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Experimental Investigation of the Response of a Driven Pile in Soft Silt

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ABSTRACT: The paper describes the results of field tests carried out using highly instrumented piles at a very soft estuarine clayey silt deposit at Kinnegar, Belfast. The site has been used for a number of years as a geotechnical test bed site and has been comprehensively characterised using both in-situ tests including Cone Penetration Tests (CPT) and by means of an extensive laboratory test program.
The instrumented pile used in the investigation was developed at University College Dublin and includes sensors which allow readings of both total radial stress and pore pressure during installation, equalisation and load testing to be made at a number of locations along the pile shaft. The radial stress and pore pressure developed during installation and equalisation are discussed in terms of the CPT q_{cnet} value and compared with similar results from the literature.

1 INTRODUCTION

The importance of the effect of stress changes during pile installation on the final capacity of piles is well acknowledged. The similarity between the installation of the Cone Penetrometer (CPT) and displacement piles has led to the formulation of a number of design methods linking the shaft resistance (q_s), with the CPT end bearing resistance q_{cnet}, for piles in a range of materials, most notably the Imperial College design methods described in Jardine et al. (1998). Lehane et al 2000, propose a q_c design method, which incorporates the h/D or friction fatigue effect, plasticity index, I_p, and the relative void index, I_{vr}, (defined using Burland's (1990) empirical correlations with void ratio at the liquid limit). In order to determine the latter parameter oedometer tests on high quality samples are required. However, an approach as comprehensive as this is not particularly amenable to everyday design. Randolph (2003) found that while similarities existed in the normalized radial total stresses (σ_r/q_c) mobilized during the installation of piles in over-consolidated London Clay and Glacial Till, wide variations in the behaviour of piles driven into soft clay were noted. With this in mind, a series of pile tests were carried out at a soft silt test bed site to supplement the available database of installation measurements.

2 SOIL CONDITIONS

The test site is located at Kinnegar on the eastern shore of Belfast Lough, 10 kilometres from Belfast city centre. The site comprises a layer of recent fill about 1.2m deep overlying a thick sandy silt layer, approximately 2m thick, that in turn overlies a layer of very soft organic clayey silt, which is approximately 6m thick. The water table at the site is tidal, varying from 1 to 1.3m below ground level (bgl).

The estuarine silt, known locally as sleech, was laid down over the past 3000 years in water depths between 3m and 9m Manning et al. (1970). Between 1m and 3m bgl. the proportion of sand and clay is 20% and 10% respectively, whilst below this level these proportions reverse (see Figure 1a).

A summary of six CPT q_{cnet} profiles shown in Figure 1b, revealed that whilst q_{cnet} is quite variable in the sandy silt, the clayey silt is surprisingly uniform, with q_{cnet} varying from 175 kPa at the top, to 350 kPa at the bottom of the deposit. Uncorrected vane shear strengths were found to follow a similar trend with depth, with s_{uvane} increasing from 20 to 25 kPa with depth. The clayey silt has a relatively high plasticity index (PI=35%), a constant volume friction angle (ϕ'_{cv}) of 34°, and a yield stress ratio which varies from 1.5 at 3m bgl to 1.1 at 6m bgl. Detailed soil properties can be found in Lehane (2003), McCabe & Lehane (2003) and McCabe (2002).
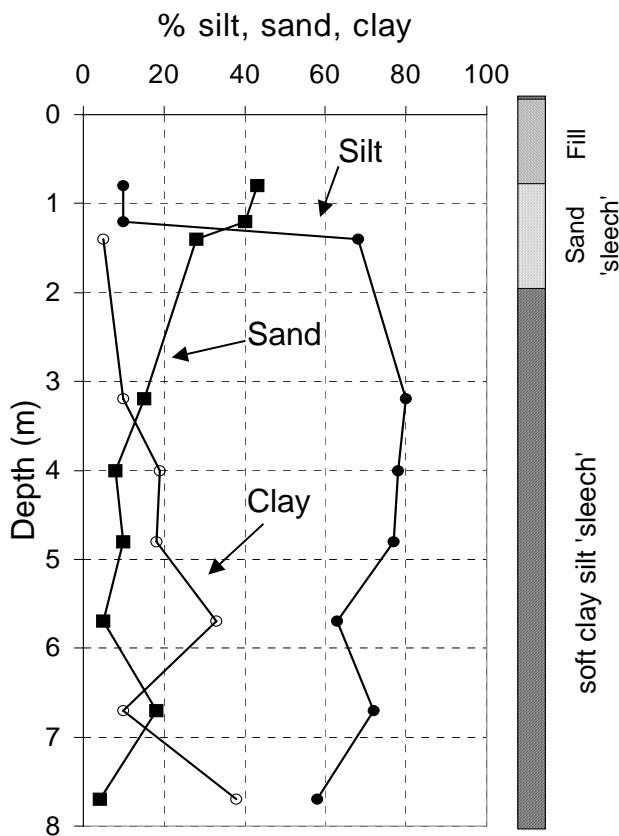
Figure 1(a). Site Stratigraphy

