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A SIMPLE METHOD FOR PREDICTING COHESIVE PILE DEFORMATIONS FROM DISPLACEMENT PILE INSTALLATION INDUCED GROUND MOVEMENT

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KEYWORDS

Displacement pile installation, SSPM, SSI, Soil movement

ABSTRACT

Prediction of ground deformations resulting from the installation of displacement piles in greenfield conditions can be calculated using theoretical solutions such as the shallow strain path method (SSPM). The induced ground deformation from piling work may cause damage to nearby buildings' deep foundations. To study this potential damage, complex finite-element calculations may be necessary. In this article, a simple approach using the SSPM is presented for estimating the horizontal deformation of existing piles induced by nearby displacement pile installation. The method was based on the results from actual field measurements and finite-element calculations.

1. INTRODUCTION

With the ongoing urban densification in larger cities, taller buildings are being constructed today on land with poorer ground conditions than before. Foundations on such land require extensive piled foundations. In these urban areas, buildings are constructed in the vicinity of existing structures, imposing increasingly stringent requirements to prevent damage to these existing structures. In recent years, this issue has been particularly emphasized in Gothenburg, where the geotechnical conditions primarily consist of clay to significant depths (>100m), alongside a surge in the construction of tall buildings adjacent to major infrastructure such as tunnels and bridges, as well as near older, fragile buildings.

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In Sweden, pile foundations are traditionally prefabricated displacement piles of solid concrete or hollow steel pipes. An effect of installing displacement piles in clay is that the installation causes ground movement, which can lead to damage to nearby buildings and infrastructure. This problem is not new but has lately been a topic of discussion not only in Sweden (e.g., [3], [4]) but also in other countries with similar geotechnical conditions (e.g., [8], [9]). The magnitude of these ground deformations is directly proportional to the installed volume of displacement piles, and the extent of the movement relates to the pile length. In greenfield conditions (GF) - i.e., a flat ground surface, deep clay deposit, and no heavy buildings and structures near the installed piles. The Shallow Strain Path Method (SSPM) ([1]) has been proven to estimate displacements of light buildings and structures, as well as ground deformations, with good agreement with field and laboratory measurements (e.g., [2], [6]). The SSPM method provides a simple and fast tool for calculating ground deformations resulting from installations of displacement piles.

However, in geotechnical design, the primary concern is the deformations and potential damage to existing structures, with the GF movement being of secondary importance. The presence of existing structures supported by deep foundations has been shown to alter the magnitude/distribution of displacements compared to the predicted results from the GF situation ([5], [7]). Simple methods able to quantify this influence are not available, and practicing engineers are left to rely on engineering judgment/experience or need to use numerical methods to analyze this problem. Even simplified numerical analysis of the installation of piles and their effect on nearby structures requires three-dimensional modeling and can become complicated and time-consuming for both personnel hours and computing time.

In this paper, the installation of displacement piles for a new building in central Gothenburg, Sweden, and their effect on two nearby buildings are analyzed by comparing the measured deformations with predictions using SSPM and the Finite Element Method (FEM). Based on the insights gained from the comparison, a practical approach is suggested for estimating the horizontal deformations of existing piles due to displacement pile installation in clay.

2. METHODOLOGY

The installation rate of prefabricated displacement piles, in combination with the low permeability of natural clays, results in undrained loading conditions with constant volume behavior of the displaced clay. This constant volume condition has been utilized for two methods of predicting displacements due to pile installation. The first method is the SSPM ([1]). The SSPM is based on theories from fluid mechanics and assumes a frictionless and constant volume material. It provides displacements due to the installation of a pile in an infinite half-space with a stress-free surface. The solution is based on an incompressible material, and the displacements from the installation of multiple piles can thus be calculated by the superposition of the single-pile solution.

The second method relies on FEM where the installation of piles has been simulated by the horizontal expansion of a soil volume where the expanded volume corresponds to the volume of soil displaced by the installed piles. The volume of multiple individual piles will in this work be grouped together to a larger single volume to reduce the number of expanding soil volumes as proposed by [3]. The influence of existing structures in FEM can be modeled using various levels of fidelity. In this study, a simple strategy was used to enable the modeling of the large geometrical system of existing foundations. The soil was modeled using solid elements with a linear elastic material model. The walls and foundation slab of the existing structures were modeled using plate elements connected by interface elements to the soil. Existing piles were modeled using the embedded beam element in Plaxis 3D ([10]), where the stiffness of the pile is applied on top of the existing finite element, avoiding the need to create separate volume elements to represent the pile. The embedded beam formulation has been shown to capture the behavior of the volume pile to a reasonable degree. However, the accuracy of the embedded beam element is not ideal and should be used with caution in the case of lateral loading, especially when approaching failure.

