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INSTALLATION OF A REDUCED-SCALE PILE GROUP IN SILT

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SUMMARY: This paper presents measurements of total stress and pore pressure made during and after the installation of a reduced scale group of five piles in a soft estuarine silt. The instrumentation includes pore pressure and lateral stress sensors on the shaft of the centre pile, in addition to pneumatic piezometers positioned in the ground both within and beyond the pile group perimeter. When examined in conjunction with other data from the same site, the results demonstrate the effect of multiple pile installations on the stress regime in the ground.

Keywords: Driven pile groups, equalization, excess pore water pressure, installation, lateral stress.

INTRODUCTION

It is well established that displacement piles induce significant changes to the *in situ* effective stress regime in clays and silts. Changes in total stress and pore pressure accompany pile penetration, with further changes occurring for a period after installation (referred to as equalization). The effective stress regime in existence upon complete equalization has a major bearing on subsequent pile performance under load. In the case of a single pile, this stress regime is difficult to predict accurately, as soil properties, pile type, installation procedure and other factors are influential[1]. In the case of a closely-spaced pile group, the overlapping stress fields generated by neighbouring installations render the prediction of equalized stresses even more challenging.

There is a shortage of high quality field data for pile groups which track changes in horizontal total stress and pore pressure from the point of installation through to the fully equalized stress condition. In this paper, these data are presented for a reduced-scale pile

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group (comprising closed-ended steel tubular piles) driven in the soft silt underlying Belfast. A load test to failure was subsequently carried out on a piled raft foundation incorporating this pile group. The results of this second exercise will be published later.

These new total stress and pore pressure measurements supplement earlier work at the same site, in which (i) horizontal total stresses and pore pressures were measured on reduced-scale single piles[2,3] and (ii) horizontal total stresses were measured on a full-scale precast concrete pile group[4].

TEST SITE AND FIELD TEST DETAILS

Test Site

The field tests described in this paper were carried out at Kinnegar (about 10km north east of Belfast city centre) in Northern Ireland. Activity at this site has been described in numerous geotechnical reports and publications over the past decade. The stratigraphy comprises approximately 7.5m of lightly overconsolidated estuarine soft organic silt (known locally as *sleech*), for which typical properties are shown in Table 1. The *sleech* is overlain by 1.0-2.0m of granular made ground and underlain by medium dense sand at ≈8.5m depth. The water table varies both seasonally and tidally between ≈1.0m and ≈1.5m below ground level. Characterization of the made ground and *sleech* has been reported elsewhere[5,6] for this site.

Table 1: *Typical properties of the sleech*

Clay Fraction (%)	20 ±10
Fines Content (%)	90 ± 5
Water Content (%)	60 ±10
Plasticity Index (%)	35 ± 5
Organic Content (%)	11 ± 1
Peak Vane Strength (kPa)	22 ± 2
Yield Stress Ratio (YSR)	1.1 to 2.0
Friction Angle in triaxial compression (^{o})	33 ± 1

Pile Details and Installation Procedure

The precast reinforced concrete raft (700mm × 700mm in plan, 120mm thick) is shown in Figure 1a being lowered to 2.1m below ground level to be founded on the *sleech*. The five 80mm diameter vertical voids were left to accommodate the subsequent installation of five piles through the raft. The pre-formed timber box depicted in Figure 1b was installed after placement of the raft to allow the original excavation to be backfilled to ground level.

The model piles were closed-ended stainless steel tubes (diameter D=73mm, wall thickness 5.16mm, length ≈1.7m) which were pushed through each of the five voids. Verticality of the tubes was guaranteed by this process, and when installation was complete, all piles extended 1.58m (or 21.6D) below the raft base. A steady installation rate of 25-35 mm/s was achieved and a maximum load of 5 to 6 kN was recorded by a load cell positioned above each pile head during installation. The centre pile (3) was installed first, followed 45 minutes later by the corner piles in an anticlockwise order 1,4,5,2 (see

Figure 2) with ≈10 minutes between successive installations. The centre-to-centre spacing (s) between the corner and centre piles was 219mm (s/D = 3). A flange at the head of each pile was bolted to the raft (Figure 3), thereby disabling relative movement between cap and piles. This group of piles is denoted as G4 in keeping with the nomenclature of earlier pile group research at the Kinnegar site.