pore pressure sensors were monitored continuously. A load cell was used at the pile head to measure the axial load mobilized during pile jacking. Prior to installation a 100mm diameter
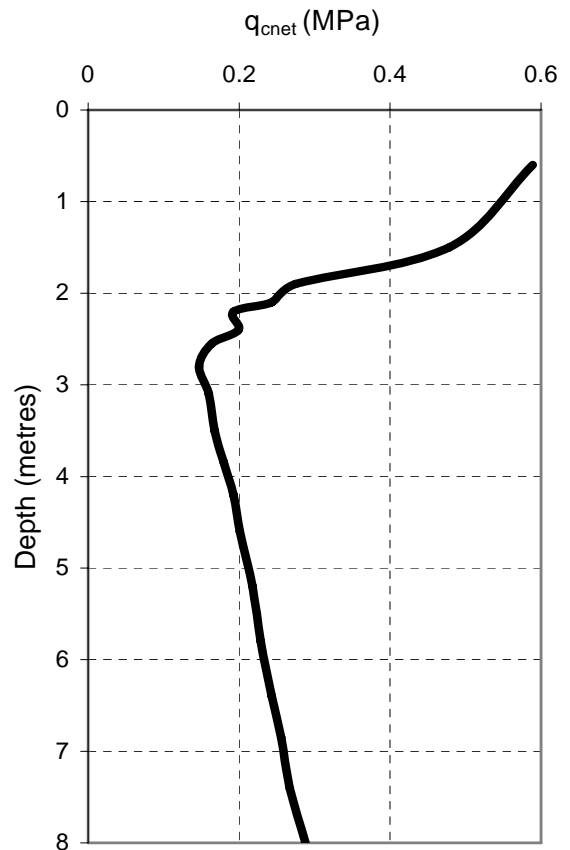