3. CASE HISTORY

The analyzed case history involved the development of a new neighborhood in Gothenburg, Sweden, comprising office and residential buildings. This area, situated in the floodplain of the Göta River near its mouth at the sea, was previously a harbor basin. The soil profile consists of a 4-m-thick layer of fill material containing sand, silt, and clay, along with remnants of old dock structures. Beneath this layer lies clay, extending to a significant depth (>100m). This paper focuses on soil displacements resulting from pile installation for the foundation of one of these new office buildings, known as Habitat 7

The construction of Habitat 7 began with the installation of sheet-pile walls (SPW), followed by excavation to a depth of 3 meters, and then the installation of piles from a 1-m-thick gravel bed. In total, 149 piles were driven in a span of 7 weeks. The piles are a combination of concrete and timber where the top 30m part consists of concrete and the bottom 12 of timber. Additionally, a few hollow cylinder steel piles were used in the foundation of a crane. To reduce the displacement during the installation of the piles, soil was extracted up to a depth of 14 m using auger screws in the location of some of the combined displacements piles to reduce the displaced soil volume. A plan of the foundation is presented in Figure 1. An extensive monitoring program was implemented focused on tracking displacements and preventing damage to the two existing office buildings with deep foundations, namely Stuveriet and

Brick Studio (see Figure 2). In this analysis, three monitoring points were studied in more detail, with S1 and S2 mounted on the building of Stuveriet and B1 mounted on the building of Brick Studios. To be able to monitor the displacement of the existing piles, inclinometers were installed at the location of S1 and B1. The inclinometers were fixed at their top to the building foundation slabs of the respective buildings.

The details of the foundations for the nearby buildings Stuveriet and Brick-Studios can be found in Table 1; some simplifications regarding foundation geometry and pile layout have been made. A large number of 28m long timber piles below the left slender part of Stuveriet was excluded from the numerical analysis to reduce the model complexity. All buildings in this study, were founded on so-called cohesive piles. There were a few end-bearing piles installed under Stuveriet, but they were only used to decrease downdrag forces for the cohesive piles.

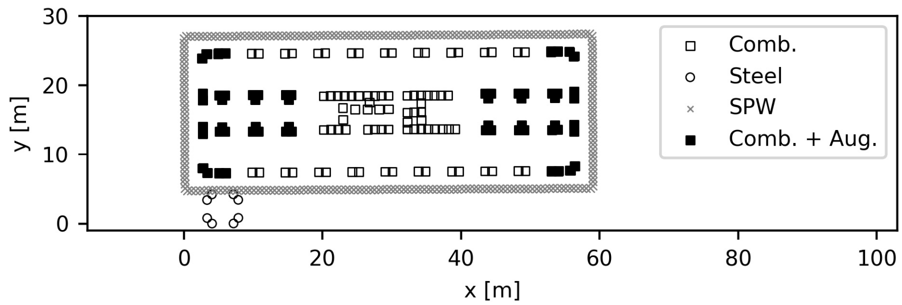

Figure 1 Deep foundation plan for Habitat 7 includes combination (concrete and timber) piles (Comb.), open-ended cylindrical steel piles (Steel), and sheet pile walls (SPW). The locations where auger screws were used before installation of the combination piles are also shown (Comb. + Aug).

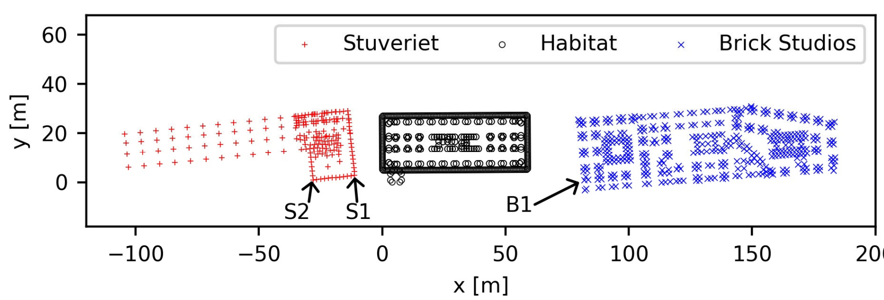

Figure 2. Overview of the existing pile foundations of Stuveriet and Brick studios and the deep foundation works of Habitat.

