Influence of pile installation techniques on ground heave in clays

M.D. Larisch[1, 2], D.J. Williams[1] and A. Scheuermann[1]

[1]Geotechnical Engineering Centre, School of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia
[2]Piling Contractors Pty Ltd, PO Box 346, Lawnton Qld 4501, Australia

ABSTRACT

The installation of driven displacement piles in clays creates vertical soil movement that is commonly known as heave. Numerous researchers have developed theoretical models to calculate the expected volume of soil heave due to pile driving.Screw auger displacement piles are a relatively new and, due to their cost-effectiveness, increasingly popular piling technique that has been used successfully in Australia and New Zealand over the past two decades. Soil heave in clays during the installation of screw auger displacement piles has not been investigated in detail, even though the effects are commonly known throughout the industry.

The authors introduce some of the most popular general soil heave theories and compare their validity to screw auger displacement pile applications. The paper presents the measured ground heave results of three screw auger displacement piles during a field test in hard clay and correlates the results with the well-established SSPM heave theory.The installation process of driven and screw auger displacement piles is fundamentally different and the paper investigates and discusses whether or not common heave models for driven piles can be applied to screw auger displacement piles where the soil at the auger tip is physically cut, sheared and disturbed by the action of the auger.

Keywords: clay, driven piles, heave, pile installation, screw auger displacement piles, soil movement

1 INTRODUCTION

The installation of closed end driven and drilled displacement piles in clay formations results in horizontal and vertical soil movements of the ground surface. The soilarounda pilethat is installed using such displacement techniques, tend to move upwards during the installation process, because this direction is the only one that is unrestrained.Thisphenomenon is known as ground heave and has been investigated by numerous authors researching this topicover the last 40 years (Adams and Hanna 1971, Hagerty and Peck 1971).

Whereas closed end driven piles have been successfully used worldwide for centuries as structural elements, drilled displacement piles are a relatively new technology that has gained increased popularity over the past two decades. The system was invented in Europe in the 1990s and is based on the installation of a purpose-built displacement tool (typically 360 to 450 mm in diameter), which ispushed and rotated into the groundby hydraulic piling rigs, causing soil displacement. Once the design depth is reached the hollow stem of the displacement tool is used to place concrete under pressure to form the pile shaft.The process is described in detail byBottiau et al. (1998).

2 GROUND HEAVE DURING THE INSTALLATION OF DRIVEN CAST *IN SITU*DISPLACEMENT PILES

Ground heave refers to the vertical soil movement at the ground surface surrounding a pile and may lead to the uplift of neighbouring pilesthat have already been installed (Gue, 1984). Healy et al. (1981) concluded that ground heave andupliftas a result of pile driving can cause several problems which include but are not limited to: (i) squeezing, necking or cracking of the piles, (ii) pile shaft lifting from its base; (iii) loss of load capacity in end-bearing, (iv) the separation of pile segments or units due to cracking; and (v) additional tensile forces on pile joints for pre-fabricated piles.

However, while the damage caused by ground heave is often permanent, ground heave itself can be a temporary phenomenon. An investigation conducted by Cummings, Kerkhoff, and Peck (1950) indicated that ground heave of a magnitude of 330mm at the centre of a group of timber piles driven to

33.5m depth below the ground surface into soft volcanic clay, settled back almost to its original position after about one month.

2.1 Driven piles

Over the past 50 years several researchers have developed different methods to predict ground heave in clay during the installation of driven piles (prefabricated and cast *in situ* piles). Two of the most recent and commonly usedof these methods arethe *Strain Path Method*(SPM) and the *Shallow Strain Path Method* (SSPM), which are presented in this section of this paper.

The SPM was developed by Baligh (1985)to analyse the penetration of driven piles in clay formations, and is based on the assumptions that: (i) the soil is undrained, (ii) the penetration rate is constant, and (iii) the soil deformations and strains are dependent on the rotational flow of an ideal fluidrather than on the shear strength of the soil.The penetration is assumed to occur ‘deep’ within a soil formation, and boundary conditions (such as the ground surface) are not consideredin this model. Consequently, the analysis of pile penetration using the SPM can only be applied to the analysis ofdisplacements near the pile toe. Displacements close to the surface cannot be predicted; therefore the method was refined bySagaseta (1988)to theSSPM.

