Opportunities and challenges of press-in piling for sustainable inner city quay wall development in Amsterdam

K. Duffy

Post-doctoral Researcher, Department of Geosciences and Engineering, TU Delft, The Netherlands

Geotechnical Engineer, InGEO Consulting, Delft, The Netherlands

K. Gavin

Professor of Subsurface Engineering, Department of Geosciences and Engineering, TU Delft, The Netherlands

Managing Director, InGEO Consulting, Delft, The Netherlands

ABSTRACT

Amsterdam is renowned for its picturesque canals, lined by tall, narrow buildings on either side. Hundreds of kilometres of quay walls support these canals, all founded on long, slender timber piles. Yet many of these quay walls are falling into disrepair and the remaining lifespan of these quay walls is often unknown. Consequently, an extensive amount of research and pilot projects are ongoing, investigating how these walls can be upgraded without intruding on the urban environment. Press-in piling presents an excellent alternative to conventional piling techniques because of its effectiveness in tight working spaces, generating low noise and vibrations as it does so. However, Amsterdam poses some unique geotechnical challenges. Built on marshland, soft clay and peat deposits are widespread throughout. Underlying these deposits are dense sands, the primary load-bearing layer for piled foundations. Understanding how piles behave in these sands is therefore vital, particularly in the case of piles with low embedment depths or in areas where there are thin weak zones in the vicinity of the pile tip. With the growth of press-in piling in the Netherlands, this paper presents some of the opportunities and challenges facing press-in piling, with a particular focus on how the Cone Penetration Test can be used to improve pile design and installation forecasting.

Keywords: *Redevelopment, cone penetration testing, ground modelling, axial capacity*

1. Introduction

Canals have been a perpetual feature of the Dutch urban landscape (**Fig. 1**). They have served several key functions throughout history, including water management, defence and transportation. While the importance of some functions have diminished over time, the picturesque inner city of Amsterdam still attracts millions of tourists every year. In recognition of this, the city was incorporated as a UNESCO World Heritage Site in 2010, with the goal of protecting the architectural and cultural significance of the canals and their surroundings.

Quay walls line either side of the canals. Many of these quay walls were constructed before the 20th century, like the one shown in **Fig. 2**. The top of the quay wall, the superstructure, is made of masonry and rests atop a timber floor and backfilled with made ground. Rows of timber piles are connected to the timber floor and are used to transfer both axial and lateral loads to the subsurface below. From the 1930s, quay walls began to

Fig. 1. A canal of inner-city Amsterdam, lined by quay walls (photograph by Fabien Dany, CC BY-SA 2.5 license)

incorporate concrete into the superstructure and eventually, the timber piles were replaced with concrete and steel piles as well as anchors (de Gijt, 2010).

Many of these quay walls can be up to three hundred years old, proving to be remarkably robust over time, even though the introduction of motor vehicles in the early 20th century have imposed heavier-than-envisaged loads on top of the quay wall. Nowadays, quay walls facilitate local transportation, parked vehicles and utility lines, as well as street furniture and trees. However, visibly aging infrastructure along with several recent failures (Telegraaf, 2017; AT5, 2018; Korff, Hemel and Peters, 2022) have suggested that many of these quay walls are approaching the end of their technical lifespan, potentially posing a severe safety risk.

But restoring the full functionality of a quay wall is more than just a technical and safety problem: integrating restoration work with urban activities and sustainability principles requires construction work to be efficient and with little intrusion on the local environment. Some of this is being researched in the *Urbiquay* programme, funded by the Dutch research council (NWO). Other research programmes include the *Innovatiepartnerschap Kademuren* and Living Labs managed by Amsterdam City Council.

Press-in piling offers a viable solution for urban quay wall redevelopment. The consortium of G-Kracht (Giken Europe, Gebr. De Koning and Van Gelder) recently completed demonstration cases with the walk-on GYRO PILER™ in Amsterdam (McNamara and Panchal, 2023) and the Hague (Kitano, 2022). However, experience with press-in piling in the Netherlands is still limited (Dieteren *et al.*, 2018) and the industry generally focusses on driven and cast-in-situ pile types.

With the growth of press-in piling in the Dutch market, this paper presents some of the geotechnical challenges for press-in piling in the context of urban quay wall regeneration. Its growth also offers potential research avenues which contribute to the global understanding of press-in pile installation and their response under loading.

