Predicting Free Field Lateral Ground Movements due to Pile Driving in Soft Clay in Melbourne, Australia

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ABSTRACT

It is widely known that driving piles and pile groups into soft saturated clay can lead to substantial ground movements. Such movements can have serious implications for brownfield sites where existing infrastructure, such as inground services or existing pile groups, may be located nearby. It is important to be able to confidently predict the associated ground movements due to pile driving in these situations so the proposed pile or pile group can be optimised, or controls implemented, to mitigate potential impacts on existing assets. This paper presents two methods of analysis, namely the Shallow Strain Path Method (SSPM) and Plaxis 3D, applied to compute free field lateral ground movements associated with driving large pile groups in soft clay at a site in Melbourne, Australia. A brief discussion is also provided on the response of a pile to the estimated ground movements. The methods of analysis are compared with site data and overall good agreement is observed between both methods of analysis and the site observed data.

Keywords: soft clay, pile driving, lateral ground movement, finite element method, shallow strain path

1 INTRODUCTION

Driven precast concrete piles are displacement piles (AS2159 2009), meaning their installation causes soil displacement equivalent to the entire embedded volume of the pile. Where piles are driven into soil profiles which typically comprise a granular or cohesive soil of appreciable strength, the displaced soil tends to densify or compact locally to the pile, and the geotechnical design of the pile can take advantage of this by adopting higher design parameters. However, when piles are driven into soft saturated clays, no densification occurs in the clay and the volume of soil displaced is far greater, potentially leading to appreciable ground movements adjacent to and surrounding the pile. At brownfield sites, the impact these ground movements can have on adjacent existing infrastructure can be serious and must be considered in design. This paper presents two methods that were successfully applied to predict lateral ground movements associated with pile driving in soft clay at a brownfield site in Melbourne, Australia.

2 LITERATURE REVIEW

Pile driving in soft saturated clayey soil and the impacts it can have on surrounding infrastructure has been well documented in many laboratory tests and case studies (Hagerty and Peck 1971, Poulos 1994, Sagaseta et al. 1997, Sagaseta and Whittle 2001, Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, Rainer Massarch and Wersall 2013, Hernquist and Nguyen 2016, Edvardsson and Melin-Nyhom 2018, and Attari et al. 2018). From the available case studies and laboratory tests it is observed that ground movement in soft clay due to pile driving is a complex phenomenon, and consequently can be difficult to predict accurately. However, of the available data and case studies, it has been shown that the magnitude and overall trend of lateral ground movement may be estimated by combining engineering judgement and existing published methods of analysis.

There are many methods of analysis available to estimate ground movements associated with pile driving in soft clay. The methods vary from: simple empirical methods such as Rehman's method (after Olsson and Holm 1993 as cited in Edstam and Kullingsjo 2010); analytical methods such as cavity expansion theory (Carter et al. 1979); semi analytical methods such as the Strain Path Method (SPM) (Baligh 1985) or the Shallow Strain Path Method (SSPM) (Sagaseta et al. 1997, Sagaseta and Whittle 2001); and numerical methods such as the finite element method (FEM). Various authors have investigated these methods (Poulos 1994, Xu et al. 2006; Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, Hernquist and Nguyen 2016, Edvardsson and Melin-Nyhom 2018, Attari et al. 2018) and have shown that satisfactory estimates of the magnitude and trend of lateral ground movement due to pile driving in soft clay can be obtained. Of these available methods, the SSPM and FEM (eg Plaxis 3D Bentley Systems) tend to be more prevalent in the literature, albeit with some level of calibration or modification to the method. These two methods, and one such modification, are described in more detail in the following sections of this paper. Two case studies that have applied the SSPM and / or 3D finite element analysis (FEA) compared with observed lateral movements are presented in Figure 1.

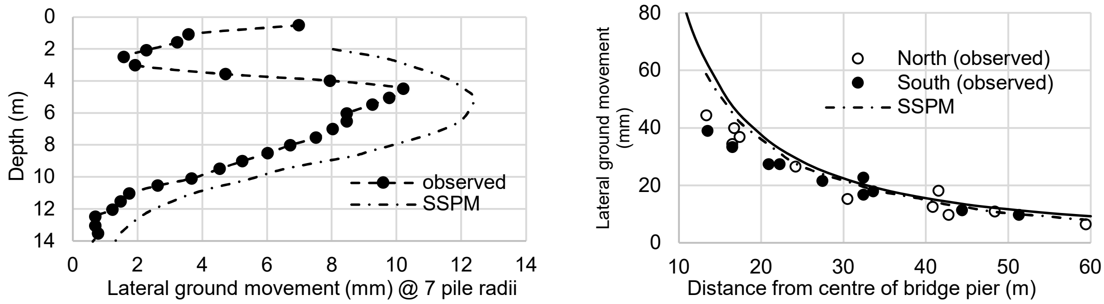

Figure 1: Selected Case Studies: LEFT – Single Shanghai 1.02 m diameter steel tube pile (Xu et al 2006). RIGHT – Partihallen highway bridge, 60 pile group 16.2 m x 6.4 m (Edtsam and Kullingsjo 2010).