(a) (b)

Fig. 1: *(a) Installation of pre-cast reinforced concrete raft foundation with voids for piles, (b) placement of box to backfill around the raft*

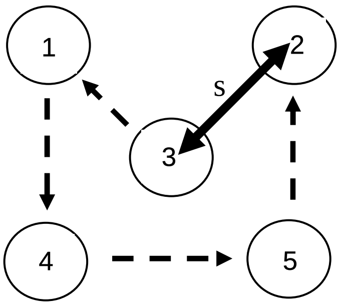

Fig. 2: *Installation order of piles in G4*

Fig. 3: *Pile-to-raft fixity arrangement*

Instrumentation

The centre pile of group G4, developed at University College Dublin (and subsequently referred to as the UCD pile)[7], comprises three instrumented units along the pile shaft and one at the pile base (see Figure 4, h = distance above the pile base level, D = external pile diameter). Each unit consists of a pore pressure sensor and horizontal stress sensor (of the low profile ENTRAN type) located diametrically opposite each other. Each total stress sensor is located flush with the pile shaft, whereas the pore pressure sensor is set behind a porous stone which is flush with the pile shaft. A total stress and pore pressure sensor are located side by side on the base instrument unit. Pneumatic piezometers were installed within and outside the perimeter of G4.

Previous Research at the Kinnegar Site

A programme of full-scale pile group testing has previously been carried out at this site[4]; the pile groups G1 to G3 comprised five 250mm (=B) square precast concrete piles installed rapidly with light driving to 6m embedment. The plan configuration, spacing to 'equivalent diameter' ratio of the piles ($s/D_{eq} = s\sqrt{\pi}/2B$), numbering system and installation sequence were the same as for G4. Subsequent reference is made in this paper to pile group G1, the centre pile of which incorporated two flat-jack total stress sensors at depths of 3.25m (h/B=11) and 5.23m (h/B=3) below ground level. Pneumatic piezometers were also installed around G1.

Single pile load tests were also carried out using the UCD pile[2,3]. Subsequent reference is made to one of these tests, BF2, in which the pile was installed slowly, with jacking strokes ranging from 100mm to 400mm in length.

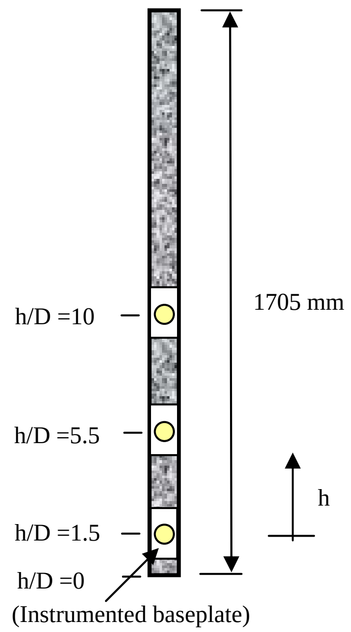

Fig. 4: *UCD pile, installed at centre of group G4*

STRESS MEASUREMENTS DURING AND AFTER PILE INSTALLATION

Horizontal total stresses

Since the UCD or centre pile (3) of G4 was the first to be installed, it may be considered as a single pile up to the point at which the first of the corner piles entered the ground. The horizontal total stress response on the centre pile, normalised by the base resistance developed during installation (σ_h/q_b) is shown in Figure 5a. This response reflects the centre pile's own installation and that of the corner piles. The data is compared in Figure 5b with equivalent data from group G1.