The SSPMsimulates undrained pile penetration from the stress-free ground surface. The method introduces the interaction between a point source and a mirror image sink to representthe pile. The source S is located at a defined depth ‘h’ below the ground surface, while its mirror image sink S’ is at a height ‘h’ above the ground surface. The superimposing action of the two will eliminate normal stresses, but will double the shear stresses.Sagaseta and Whittle (2001) developed Equation(1), which calculates the theoretical value of ground heave around a cylindrical driven pile in clay:

$$S_z(x) = \frac{1}{8}\left(\frac{d^2}{x} - \frac{d^2}{\sqrt{L^2 + x^2}}\right) \tag{1}$$

where: S_z = vertical soil displacement at the ground surface (ground heave)
d = pile diameter (m)
L = length of the pile (m)
x = distance from pile axis (m)

Luo (2004) has proposed using the cavity expansion model (CEM) to improve the SSPM in order to consider the plastic zone around pile. The authors of this paper adopted this approach with replaces the pile diameter d with an equivalent pile diameter d_{eq}.

The ground heave around a closed end driven pile is related to the diameter and the length of the pile and the distance from the pile axis.However, Sagaseta and Whittle (2001) highlighted that laboratory tests have shown that the SSPM is capable of reliably predictingthe deformations within acohesive soil mass, but generally slightly underestimates the vertical heave measured at the groundsurface. Despite this limitation, the authors of this paper have used the SSPM to predict the expected ground heave for drilled displacement piles installed in stiff to hard clay.

2.2 Drilled displacement piles and columns

Ground heave generated by drilled displacement piles is described by Larisch et al. (2014). Vertical soil movements of up to 500mm and lateral shifts of about 150mm were observed on different projects in Australia in recent years as a result of the installation of drilled displacement piles and columns in clay. Unfortunately, the prediction and estimation of ground heave during the construction of drilled displacement piles and columns has not been investigated in detail and predictions are mainly based on the research for driven piles as both systems displace the soil during installation.

The main difference between the displacement action of drilled and driven displacement piles is the influence of the auger action of the drilling tool. Different drilled displacement augers cut, transport and displace soil during the installation process to a different degree. The soil is cut and disturbed by the auger tip during penetration. The disturbed soil is then transported through the auger flights to the displacement body of the tool, where it is pushed into the borehole wall, causing soil movements. The degree of dilation of the disturbed soil is unknown and the effects of tool installation and constant penetration rates were investigated during a recent research project by The University of Queensland.

3 FIELD TESTS AT LAWNTON

For this research, large-scale tests were carried out at Lawnton, Queensland (Australia), to understand the ground heave behaviour of drilled displacement piles installed in stiff to hard clay formations. In the past, unpredicted ground heave occurred during the installation of drilled displacement piles and columns, particularly when a firm to hard clay layer was located close to the ground surface. Three drilled displacement piles of identical lengthwere installed at the Lawnton site, in similar ground conditions, using different installation rates and dissimilar full displacement augers for each test pile.

3.1 Soil profile and test augers

The Lawnton test site comprised stiff to hard clay layers of about 8 m thickness. The clay was underlain by gravel and decomposed rock. The three test piles (piles C, D and E) were installed to 4 m depth in order to understand the vertical soil movement during the installation of screw auger displacement piles in the stiff to hard clay. The ground conditions at site and the different full displacement augers used for the project are displayed in Figure 1.