Figure 1(b). CPT q_{cnet} profile

3 PILE INSTALLATION

The instrumented pile used for testing was designed and constructed at University College Dublin. The pile is a stainless steel 73mm diameter, flat base, closed ended pile. The instrumentation consists of total radial stress and pore water pressure sensors located at three levels along the pile shaft, see Figure 2. The position of each sensor is described in terms of its distance from the pile base (h) normalized by the pile's diameter (D). The instrumentation employed in the model pile consisted of Entran EPN-D1 pressure sensors, utilised in two ways to measure total stresses and pore pressures. Total stresses were measured with the sensors assembled flush with the pile wall while pore pressures were recorded by assembling the sensor behind a high air-entry ceramic disc, flush with the pile surface, (the ceramic and void between sensor and back of ceramic were saturated with a glycerine fluid) which allowed pore pressures alone to act on the sensing face. The sensors operate on the principle of a Wheatstone bridge with a sensing face 7.5mm in diameter and a full range of 1500kPa. The pile was hydraulically jacked into the ground at a rate of 2cm/sec in 100mm increments to a total depth of 4.25m below ground level. As the pile is in sections ranging in length from 1 to 1.7m long, pause periods were required during installation to allow additional sections to be added. These resulted in total installation time of 117 minutes. During installation the total stress and
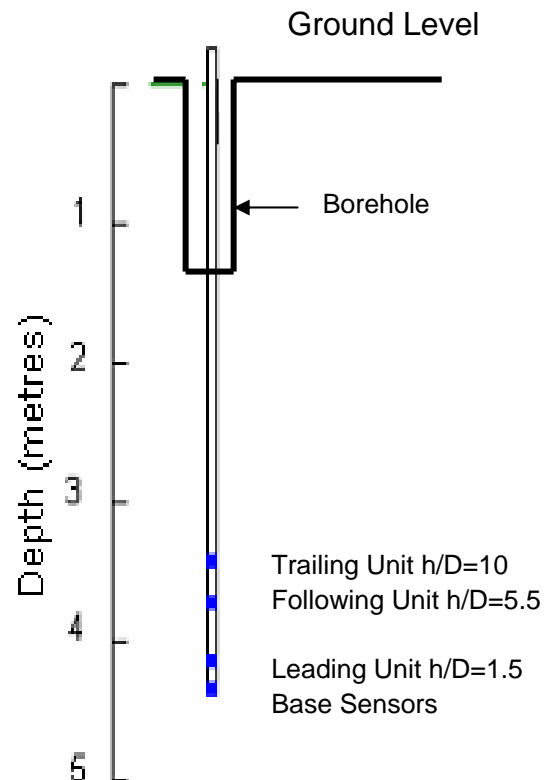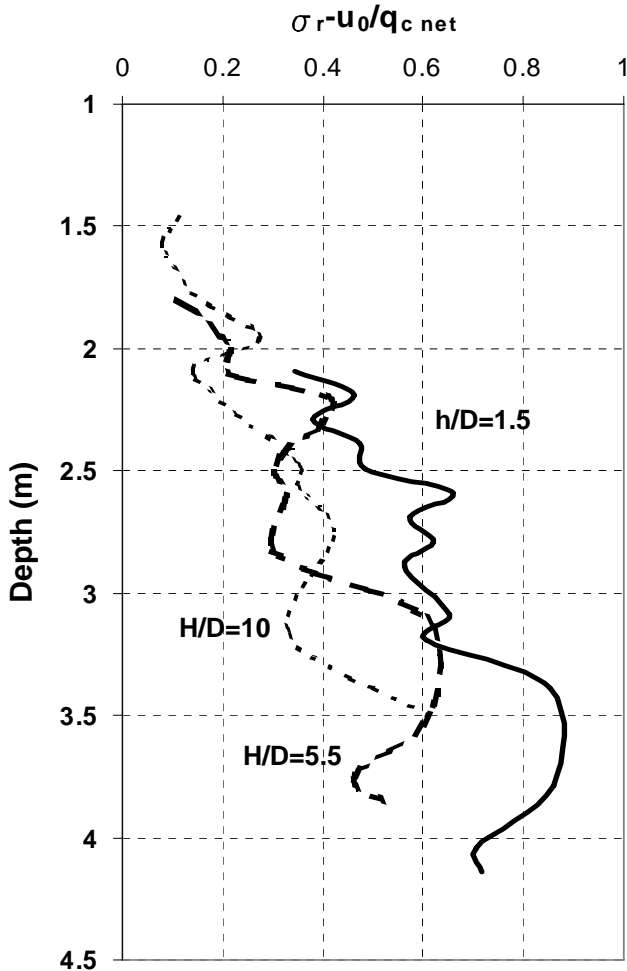