From these data, the well known[8] inverse dependence of the maximum value of σ_h on h/D (or h/B) value is observed. Moreover, the rate at which σ_h subsequently decreasesis slightly greater closer to the pile base, probably reflecting the greater 3-D nature of drainage at this position[9]. In Figure 6, σ_h values on the centre pile are normalised by the maximum reached during the installation of this pile ($\sigma_{h\,max}$) and are compared with those measured on pile BF2. The individual peak σ_h values are in fact different (the BF2 values are ≈20% higher for a given h/D value) but it has been shown that such variations can be accounted for by differences in the installation procedures and instrument depths[2]. Figure 6 also shows that while there are additional increases in σ_h on the centre pile accompanying each corner pile installation, these increases tend to be temporary, with horizontal stresses returning relatively close to single pile values within a short period of time.

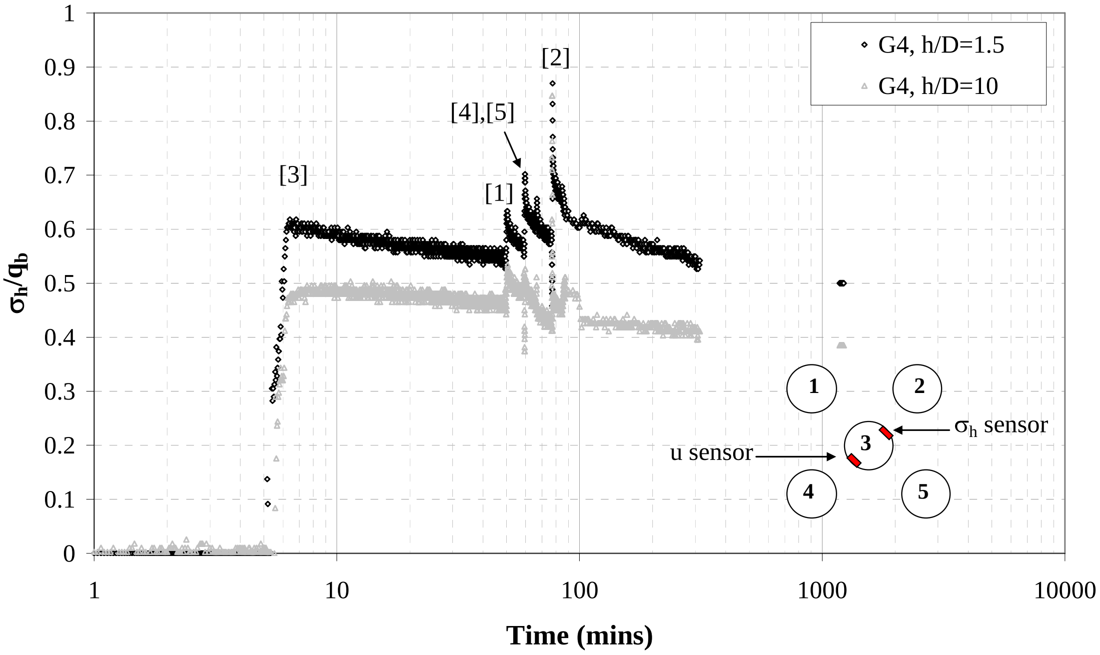

Fig. 5a: *Variation of σ_h/q_b for G4*