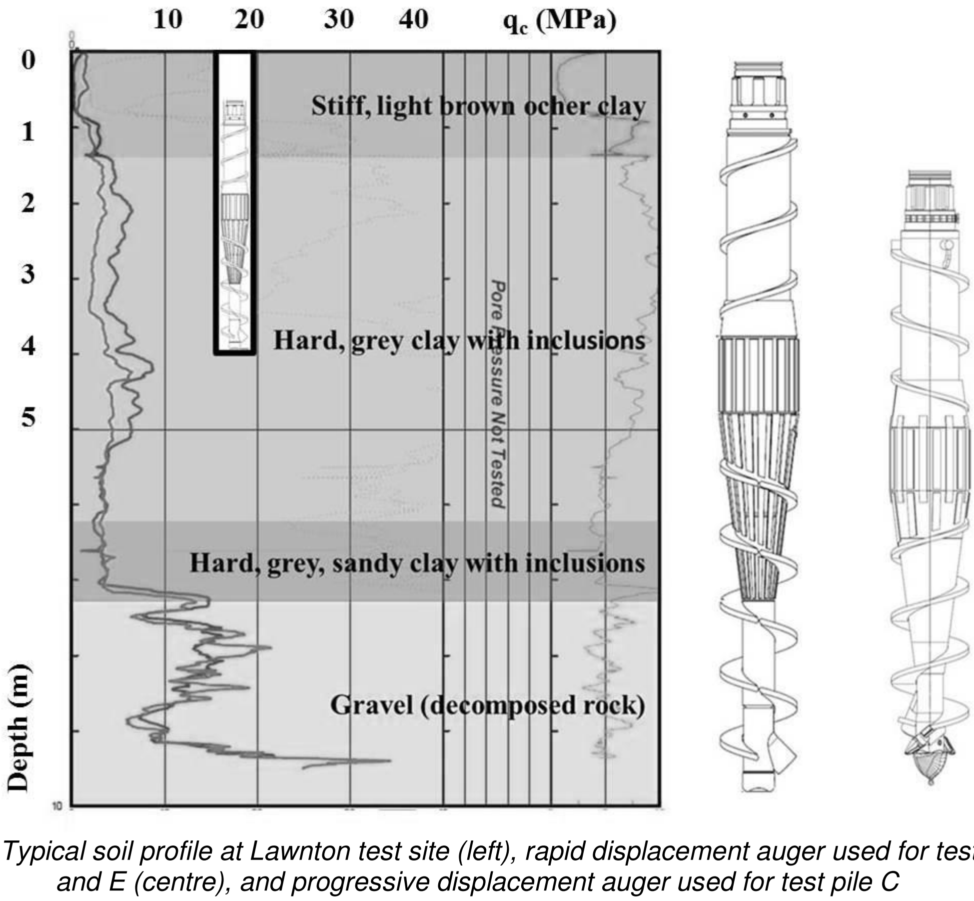

Figure 1. Typical soil profile at Lawnton test site (left), rapid displacement auger used for test piles D and E (centre), and progressive displacement auger used for test pile C

The minimum installation rate of the test piles was calculated on the basis of Vigianni's research (1993), as shown in Equation (2). Even though Vigianni's formula was originally developed for Continuous Flight Auger (CFA) piles, the method was found to be applicable for drilled displacement piles in fine-grained soils (Larisch 2014).

$$V_{a,(min)} \geq nl\,(1 - (d_o^2/d^2)) \qquad (2)$$

where:
- $V_{a,(min)}$ = minimum penetration rate (m/min)
- n = rate of rotation of the drill tool (rev/min)
- l = auger pitch (m)
- d = outer auger diameter (m)
- d_0 = auger stem diameter (m)

The minimum penetration rate$V_{a,\ (min)}$ for both test augers was calculated to be 1.8 m/min.The two different auger typesused for the installation of the test piles are shown in Figure 1.Two different piling rigs,with different rotational torque and vertical pull-down capacities,were utilised for the pile installation to investigate the influence of penetration rates on ground heave.As shown in Table 1, test piles C and E were installed with the same piling rig, but with different augers. Test pile E was installed with a more powerful piling rig and with the same auger as test pile D.

Table 1–Summary of pile depth, maximum installation torque, penetration rates and auger types for test piles C, D and E

Pile number	Pile depth (m)	Maximum installation torque used (kNm)	Maximum penetration rate (m/min)	Minimum penetration rate (m/min)	Auger type
Pile C	4.0	120	2.0	0.7	Progressive displacement tool
Pile D	4.0	120	2.0	0.9	Rapid displacement tool
Pile E	4.0	280	2.0	1.8	Rapid displacement tool

Each pile was installed using an automated rig monitoring system, which monitored the penetration rate, rotational torque, auger rotations, concrete pressure, concrete volume and the extraction rate of the drill tool as well as general information like the pile number, diameter, date, etc.

As shown in Table 1,test piles C and D were installed with a piling rig with only 120 kNm rotational torque and 150 kN vertical pull-down force capacities. The energy input of this piling rig was insufficient to keep the tool penetration constant in the stiff to hard clay formation as displayed in Figure 2. Due to the high friction between the full-displacementdrilling tool and the cohesive soil, the penetration slowed down to below the recommended value of 1.8 m/min. In contrast, test pile E was installed with a more powerful piling rig providing 280 kNm rotational torque and 300 kN vertical thrust capacities, which have been utilised to about 90% for the installation of test pile E. The minimum installation rate of 1.8 m/minwas achieved for the entire installation process of test pile E.