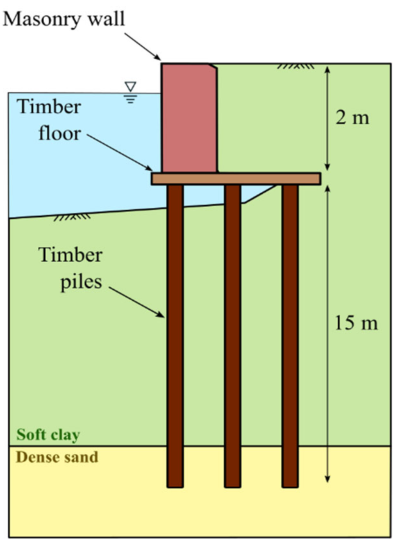

Fig. 2 An example of an urban quay wall built before the 20th century

2. Geology of Amsterdam

Amsterdam is located in west of the Netherlands on the southern bank of the Amstel river, 25 km from the North Sea coast. The city sits on top of a 60 m deep glacial basin (**Fig. 3**) formed roughly 200,000 years ago in the middle of the Pleistocene geological epoch. The basin was then a large freshwater lake, extending into the present-day North Sea. Flanking its boundaries were glacially-pushed deposits, mainly composed of coarse sand and gravel. (de Gans, Beets and Centineo, 2000; Schokker *et al.*, 2015). The low-energy depositional environment resulted in glaciolacustrine clay and silt deposits first beginning to infill the basin. With rising temperatures and sea-levels worldwide, the coastline began to shift eastwards towards Amsterdam and the clays and silts soon became covered with marine sands. The coastline retreated again towards the end of the Pleistocene, leading to the proliferation of fluvial deposits along with wind-blown sands. These deposits covered the top of the glacial basin (de Gans, Beets and Centineo, 2000), deposits which are found today at a depth of 10–15 m below the ground surface (**Fig. 3**).

The current geological epoch, the Holocene, began 10,000 years ago—a time where continued increases in sea level flooded the Amsterdam area (Beets and van der Spek, 2000). The transition between the Pleistocene and Holocene is often marked by a basal peat layer covering the late-Pleistocene sands, a layer which is now heavily consolidated. Eventually, sea-levels began to stabilise and the coastal beach barriers that had developed began to block the drainage of the tidal basin, transforming Amsterdam into a freshwater marsh (Schokker *et al.*, 2015). The marshland led to further deposition of peat and clay, ultimately leading to a soft, ten-metre-thick layer that is seen today (**Fig. 3**).

The arrival of human settlement led to drainage of the marshland and gradual subsidence of the soft Holocene deposits, often bringing the surface level to below groundwater level. As a quick remedial measure, anthropogenic soils (made ground) were deposited in urban areas to keep the ground surface above the water table, although this often just accelerated the rate of ground subsidence. Nowadays, the made ground can be up to six metres thick in certain areas and is highly heterogeneous, consisting of natural soils, rubble and industrial by-products (Dijkstra *et al.*, 2019).

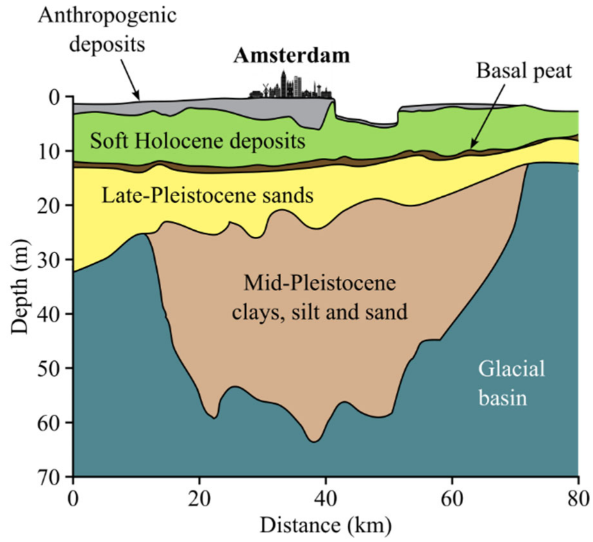

Fig. 3. Geological cross-section of Amsterdam

3. Considerations for press-in piling

Societal and environmental challenges are key limiting factors in the rehabilitation of urban quay walls. Many of the old, inner-city quay walls are in tight confined spaces, with no more than a few metres of space behind the quay walls. Therefore, mobilising the equipment spread for a typical pile installation is usually not possible, particularly when pedestrian, cyclist and vehicular traffic still needs to be facilitated for. Furthermore, when trees line the top of the quay wall, overhead clearance becomes limited. This means that piles are often installed piecewise, or else raked at an angle towards the waterside. In addition, behind many of the quay walls are old, merchant buildings, often classified as protected structures and high in both architectural and economical value. Many of these buildings are also residential, and so strict noise and vibration regulations are set in place for construction works (CROW, 2020).

Press-in piling, for the most part, provides a solution to these problems. Walk-on pilers are usually preferred since deadweight-based press-in pilers are often too large and cumbersome for the tightly confined sites. Walk-on pilers require a stable platform upon which to develop a reaction force, provided by the already installed piles. However, the soft overburden in the Amsterdam subsurface increases the risk of horizontal deformation at the top of reaction piles and so it is important that each pile is installed with sufficient penetration into the deeper sand layer. Digital twin technology can play a crucial role in this regard, whereby a digital ground or installation model is updated in real-time based on measured installation data, giving the contractor insights into productivity levels, potential risks and the adequacy of already-installed piles for providing a reaction force.