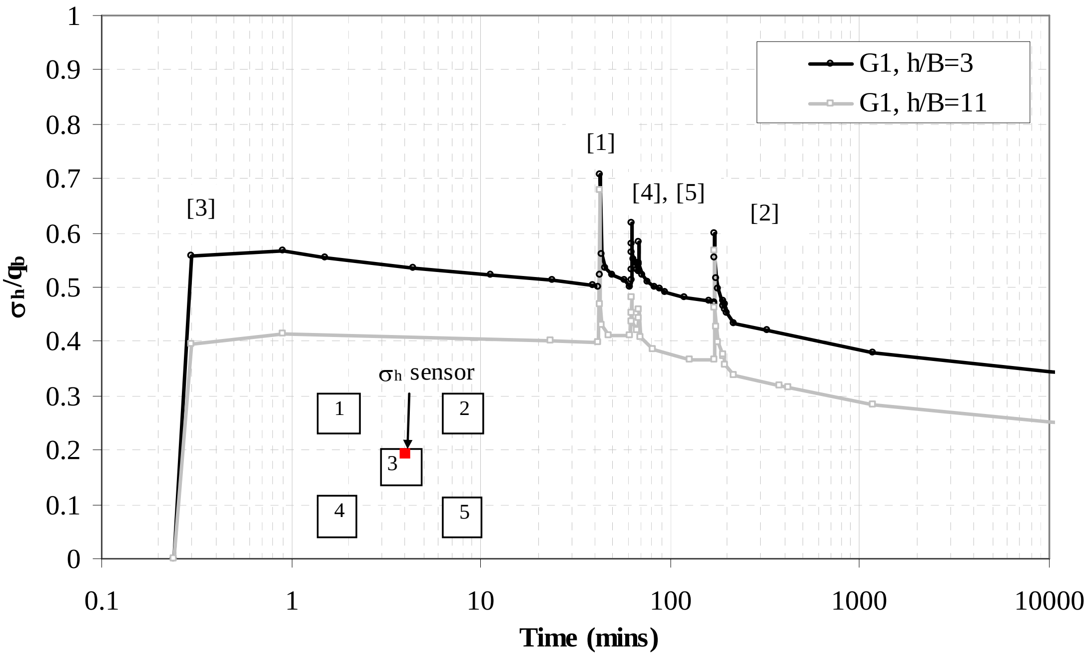

Fig. 5b: *Variation of σ_h/q_b for G1*

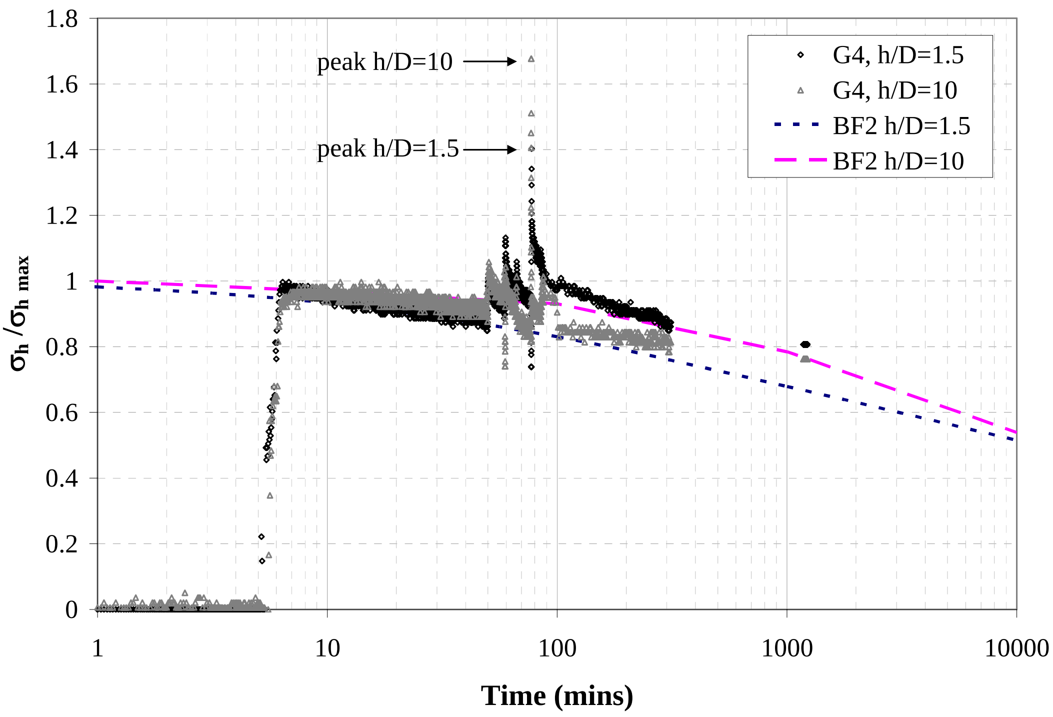

Fig. 6: *Variation of σ_h/σ_{hmax} for G4 and BF1*

The effect of each passing corner pile on the total stresses experienced by the centre pile (3) is traced more closely in Figure 7. The change in total stress normalized by the installation base resistance at that depth ($\Delta\sigma_h/q_b$) is plotted against z/D, where z is the distance from each total stress sensor (z<0 and z>0 refer to the tip of the current pile being above and below the sensor on the centre pile respectively). The data from Pile 5 has not been included as the changes are too small to be meaningfully interpreted. As expected, Pile 2 closest to the σ_h sensor generates the sharpest $\Delta\sigma_h/q_b$ response. The other responses are less distinct, due to the additional distance between other piles and the σ_h sensor and the presence of the centre pile itself as a rigid inclusion between corner pile and sensor. The following conclusions can be drawn:

(i) the lag between the sensors' responses at h/D=10 and h/D=1.5 suggests that the approaching corner pile is usually 'felt' at least 10 diameters length above the sensor

(ii) a reduction in σ_h occurs initially before $\Delta\sigma_h/q_b$ becomes positive

(iii) the maximum stress at each σ_h sensor ($\Delta\sigma_h/q_b \approx 0.3$ to 0.4 for Pile 2) is experienced when the approaching pile is still above the instrument level. It has been interpreted (given the accuracy of synchronizing computer with manual data) that $\Delta\sigma_h/q_b$ is greatest between zero and five diameters above the pile base, and has started to reduce when the pile base is level with the sensor. Other tests have been carried out by one of the authors in which sensors embedded in a chamber of sand have recorded the changes in horizontal stress due to a pile being pushed past the sensor[10]. The z/D value at which the horizontal stress is maximum is consistent with the findings on Figure 7.

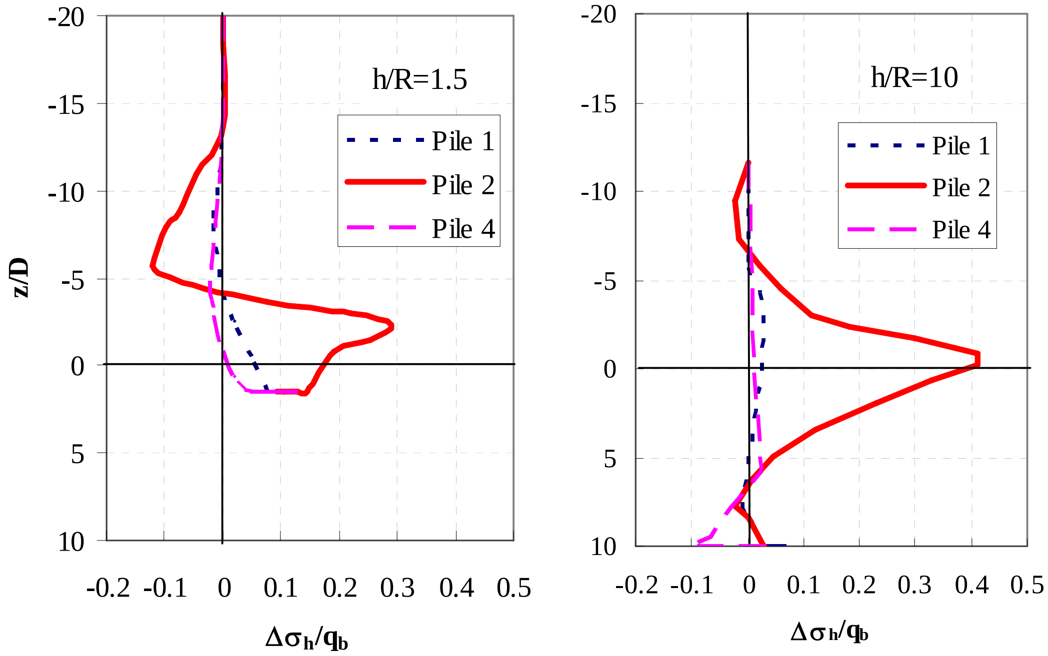

Fig. 7: *Total stresses on centre pile (3) of G4 as each corner pile base passes*