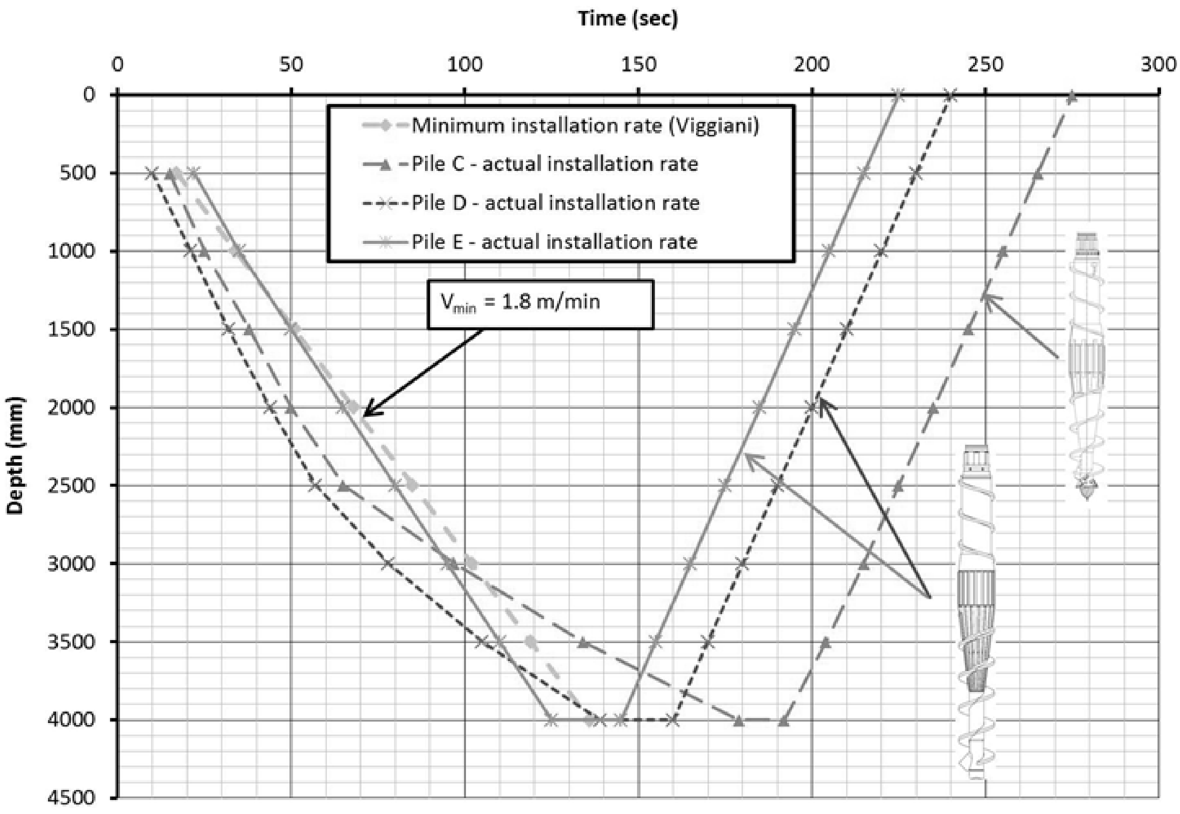

Figure 2. Installation and extraction rates of test piles C, D and E

4 ANALYSIS OF RESULTS

Ground heave on site was measured after the installation of each test pile and the results are summarised in Table 2, and Figures 3 and 4.

Table 2: Heave volumes (SSPM method v measured volume on site)

Pile number or calculation method	Pile volume (m^3)	Heave volume (m^3)	Heave percentage of pile volume
Pile C – measured heave	0.636	0.446	70.1%
Pile D – measured heave	0.636	0.445	69.9%
Pile E – measured heave	0.636	0.228	35.9%
SSPM calculation method	0.636	0.272	42.8%

Test piles C and D show similar volumes of measured ground heave of about 70% of the theoretical volume of each pile. Both piles were installed with the same piling rig, which providedan inadequate rotational torque capacity of 120 kNm. For both piles, the specified penetration rate of 1.8 m/min could only be achieved for the top 2 m of penetration. The measured penetration rates at deeper levels were less than 50% of the target value. It seemed that the auger shape has no influence on the ground heave volume if the piles are installed with inadequate penetration rates.