2.1 Shallow Strain Path Method (SSPM)

The SSPM is used for predicting ground movements caused by driven or jacked piles in clay (Sagaseta et al. 1997 and Sagaseta and Whittle 2001). To simulate a pile being installed the method adopts a spherical point source that penetrates an inviscid fluid over the full length of a pile and a point sink is introduced to account for the incompressibility of the clay. The method has been developed assuming the clay behaviour is undrained, the surface of the clay layer is stress free and the piles are floating piles (Sagaseta et al. 1997 and Sagaseta and Whittle 2001). The solution for a cylindrical pile from Sagaseta and Whittle (2001) is given in Equation 1, as follows:

$$\delta_r(r,0) = (A_p/2\pi)\, L \,/\, (r\sqrt{(r^2 + L^2)}) \qquad (1)$$

Where A_p is the cross-sectional area of the pile, L is the length of the pile and r is the radial distance from the pile.

Where end bearing piles are present a solution can be found by considering the relative displacement between the ground surface and incompressible layer (Sagaseta and Whittle 2001). Alternatively the method can be supplemented with numerical methods. The effect of driving numerous piles can be incorporated into the SSPM by using the principle of superposition.

A limitation of the SSPM is that the closed form solutions do not provide a profile of lateral ground movement with depth, and typically require numerical tools to solve for the lateral ground movement profile. However, if site specific data is available, the distribution of lateral ground movement profiles may be approximated using simple mathematical expressions. For example, some case studies from Sweden where the soil surface is relatively stress free and the soil is a deep homogeneous clay profile, a 6^{th} order polynomial has been shown to provide a satisfactory approximation of the lateral ground movement profile with depth (Edstam and Kullingsjo 2010 and Nenonen and Ruul 2011).

2.2 Finite Element Analysis (Plaxis 3D)

Plaxis 3D (Bentley Systems) is a general purpose geotechnical finite element package used for deformation and stability analyses in geotechnical engineering. An advantage of Plaxis 3D is that it can handle complex geometry and interaction effects that cannot be accounted for in methods such as the SSPM. One limitation of Plaxis 3D is the potentially significant time required to setup a model, run the calculations, and extract and rationalise the results of the analysis.

It is generally not necessary to model the entire penetration process of driving a pile from the soil surface in Plaxis 3D, and to simulate the effect of driving piles in soft clay in Plaxis 3D it is common practice to apply a positive volumetric strain to the cross section of a pile to simulate the effect of the volume of the pile displacing the soft clay.

Of the available case studies (Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, and Hernquist and Nguyen 2016), sensitivity analyses have shown the adoption of a linear elastic soil model in Plaxis 3D generally provides satisfactory estimates of the free field lateral ground movements due to pile driving.

2.3 The Equivalent Pier Modification to the SSPM and Plaxis 3D

The equivalent pier concept in geotechnical engineering is widely known and is routinely adopted to estimate the settlement of a pile group (Poulos 1993). This concept has also been applied to estimating ground movements due to pile driving in soft clay using both the SSPM and Plaxis 3D, and has been shown to compare favourably with observed ground movements, and in this instance is more commonly referred to as a ‘Super Pile’ in the literature (Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, Hernquist and Nguyen 2016, Edvardsson and Melin-Nyhom 2018, and Attari et al. 2018). When applying this modification to the SSPM or Plaxis 3D, the general approach is to replace a group of piles with a single equivalent pier or several smaller equivalent piers, having the same cross-sectional area and volume as the overall group, and is positioned at the centroid of the cluster of piles it replaces. The method has been verified against numerous cases studies where both methods exhibit similar predictions and compare well with observed data (Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, Hernquist and Nguyen 2016, Edvardsson and Melin-Nyhom 2018, and Attari et al. 2018).