Figure 2. Pile Configuration

Figure 3. Installation total radial stresses

Figure 4. Installation Pore pressure response

1.3m deep borehole was pre-augured through the fill. Static load tests, involving maintained load type compression and tension tests were performed nine days after pile installation. This paper will deal only with the radial and pore pressures developed during installation and equalization. The radial total stresses less ambient pore water pressure (σ_r-u_0) measured during installation by the three sensors, normalized by the net CPT end resistance, q_{cnet} value at that depth are shown in Figure 3. It appears from the figure that there is a tendency for σ_r-u_0/q_{cnet} to increase with depth, with values in the clayey silt (below 3m) being markedly higher than those in the sandy silt. Although there is some scatter in the data, the h/D effect described by Bond & Jardine (1991), Lehane & Jardine (1994) and others, where radial stresses at a given level reduce as the pile tip moves further away from the point are evident, with stresses mobilized at h/D=1.5 being generally ≈50% higher than values recorded as the pile tip moves further from the point under consideration.
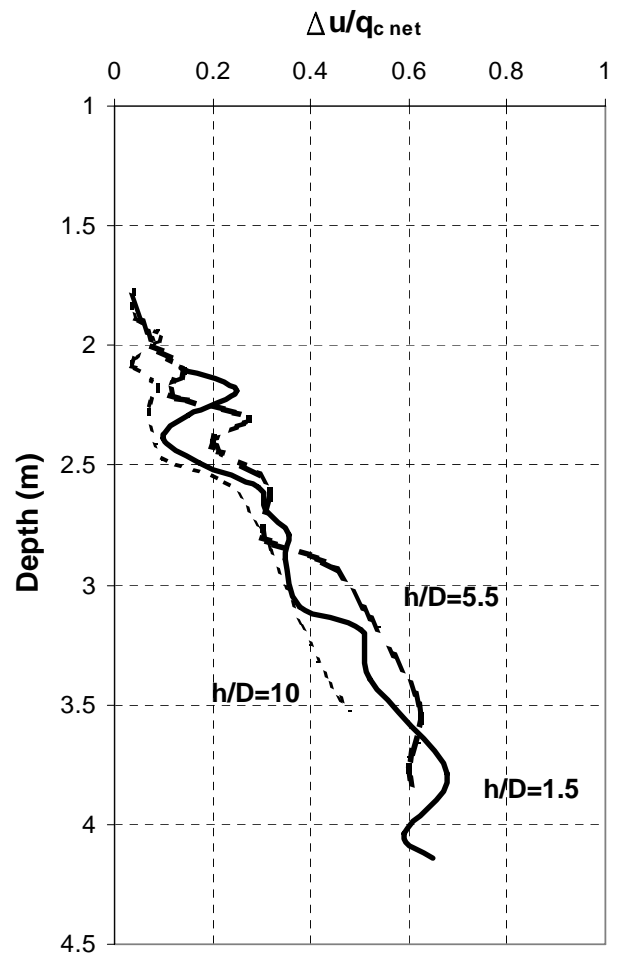
The excess pore pressures ($u-u_0$) generated during installation are plotted in a similar format in Figure 4. Again the pore pressures increased with depth, with pore pressures similar in magnitude to the total stresses being mobilized near the toe of the pile at the final penetration depth. In contrast to the total stress plot in Figure 3, there is no h/D effect obvious, with similar pore pressures recorded at all instrument clusters at the same soil horizons. The pore pressures plotted in Figure 4 are the stationary pore pressures, measured immediately after the pile has been pushed through a 100mm increment. A tendency for pore pressures to fall during load application was noted. Immediately following removal of load the pore pressures rose rapidly, with the effect that near zero effective stress were recorded near the toe of the pile immediately after each loading increment. Similar behaviour was noted by Lehane and Jardine (1994) during installation of a jacked pile in soft clay.