Test pile E was installed with the more powerful piling rig and the specified penetration rate of 1.8 m/min could be achieved throughout the entire penetration process. The ground heave volume for test pile E was only 35.9% of the theoretical pile volume and about half of the volume measured for test piles C and D. The ground heave volume of pile E is about 15% less than that calculated using the SSPM.The ground heave profiles for the three test piles and the SSPM prediction (including the cavity expansion model) are displayed in Figures 3 and 4 for the two main axes of each test pile.

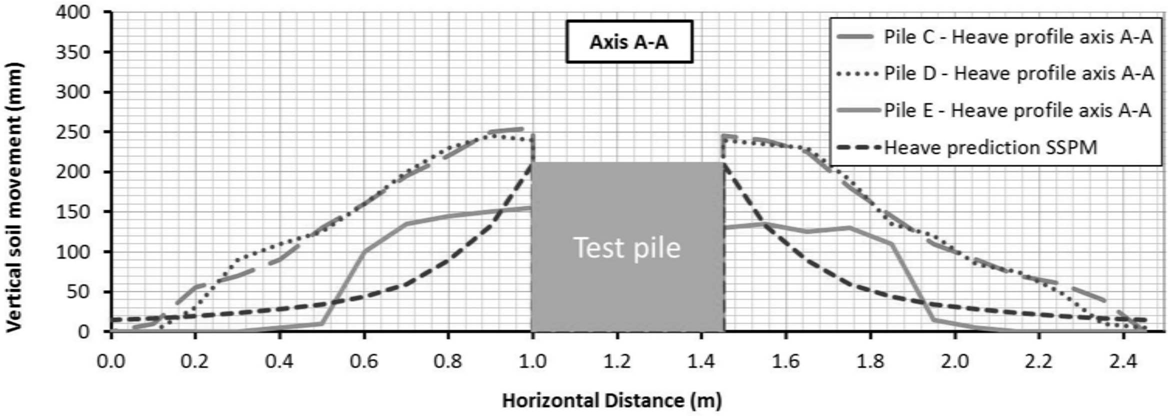

Figure 3. Schematic soil heave profiles for test piles C, D & E and SSPM prediction (axis A-A)

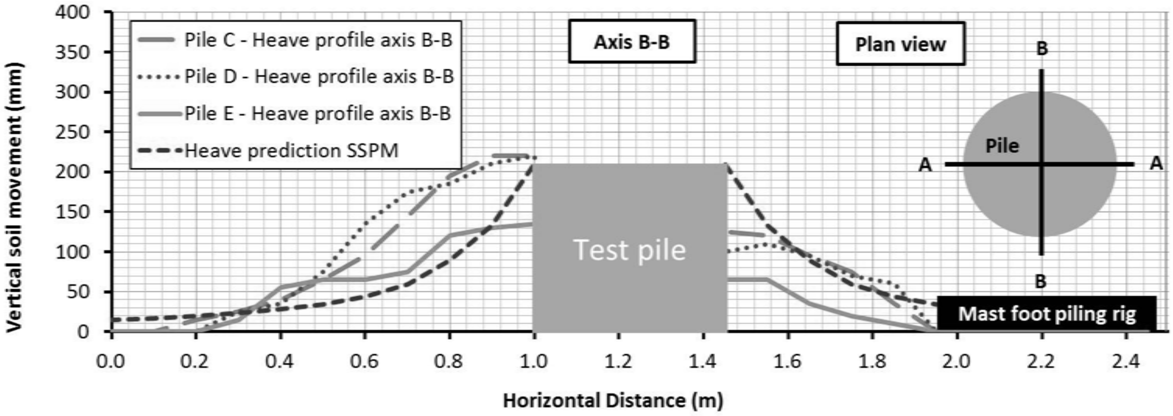

Figure 4.Schematic soil heave profiles for test piles C, D & E and SSPM prediction (axis B-B)

Surface cracks were observed as a result of ground heave (Figure 5) for all three test piles. The heave profile for all piles was altered at axis B as the mast foot of the piling rig restricted ground heave at this location. It was also observed that vertical ground movement occurred at the surface during the drilling process and was almost complete after the full penetration of the displacement body of the relevant displacement auger below ground surface level. No further heave at the surface was observed during the placement of concrete.