Pore Pressures

The variation of pore pressure on the centre pile shaft (again normalized by the value of q_b measured at that depth during installation) over the course of installation and equalization is presented in Figure 8. The general trends exhibited match those noted for the σ_h/q_b data in Figures 5 and 6. However, the pore pressure changes as corner piles are introduced are lower than the corresponding $\Delta\sigma_h/q_b$ values ($|\Delta u/q_b|<0.1$) and the horizon at which pore pressures are maximum is unclear.

In Figure 9, data from the pore pressure sensors are combined with those from the piezometers; maximum excess pore pressures Δu_{max} are normalised by the *in situ* vertical effective stress (σ'_{vo}) and plotted against the radial distance (r) from the centre pile normalized by the pile radius (R=0.5D). The $\Delta u_{max}/\sigma'_{vo}$ data is sourced as follows:

- (i) pore pressure measurements on the shaft of the centre pile of G4 (i.e. r/R=1). The Δu_{max} value after the installation of pile 3 and the maximum value over the course of group installation are represented separately.
- (ii) piezometer maxima in the soil around G4 (r/R>1); again, separate values are plotted for the centre (single) pile and the pile group.
- (iii) piezometer maxima in the soil around G1 (r/R>1).

Within the pile group, $\Delta u_{max}/\sigma'_{vo}$ values measured at the pile-soil interface (r/R=1) are 10-15% higher than those measured on single piles, the elevated values seen on the pile at the centre of the group are the temporary pore pressures caused by the installation of the corner piles (Figure 8). However, the difference becomes significant at greater r/R values. This would suggest that the excess pore pressures generated close to a group pile due to a neighbouring installation are restricted (i.e. at the critical state condition) near the centre of the group; the installation of additional piles results only in an accumulation of excess pore pressures outside the plastic zone. This trend is in keeping with another field test programme[11] in the literature in which pore pressures were found to be significant to a distance of $30R_{eq}$ ($R_{eq}=0.5D_{eq}$) beyond the perimeter of a group of 116 piles with $s/D_{eq}=5$.

It is also noteworthy that the G1 and G4 data in Figure 9 are very consistent, and the variation of $\Delta u_{max}/\sigma'_{vo}$ with r/R is roughly linear for r/R>5 (illustrated by the trendline).