Table 1 Foundation of Stuveriet and Brick Studios

	Stuveriet	Brick Studios
Basement depth	5.75 m	5 m
Foundation slab	1 m	1 m

Basement wall	0.3m	0.3m
Pile types	Concrete/wood: 43m Concrete: 56 m Steel: End bearing, top at 5 m below basement	Concrete: 48-52 m Various steel piles: 72 – 80 m

4. NUMERICAL ANALYSIS

The ground deformations resulting from the deep foundation work for the Habitat building were predicted using SSPM and finite-element (FE) calculations. The predictions entailed calculating and summarizing the deformations from all individual piles and SPW to the points of S1, S2 and B1. Plaxis 3D, 2023 ([10]) was used for the FEM simulations. The FE model is illustrated in Figure 3 and features a horizontal domain size of 600 m by 600 m and a uniform depth of 100 m. The soil was modeled with linear elastic response and a Poisson's ratio of 0.499 to ensure a constant volume condition. The pile installation was simulated using 36 expanding volumes. Each expanding volume comprised individual piles that were grouped together, determined by dividing the building's footprint area into 36 zones, with 4 rows in the width direction and 9 in the length direction. The placement of the expanding volumes within each zone was determined based on a weighted mean of the individual pile locations, considering their respective contribution volumes. The FE model consisted of approximately 300,000 volume elements, 579 embedded beams, and 17 plates. Furthermore, to make a direct comparison of the results obtained from the SSPM calculations, FE calculations were also performed without accounting for the foundations of nearby buildings (i.e., the GF conditions). The location of S1, S2 and B1 corresponds to the location of piles in the FE-model

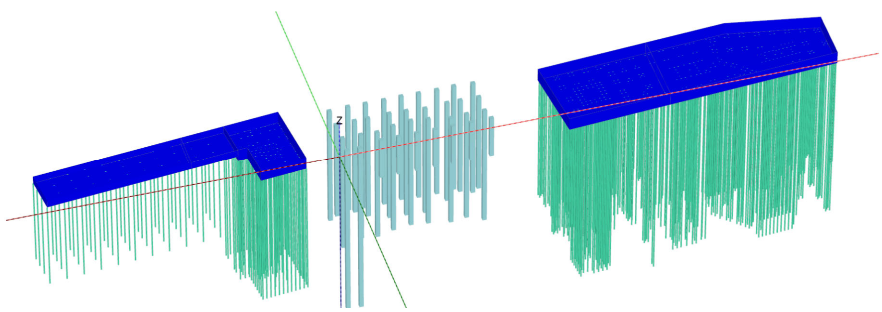

Figure 3 Finite element model for calculating the displacements of Stuveriet (left) and Brick Studios (right) due to the installation of Habitat piles (middle).

5. RESULTS

The calculated and measured horizontal and vertical deformations of the two buildings, Stuveriet and Brick Studios are shown in Figure 4. The results indicate that the predicted GF displacements from Finite Element Method (FEM) and SSPM exhibit similar magnitudes and depth-dependent shapes. However, the deformations calculated in FEM show higher horizontal displacement (10-30%) and lower vertical displacement (10-30%). The FE simulation and the inclinometer measurements show that the movement of the top of the pile in point S1 and B1 were reduced in relation to both the GF movement and the predicted and measured movement deeper in the soil. The difference in vertical displacement between S1 and S2 is reduced from 6,5mm to 4,5mm when the existing foundation is included in the FE analysis while the field measurement shows a difference of 3mm.