Figure 5.Ground heave occurring during the installation of test pile E (axis B-B)

The measured ground heave volume for test piles C and D was almost identical and followed a triangular shape with a maximum height of the heave cone next to the pile of about 250 mm. The radius of the heave cone measured from the edge of the pile was about 1.0 m.

The measured ground heave shape of all test piles was not matched by the concave-shaped ground heave predicted by the SSPM prediction. In particular, the ground heave profile of test pile E followed an almost trapezoidal shape with a maximum heave of 150 mm at the edge of the pile and a much smaller radius of only about 500 mm measured from the pile edge. The measured ground heave along axis B-B (opposite to the mast foot) showed a stepped shape and a radius of about 800 mm, as shown in Figure 5.

Figures 6 and 7 show,respectively the schematic heave cones and the assumed basic cone-shaped failure pattern of the stiff to hard clay as a result of the penetration of test piles C, D and E. The sketches are not drawn exactly to scale and the CPT ratio is added on the left hand site of each figure. The CPT ratio expresses the ratio of cone resistance q_c after and before pile installation at each test pile location. It is observed in Figures 6 and 7 that a CPT ratio of < 1, which indicates a reduction of soil strength after pile installation, is observed for test piles C and Ddown to 2.5 m depth. Below this level, the CPT ratio increased above 1, indicating improved soil strength as a result of pile installation. Calculating the shape of the heave cone by using the dimensions of the surface heave and the depth at which the CPT ratio = 1, provided the authors with the angle of the theoretical heave cone (23.6°), which is almost identical to the friction angle φ of the clay (24.7°) obtained by laboratory tests.

For test pile E (Figure 6), the critical depth, where the CPT ratio increases above 1 is located at about 1.25 m depth below ground level. The angle calculated by the dimensions of the ground heave pattern at the surface and the depth of 1.25 m is 23.6°; similar to that for test piles C and D. Consequently, the shape of the heave cone is similar for all three test piles, with only the critical depth being different. It was observed that the measured heave volume for all test piles is about 10 to 15% higher than the theoretical pile volume inside the heave cone. This effect could be a result of soil dilatation during the drilling process.

It was found that the SSPM overestimated the ground heave for test pile E (installed with a constant penetration rate of at least 1.8 m/min) by about 15%. The SSPM underestimated the ground heave volume by about 60% for the other two test piles installed with inadequate penetration rates.