4 EQUALIZATION
Once the pile reached its final penetration depth, all load was removed and the excess pore pressures ($\Delta u = u-u_0$) that had developed during installation were
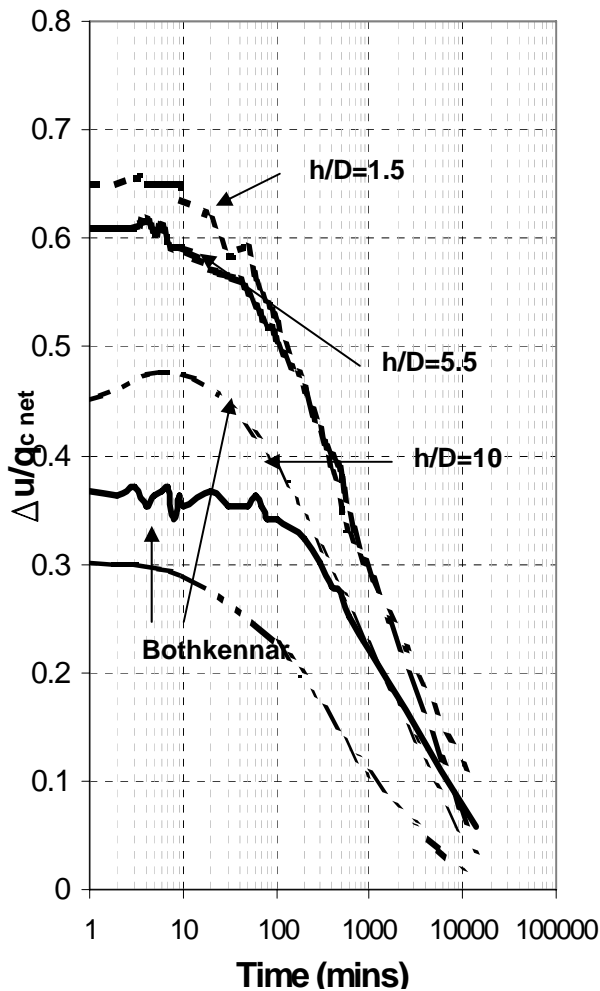
Figure 5. Pore pressure response during equalization

Figure 6. Total stress response during equalization

allowed to dissipate to their ambient hydrostatic levels (u_0). The progress of dissipation is shown in Figure 5 where the excess pore pressures are normalized by the q_{cnet} value and plotted against time on a log scale to allow the full dissipation to be displayed.

Dissipation of excess pore pressures around the small diameter pile were relatively rapid, with 50% dissipation occurring within the first 10 hours after installation was completed. The rate of dissipation at the furthest location from the base ($h/D = 10$) is slightly slower than the other two sensors, however, all levels reach full dissipation after 8-9 days. Pore water pressure dissipation results in reductions of the total stresses surrounding the pile. Additional stress changes, which occur due to volume changes associated with consolidation, cause a redistribution of stresses surrounding the pile. Figure 6 shows the magnitude of the total radial stress reduction over a 9-day period. The radial total stress at the end of equalization is seen to be approximately 50% of the peak value at all locations. Final total stresses correspond to 20-25% of the q_{cnet} value at that depth.
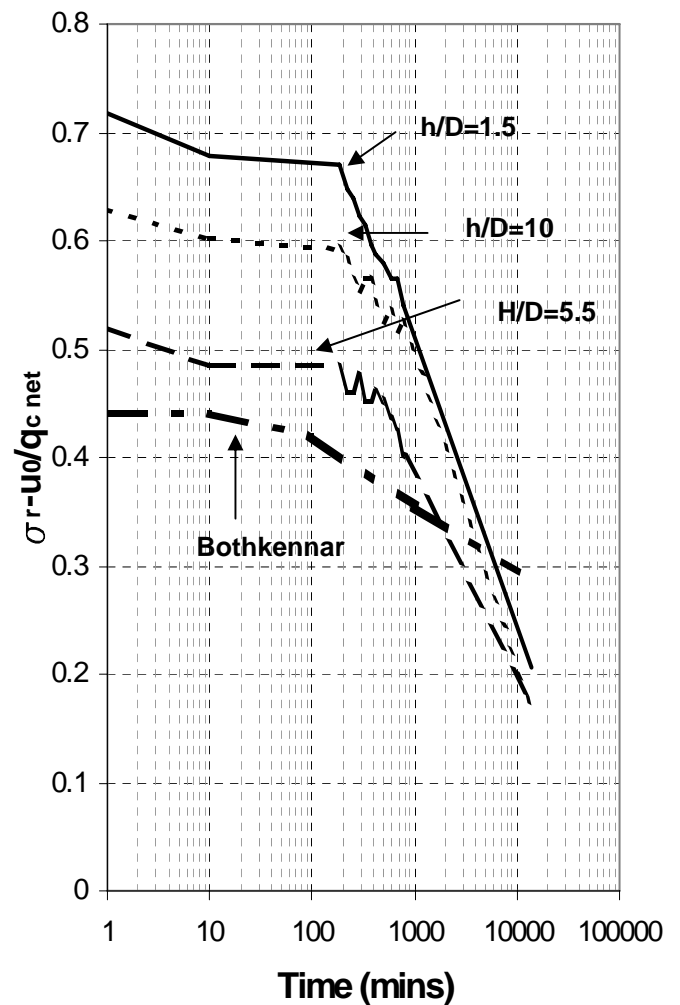
5 EFFECTIVE STRESS DURING EQUALIZATION