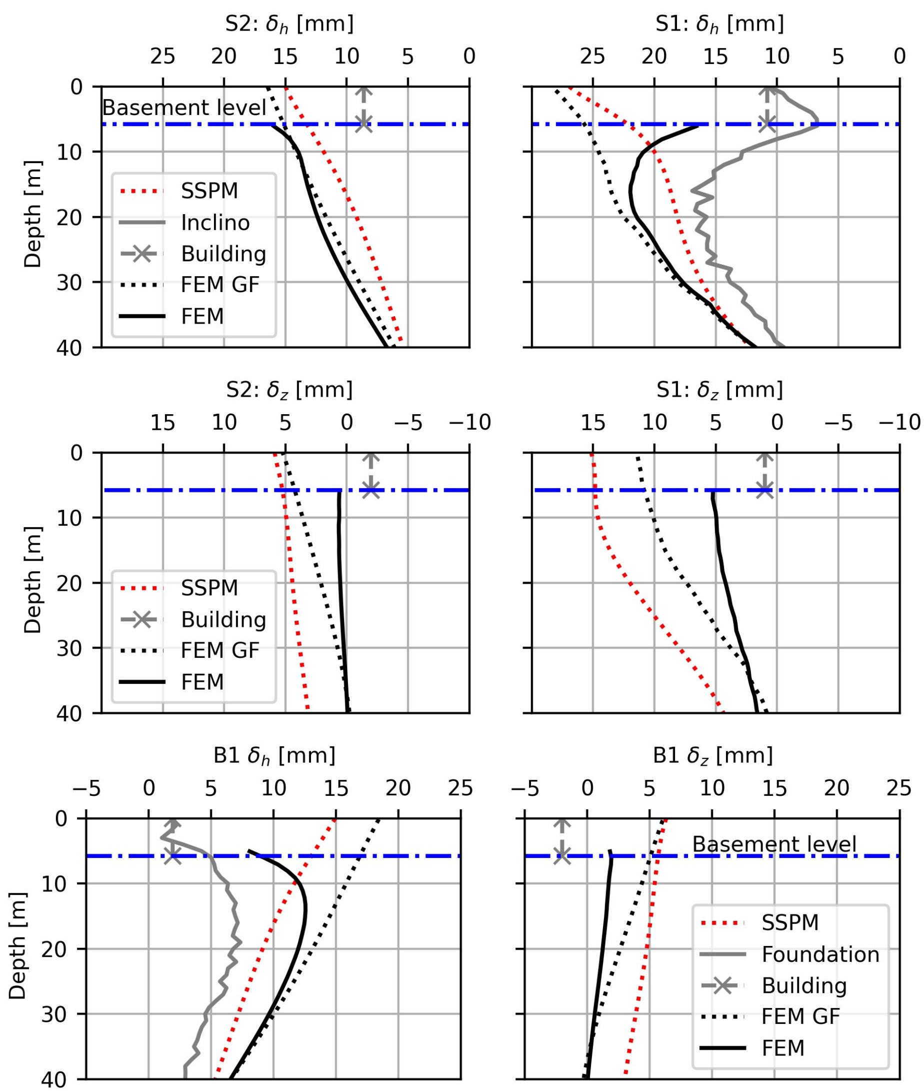

Figure 4 Measured and predicted horizontal and vertical movement for measurements point S1 and S2 on Stuveriet and B1 on Brick Studios.

6. A SIMPLE METHOD FOR EVALUATING PILE DEFORMATIONS

Horizontal ground deformation due to displacement pile installation was shown to induce bending of existing piles of nearby buildings. The bend shape of the pile leads to a reduction of the axial load-bearing capacity of the piles due to second-order moments. If the piles are already highly utilized, their capacity may be exceeded. The deformed shape of the piles determined through FE calculations and the measured deformations, from inclinometers fixed at the top of the foundation slab is similar. Large curvatures of the pile are isolated to the upper part of the pile corresponding to a buckling length equal to about 5m ([11]). Consequently, the pile's shape can be assumed to be equal to the predicted greenfield displacement shape below a depth corresponding to the buckling length. Over the buckling length, the pile has a curvature that connects to the deformations of the building at its top. Figure 5 illustrates the result of this simple adjusted SSPM method for estimating the deformed shape of the piles located at S1, S2, and B1. The proposed methodology results in both larger curvatures and deflection ratios in the piles compared to the FEM and measurements and seems to be conservative for the case studied herein.

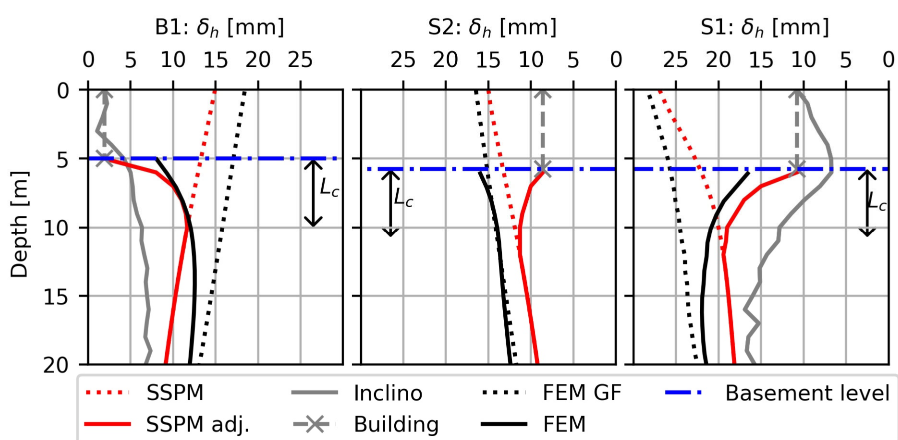

Figure 5 Measured and predicted horizontal and vertical movement for measurements point S1 and S2 on Stuveriet and B1 on Brick Studios.

7. CONCLUSIONS

The results of the study revealed that ground deformations resulting from the installation of displacement piles were strongly influenced by nearby building foundation. The study utilized the Finite Element Method (FEM), which successfully accounted for the restraining effect of the existing foundation on both horizontal and vertical movement. Additionally, the study demonstrated that a simple methodology, based on greenfield predictions of ground displacements and measured building movement, could provide an initial conservative estimate of existing pile deformations. The simple methodology gave estimates of the pile deformations with reasonably good agreement with both field measurements and FE calculations.

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