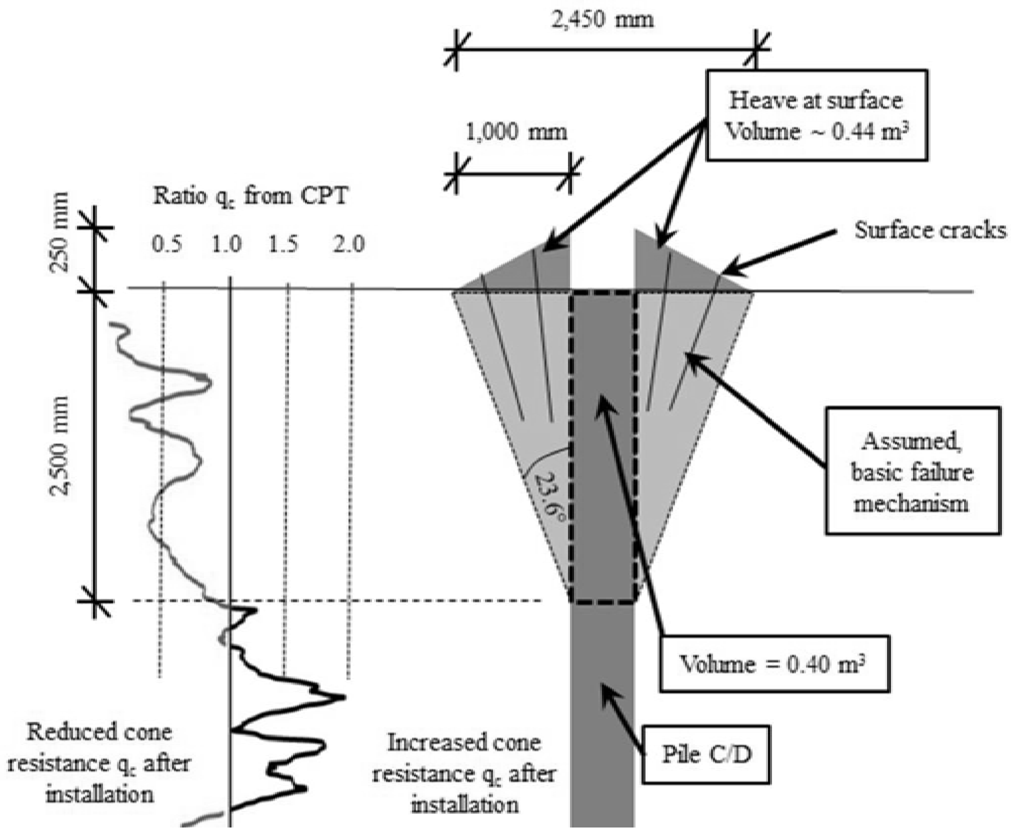

Figure 6.Schematic heave cone, heave volume and CPT ratio for test piles C and D (not to scale)

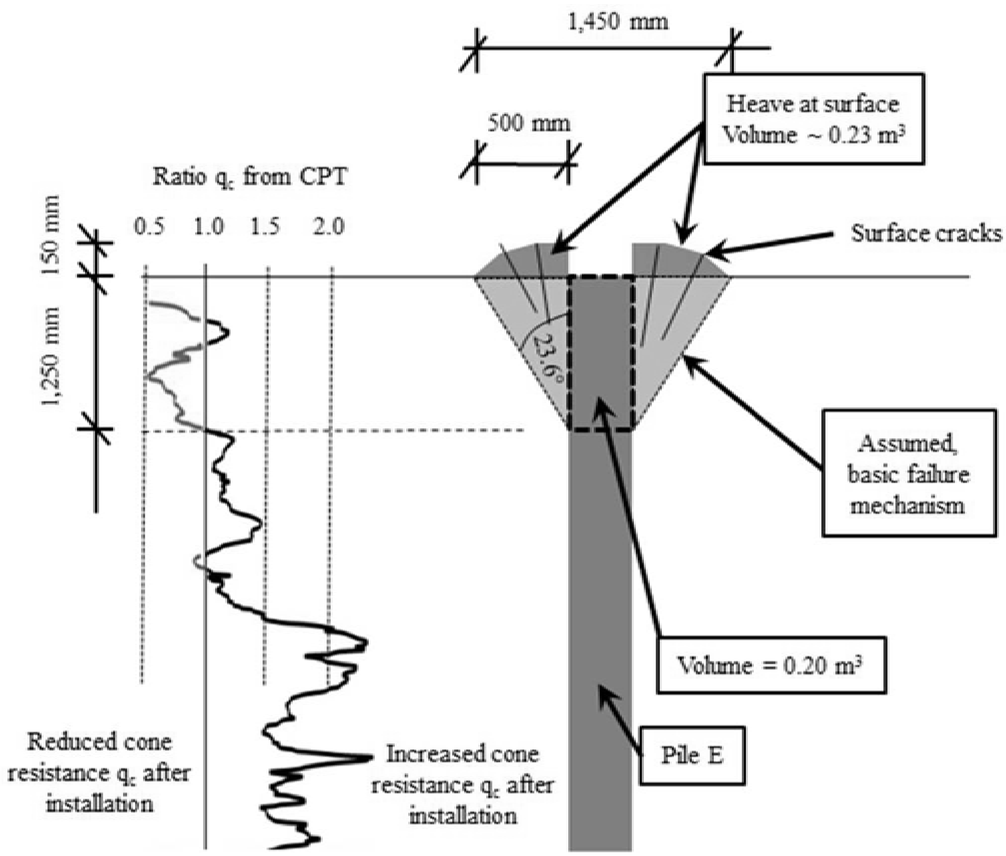

Figure 7.Schematic heave cone, heave volume and CPT ratio for test pile E (not to scale)

5 CONCLUSION

Ground heave in clay formations caused by the installation of drilled displacement piles can be reliably predicted by the SSPM if (i) the penetration rate of the drill tool is constant, and (ii) Vigianni's method (1993) is used to specify the required minimum penetration rate.