The variations in radial effective stress (σ'_r) with time in the Belfast sleech are compared in Figure 7 to similar measurements from a soft clay site (Bothkennar), a glacial till (Cowden), both reported in Lehane and Jardine (1994), Despite the large fall in radial total stress at Belfast during equalization, σ'_r is seen to increase steadily from minima at the end of installation ($<0.1q_{cnet}$), to final values of approximately $0.25q_{cnet}$. During equalization the pore pressures dissipation exceeds the reduction in radial total stress and a 150% increase in radial effective stress is evident at $h/D=1.5$ at Belfast. These fully equalized values show little h/D dependence, with σ'_r/q_{cnet} reducing only slightly with increasing h/D, When compared with similar equalized data from other sites it appears that despite large differences in normalized installation total radial stresses σ_r/q_{cnet}, σ'_r/q_{cnet} at all sites lie in the range 0.2-0.3.
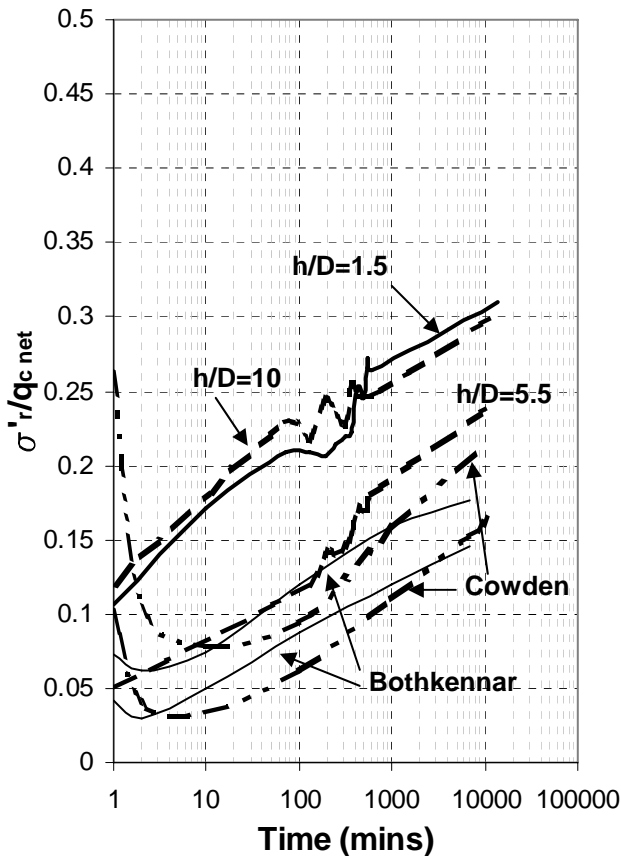
Figure 7. Evolution of radial effective stress at a number of sites

6 CONCLUSIONS

The experiments have shown that very high porewater pressures develop during pile installation in Belfast Sleech. A consequence of this is that σ_r/q_{cnet} values measured during pile installation are high relative to stiffer soils, where pore pressures may be low or even negative during pile installation. Measurements of equalized radial effective stress at a number of sites suggests that direct relationships between shaft resistance and CPT q_{cnet} for piles in Silt and Clay may be possible.

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