3 CASE STUDY AT A BROWNFIELD SITE IN MELBOURNE, VICTORIA, AUSTRALIA

3.1 Project Background and Geology

The project site is located within the Yarra Delta geological group, about 1 km west of Melbourne. Ground conditions typically comprise 3 m to 6 m of dredged sandy / gravelly fill, overlying a soft normally to slightly over consolidated silty clay, locally referred to as Coode Island Silt (CIS), to a depth of up to 15 m. Underlying the CIS, is the Fishermens Bend Silt (FBS) and / or Quaternary Aged Alluvium (Qha) which comprises mixtures of firm to very stiff / medium dense clay, silty clay, sand and silty sand, which is further underlain by the Moray Street Gravels (MSG) which typically comprise dense sands / gravels and / or the Melbourne Formation (MF). A summary of the geotechnical properties adopted for the Plaxis 3D analysis is given in Table 1.

Table 1: Geotechnical properties adopted in Plaxis 3D analysis

Geotechnical Unit	Unit Weight (kN/m^3)	Drained Elastic Modulus (MPa)	Poisson’s Ratio
Dredge Fill	18	10 to 15	0.3
Coode Island Silt	16	2 to 5	
Fishermens Bend Silt	18	10 to 30	
Quaternary Aged Alluvium	18	10 to 15	
Morary Street Gravel	20	35 to 70	
Melbourne Formation	21	$\geq$ 60	

The project comprised the construction of numerous large pile groups (typically between 12 to 25 piles per group) in close proximity to existing pile foundations and other surface infrastructure. Due to the presence of contaminated and / or acid sulfate soils, the preferred option was to use 400 mm square precast concrete driven piles to construct the pile groups. Owing to large loads each pile group would be required to support, the piles were designed to be driven to refusal on the MSG or MF.

3.2 Field Measurements and Observations

Field measurements were obtained from three inclinometers during early piling operations of a square 12 no. pile group at the site, shown in Figure 2.

In the right of Figure 2 it can be seen that in the upper 4 m within the predominantly granular fill, the movements are small or negative, however, large positive movements with depth are observed and are a result of the piles being driven through the CIS and upper portions of the FBS and Qha. The maximum ground movements within the CIS were: about 90 mm but more typically 80 mm at IPI1; about 40 mm at IPI2; and about 20 mm at IPI3. It can also be seen that unlike some of the case studies (Edstam and Kullingsjo 2010 and Nenonen and Ruul 2011), the trend of lateral ground movement with depth is not comparable to a 6th order polynomial but tends to be better approximated by a gaussian distribution, albeit with minor variation and scatter indicated by the inclinometers. The difference between the case studies and the site observations is likely to be attributed to the presence of the overlying dredged granular fill materials not undergoing appreciable lateral movement during pile driving but also providing some overburden / confining stress to the surface of the soft clay.

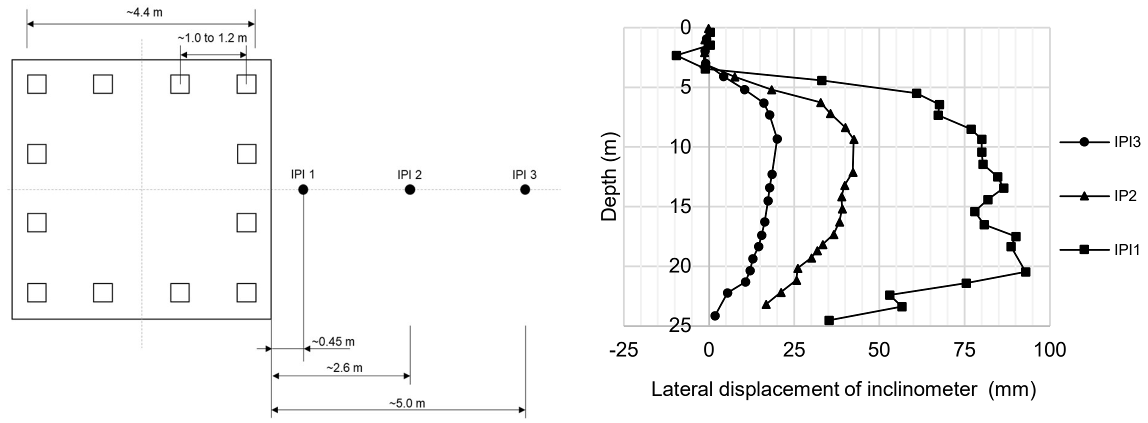

Figure 2: LEFT – Schematic of pile group and inclinometers IPI1, 2 and 3 (not to scale). RIGHT – Lateral displacement of inclinometers after pile group installation