Sufficiently powerful piling rigs were able to maintain the minimum penetration rate of 1.8 m/min for the 450mm diameter drill toolpenetratingstiff to hard clay.The SSPM predictions and measured heave volumes were within 20% accuracy. The measured shape of the heave cone was differentto that predicted by the SSPM for the three test piles installed with drilled displacement technology. The heave volume predicted bythe SSPM was variable and the method significantly under-predicted the ground heave for test piles C and D, and conversely over-predicted the ground heave for test pile E. The authors concluded that the mechanism of ground heave caused by drilled displacement piles is different to that for driven closed end piles in clay. Further research is required to investigate the mechanism of soil shearing, dilations and transport as a result of the displacement auger installation in clay and the subsequent ground heave behaviour, patterns and volumes.

The results of full-scale drilled displacement test piles have shown that the shape of the assumed basic ground heave failure pattern was similar for both sufficiently powered and underpowered piling equipment. The calculated vertical angle of the assumed heave cone (23.6°) was almostsimilar to the friction angle φ of the stiff to hard clay (24.7°). The depth of the heave cone and the diameter of the heave radius around the pile depend on the penetration rate of the full displacement drill tool. Foran adequate tool penetration rate, the ground heave radius is smaller and the horizon of the disturbed soil is closer to the surface than for an inadequate penetration rate. CPT measurements were used to verify that inadequate penetration rates caused disturbance of the clay to greater depth,leading to greater heave volumes of up to 60%, with larger ground heave radii around the test piles. Unfortunately, it was not possible to excavate the test piles and to confirm the disturbed areas.

6 ACKNOWLEDGEMENTS

The authors thank the ARC Linkage scheme and all industry sponsors for their valuable support of the research project on which this paper is based. The authors also thank Mr Renyin Hu for his valuable contributions to the analyses reported in the paper.

REFERENCES

Adams, J.L. and T.H. Hanna (1971), "Ground movements due to pile driving". Behaviour of piles, 1971: p. 127

Baligh, M. (1985)."Strain Path Method".Journal of Geotechnical Engineering, 1985. 111(9): p. 1108-1136

Bottiau, M., Meyus, I.A., Van Impe, P.O. and Russo, G.(1998), "Load testing at Feluy test site: Introducing the Omega B* pile", Proceedings of the 3rd International Geotechnical Seminar on Deep Foundations on Bored and Auger Piles, Ghent, Belgium, 19–21 October 1998, Millpress, Rotterdam, pp. 187–199

Cummings, A.E., G.O. Kerkhoff, and R.B. Peck (1950)."Effect of driving piles into soft clay".Transactions, A. S. C. E., 1950.115: p. 275-285.

Gue, S.S. (1984). "Ground heave around driven piles in clay".University of Oxford (United Kingdom): Ann Arbor.

Hagerty, D.J. and R.B. Peck (1971)."Heave and Lateral Movements Due to Pile Driving".Proceedings A.S.C.E., 1971. 97: p. 1513-1532.

Healy, P. R.,Weltman, A. J. and CIRIA Piling Development Group report PG8 (1981)."Survey of problems associated with the installation of displacement piles",International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1981. 18(6): p. 126.

Larisch, M.D. (2014), "Behaviour of stiff, fine-grained soil during the installation of screw auger displacement piles", PhD thesis, The University of Queensland, Brisbane

Larisch, M.D., Kelly, R. and Muttuvel, T. (2014). "Improvement of soft formations by drilled displacement columns", 'Ground Improvement: Case Histories and new directions', Elsevier (Oxford), by Indraratna, Chu and Rujikiatkamjorn. (accepted for publication)

Luo, Z. (2004), "Study on compaction effects and construction effects on jacked piles", Zhejiang University.

Sagaseta, C. (1988)."Discussion: Analysis of undrained soil deformation due to ground loss". Géotechnique, 1988. 38, 647-659

Sagaseta, C. and A. Whittle (2001)."Prediction of Ground Movements due to Pile Driving in Clay", Journal of Geotechnical and Geoenvironmental Engineering, 2001. 127(1): p. 55-66.

Viggiani, C. (1993)."Further experiences with auger piles in Naples area", Proceedings of the 2nd Int. Geotech. Seminar on Deep Foundations on Bored and Auger Piles, Ghent, pp. 445–455, A. A. Balkema, Rotterdam.