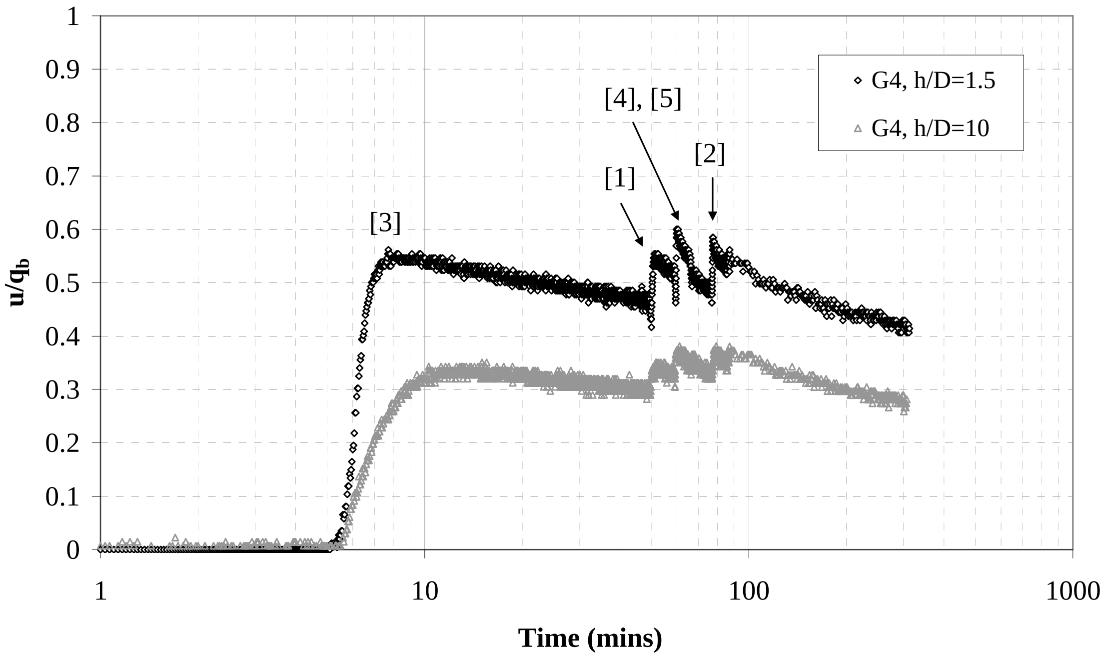

Fig. 8: *Pore pressures measured over the course of installing G4*

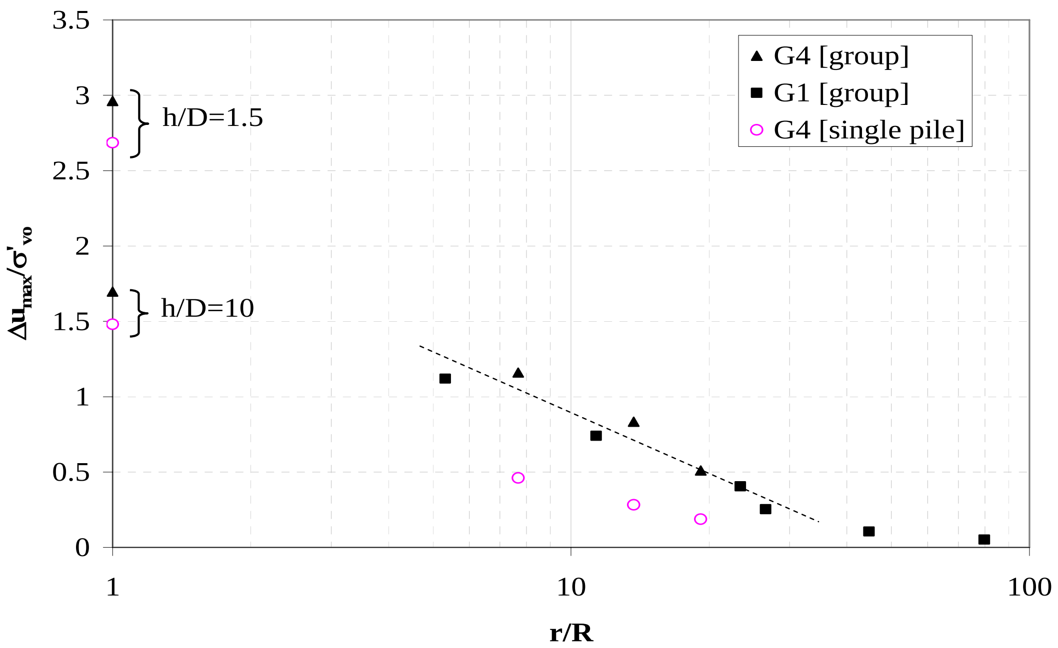

Fig. 9: Normalized excess *pore pressure surrounding a pile group*

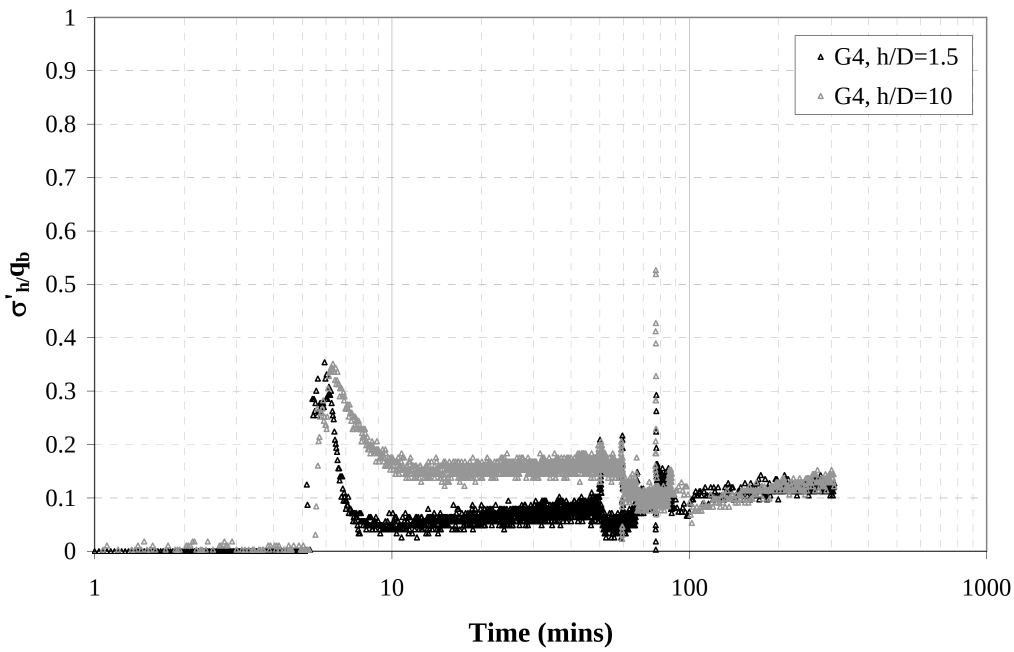

Fig. 10: *Variation of horizontal effective stress on centre pile of G4*

Effective Stresses

The variation in normalized effective radial stress (σ'_h/q_b) is plotted in Figure 10. Note that it is inappropriate to interpret the data representing the course of corner pile installation, given that the pore pressure and total stress sensors were on opposite faces of the centre pile. However, the data before and after corner pile installation is valid.

In keeping with trends observed with BF2 data and driven piles in Bothkennar Carse clay[8] (having similar geotechnical properties to the Belfast sleech), the value of σ'_h/q_b is seen to reduce suddenly at the end of installation, particularly in the region of the pile base. However, effective stresses recover and the final value of K ($=\sigma'_h/\sigma'_v$), based on the pore pressure having returned to hydrostatic levels, is ≈1.5; this compares with an at-rest value of K_0=0.5. Although the data in Figure 10 does not represent the full equalization period, σ'_h/q_b would be expected to return to ≈0.2 at equalized conditions. This equalized value is consistent with that from BF2 and data from Bothkennar clay and Cowden till[3], and would suggest that the normalised equalized effective stress is largely independent of soil type and group installation effects.

CONCLUSIONS

This paper has presented some new installation data for a pile group, and by comparing the results with previous installation data at the same site, it may be concluded that:

(i) The changes in total stress and pore pressure on any group pile generated by neighbouring pile installations at s/D>3 are not permanent and return to single pile values in a short period of time

(ii) The maximum total stress at a point on a stationary pile due to an adjacent moving pile occurs when the base of the moving pile is between zero and five pile diameters above that point.

(iii) Once the maximum possible excess pore pressures are reached within a pile group, pore pressures accumulate at greater distances from the group. The zone of elevated pore pressure is therefore much more extensive for a group than a single pile, and the relationship between $\Delta u_{max}/\sigma'_{vo}$ is directly proportional to r/R (for r/R>5).

(iv) The normalized effective stress after equalization for the pile group in this study may be represented by $\sigma'/q_b \approx 0.2$. This group value is in keeping with measurements for single piles in different soil types.

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