3.3 Results and Discussion of Analysis Methodologies and Comparisons with Field Measurements

The SSPM and Plaxis 3D were applied to predict the lateral ground movements due to the installation of the 12 no. pile group. Based on the findings of Edstam and Kullingsjo (2010), Nenonen and Ruul (2011) and Hernquist and Nguyen (2016), a linear elastic soil model has been adopted for the Plaxis 3D analysis using the typical properties in Table 1. The analysis using Plaxis 3D and the SSPM included modelling individual piles and the replacement of them with a single equivalent pier. The equivalent pier method considered a positive volumetric expansion of 10% in Plaxis 3D and an equivalent pier diameter of 1.41 m in the SSPM. The lateral ground movement profile with depth ($U_x(z)$) for the SSPM has been derived from a gaussian distribution as defined in Equation 2:

$$U_x(z) = [U_{x,max} \exp(-(a^2)/(2(Kx_0)^2)] \quad (2)$$

Where $U_{x,max}$ is the lateral soil displacement/movement estimated from the SSPM, "a" is the distance from the mid-point of the soft clay layer, x_0 is the distance from the centre of the pile / pile group being driven and K is an empirical factor and is estimated to be between 0.25 to 0.5 of the thickness of the soft clay layer (in Equation 2, Kx_0 is the distance to the point of inflexion of the lateral ground movement profile from the centre of the soft clay layer). It is of importance to highlight that a gaussian distribution is a well-established tool in geotechnical engineering, where it has been routinely adopted in tunnelling engineering (Mair et al. 1996) and also mine subsidence (Holla 1987) to estimate the distribution of surface settlement troughs.

Some results of the analysis compared with observed data have been presented in Figure 3.

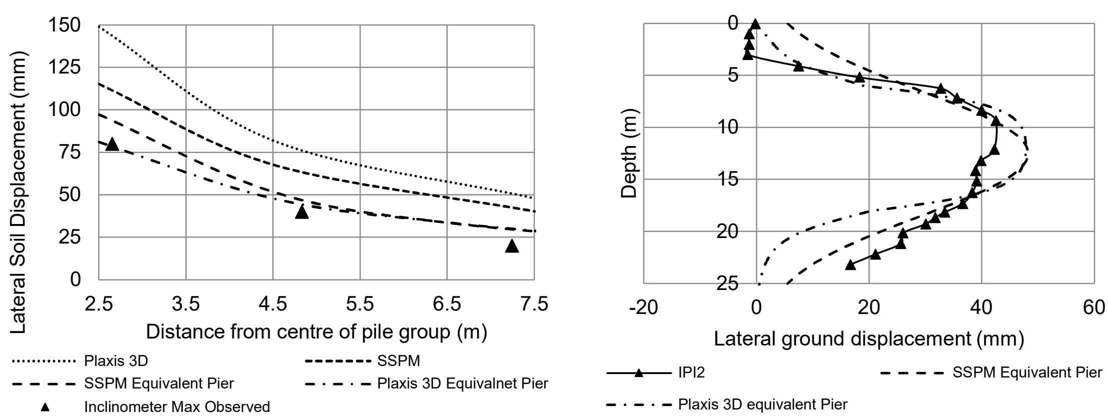

Figure 3: Comparison of observed and predicted lateral displacements. LEFT: Lateral ground movements vs distance from centre of pile group. RIGHT: Lateral ground movement profile for IPI2.

The left of Figure 3 presents the maximum observed and predicted lateral movement from the inclinometers and analysis. When adopting the equivalent pier modification, the predictions compare well with observed data. However, when the individual piles are modelled the methods do not compare well, and exceed the observed data by about 1.5 to 2 times.

Additional analyses were performed in Plaxis 3D to assess the effect of the piles being modelled in a single stage or individually activated in consecutive stages. The difference between activating the piles in a single stage or adopting individually activated piles in consecutive stages did not provide an appreciable difference in the overall magnitude or trend of lateral ground movements. It should also be noted when considering the SSPM with an equivalent pier, the estimated movements closer to the source of movement are unlikely to yield realistic estimates of movement since the SSPM is more applicable to small strain applications. These behaviours are generally consistent with many of the available case studies (Edstam and Kullingsjo 2010, Nenonen and Ruul 2011, Hernquist and Nguyen 2016, Edvardsson and Melin-Nyhom 2018, and Attari et al. 2018).

The right of Figure 3 presents the comparison of observed and predicted lateral ground movement profiles based on the equivalent pier concept for IPI2. It is evident that the overall trend of lateral ground movement compares reasonably well between the observed and predicted movements. It should be noted that the predictions presented in Figure 3 were based on the nearest available borehole, which was some 40 m from the installed inclinometers, and it is possible that there is some variation in the actual and assumed thickness of the CIS. The SSPM and lateral ground movement profile derived using a gaussian distribution was further validated against additional pile driving undertaken in connection with the project and also other pile group geometries in Plaxis 3D.

