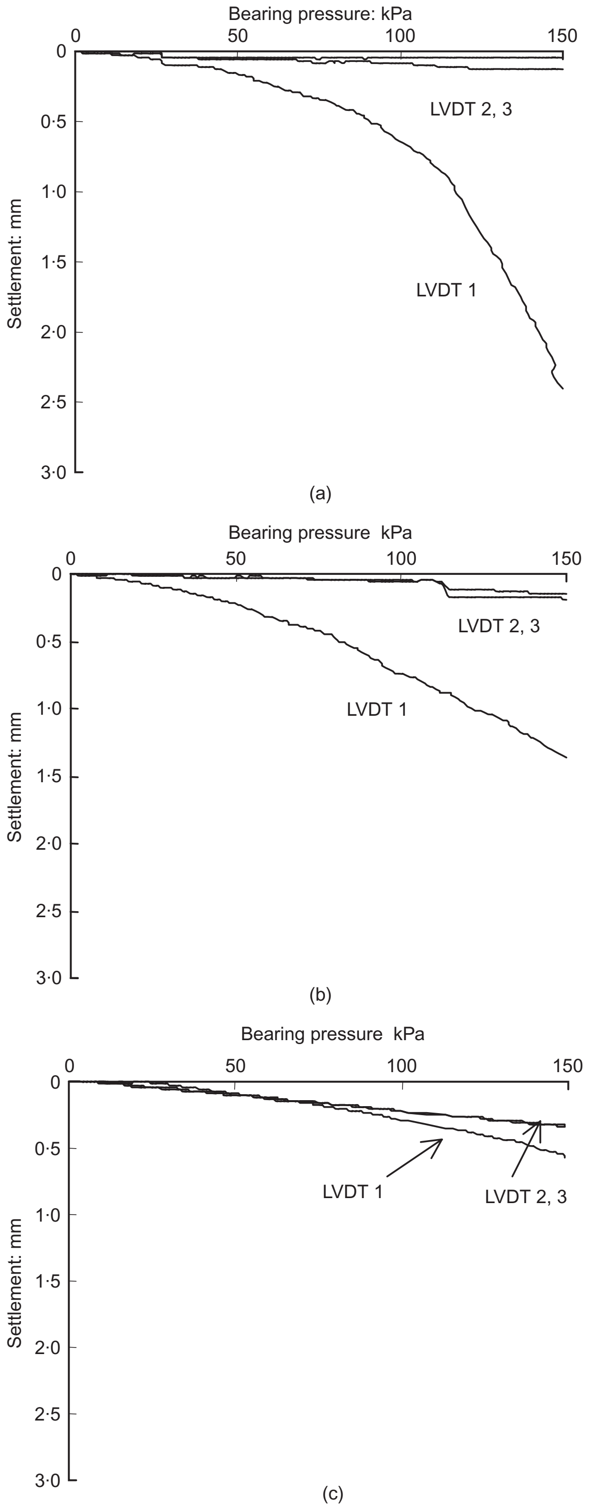

Fig. 11. Settlement of footing and surrounding clay at low-to-moderate bearing pressure: (a) no column; (b) 50 mm diameter column; (c) 60 mm diameter column

Load-carrying capacity and settlement improvement of soft deposit reinforced with stone column

Figure 12 shows the net bearing pressure plotted against foundation displacement for all six tests conducted. For the purpose of settlement, the assessment was carried out under a bearing pressure of 150 kPa, although the maximum design bearing pressure considered in soft clay deposits is about 100 kPa. The footing supported on the unreinforced sample led to 2·4 mm of settlement, which reduced to 1·35 mm, 1·35 mm and 0·5 mm when the footing was supported on 40 mm, 50 mm and 60 mm diameter stone columns respectively (in all cases the columns were included with pressure cells). The relevant settlement improvement factors, n, were 1·7, 1·7 and 4·8 respectively, where $n = \delta_{ur}/\delta_r$ (δ_{ur} is the settlement without a granular column, and δ_r the settlement with a granular column). These settlement reductions are considerably less than the predictions made by Priebe (1995) and the observations reported by Black *et al.* (2011), which can be explained by the fact that the boundary condition away from the footing in the model test carried out by Black *et al.* (2011) was rigid, giving enhanced confinement to the

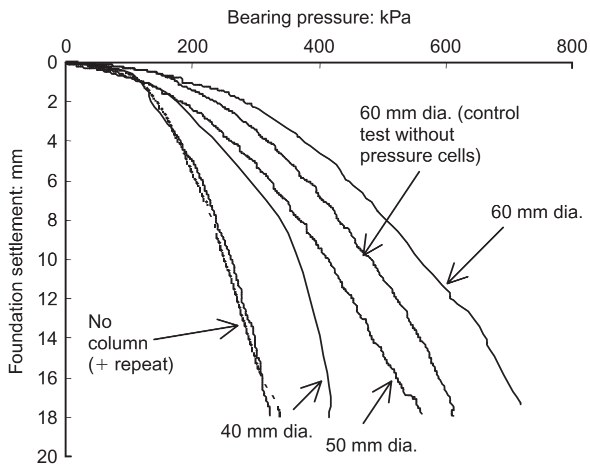

Fig. 12. Bearing pressure–settlement characteristics

stone column. On the other hand, Priebe (1995) based his predictions on the assumption that the unit cell, where the column and the surrounding clay were modelled as one unit, had zero lateral strain conditions. However, in the present model study, the boundary condition away from the foundation was flexible, thereby representing a more realistic field situation.

CONCLUSION

During the consolidation stage, the excess pore water pressure generated as result of the application of the total stress dissipated with time, and this process resulted in compression of the column and the surrounding clay. The observations show that the compression of the surrounding clay was larger than that of the column, and that it contributed towards negative skin friction on the granular column.

During foundation loading, a minimum increase in the vertical pressure in the column was observed at a depth of about five times the column diameter, and this compares favourably with previously published information. The presence of pressure cells in the column resulted in enhanced performance of the column, but the effects were not significant up to a bearing pressure of 200 kPa.

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