4 A NOTE ON FREEFIELD LATERAL GROUND MOVEMENTS AND ITS EFFECT ON EXISTING PILES

An important consideration beyond predicting free field lateral ground movement is the effect that the lateral ground movement can have on existing piles / pile groups. The actual effect is a complex soil-pile interaction problem that depends on the stiffness and strength of the soil, pile stiffness, head fixity of the pile and the distribution of ground movement. The impacts can be readily assessed using numerical methods such as Plaxis 3D, however, it is useful to have an alternative methodology to check more sophisticated methods of analysis or as a preliminary assessment tool.

A theoretical study of a pile group comprising 19 x 450 mm square concrete driven piles has been undertaken. The study has been based on typical ground conditions encountered at the project site from Section 3 and assumes a single existing 30 m long square 450 mm concrete pile 4.5 m away from the pile group. The general methodology proposed by Poulos (1994) has been adopted, where the free field lateral ground movement due to pile driving is computed, in this instance using the SSPM and gaussian distribution, and a pile-soil interaction analysis is undertaken for the existing pile subjected to the computed free field lateral ground movement. The PY software LAP (Geocalcs) was used to undertake the pile-soil interaction. The results of the analysis have been presented in Figure 4 along with results from Plaxis 3D and the simplified chart solutions of Chen and Poulos (1997).

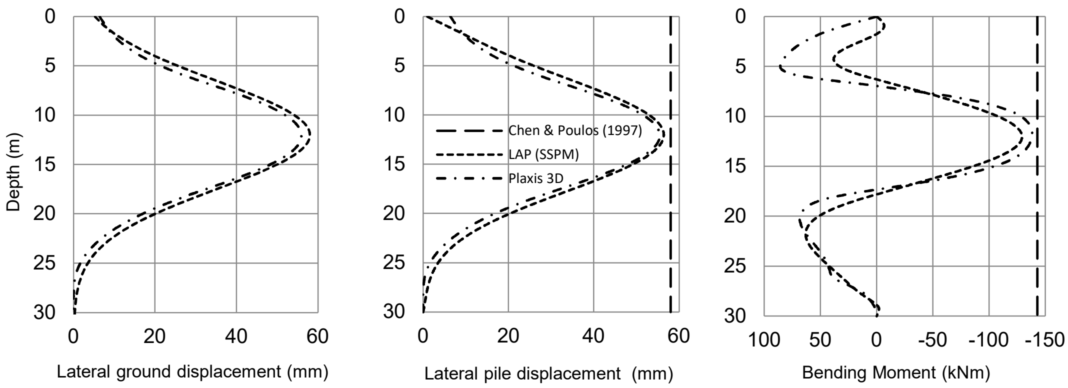

Figure 4: Theoretical study of lateral ground movement effects on a pile.

Figure 4 shows that the ground movements, and resulting maximum pile deflection and bending moment, derived from the SSPM compare well with the results of the Plaxis 3D analysis and the simple chart solutions of Chen and Poulos (1997). It is also worthy to highlight that the pile deflection is similar to the free field lateral ground movement and is due to the slenderness of the existing pile and soft ground conditions, indicating that the relative stiffness of the ground and pile is an important factor when considering the effects of lateral ground movements on existing piles.

5 CONCLUSION

The analysis methods presented in this paper can be used to establish an understanding of the resulting lateral ground movement due to pile driving in soft clay. The methods showed similar predictions and also compared well with observed site data. This is generally consistent with many of the available case studies in the literature which concluded these methods capture overall magnitude and trend of lateral ground movement due to pile driving in soft clay. This is with the exception of the profile of lateral ground movement with depth, which based on the available site data, was better approximated by a gaussian distribution. This highlights the importance of site-specific data and/or a monitoring program to compare predictions with. Particularly since the resulting ground movement profile effects the curvature and bending moment of an existing pile.

Notwithstanding the above, review of the many case studies within the literature indicates there is appreciable scatter in the observed lateral ground movements, which indicates that regardless of the analysis method adopted, it should be applied cautiously in conjunction with good engineering judgement. In many practical applications it would be considered appropriate to use both methods since they are expected to converge to a similar magnitude and trend of free field lateral ground movement.

Further work is underway to better establish the empirical factor K, the effect of overburden and how intermediate strong layers within the soft clay may affect the lateral ground movement profile.

6 ACKNOWLEDGEMENTS

The authors acknowledge the support from Douglas Partners Pty Ltd.

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