The choice of installation technique is also guided by the potential risk of subsurface obstructions, such as the remnants of older structures and rubble in the made ground layer. For instance, the GYRO PILER demonstration case (McNamara and Panchal, 2023) at the Singel canal used rotary push-in piles combined with water lubrication along the pile shaft. This allowed the piles to core through the existing brick of the quay wall and the made ground, reducing the installation risk and requiring minimal space.

4. In-situ testing

The Cone Penetration Test (CPT) is by far the most used site investigation tool in the Netherlands today. The Standard Penetration Test (SPT), on the contrary, is virtually non-existent, largely because of the higher resolution and data quality afforded by the CPT. Development of the CPT began in the Netherlands almost ninety years ago (Laboratory of Soil Mechanics, Delft, 1936), perhaps unsurprisingly given how conducive Dutch soil conditions were to CPT testing. Since then, the cone has changed from a mechanical cone to an electrical cone, going through many different shapes and sizes, eventually leading to the standardized version it is today. Design standards were also developed in parallel with CPT development and so much of the Dutch geotechnical design code (NEN, 2017) uses empirical CPT-based formulae for deriving the geotechnical capacity of structures such as dykes, foundation piles and settlement prediction.

Furthermore, public companies in the Netherlands are legally obliged to share any CPT or borehole data they have collected. All the data is shared on the open data platform *Basisregistratie Ondergrond*, meaning a huge amount of knowledge is available on the Dutch subsurface. In the city centre of Amsterdam for instance, thousands of CPTs (**Fig. 4**) are freely accessible online at www.dinoloket.nl.

Fig. 4. CPT data available in Amsterdam on www.dinoloket.nl

An example of one of these CPTs is shown in **Fig. 5**, performed near the GYRO PRESS demonstration case (McNamara and Panchal, 2023). Several geological features are immediately apparent. At the surface, lie at least three metres of made ground material, underlain by soft peat, clay and loose sand. The late-Pleistocene sands begin at 12 m below ground surface, separated by a thick bed of sandy clay. To guarantee sufficient capacity, the piles in the GYRO PRESS demonstration case penetrated through the first sand layer and were founded in the sand layer beginning at 17 m depth. In this layer, the cone resistances q_c are 20–30 MPa on average, sometimes reaching peaks of nearly 50 MPa.

5. Integrating the CPT into press-in pile design

With most of the press-in piling market based in eastern Asia, research (Ishihara and Haigh, 2018; Ishihara and Kusakabe, 2021) has inevitably focused on correlations with the Standard Penetration Test. Fully instrumented, full-scale tests on press-in piles, paired with an adjacent CPT, are relatively limited in comparison. Complex press-in pile types, such as the rotary press-in GYRO PRESS piles, suffer in particular from the lack of full-scale field tests (Brown and Ishihara, 2021), including those where the residual stresses have been incorporated into the interpreted pile base and shaft capacities (Ishihara, Haigh and Koseki, 2020).

Recent changes to the Dutch design code (Van Tol *et al.*, 2013; Gavin, Kovacevic and Igoe, 2021) have prompted a substantial amount of research into pile installation and axial response. Several full-scale test sites have been established in recent years (Putteman *et*

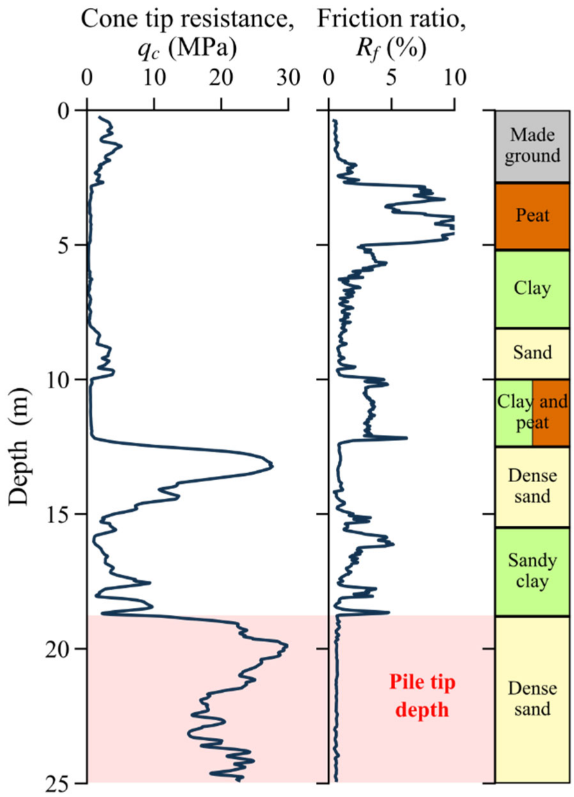

Fig. 5. Typical CPT profile in Amsterdam, near the GIKEN demonstration case

al., 2019; Duffy *et al.*, 2022, 2024), all aimed at understanding the axial response of different pile types in dense sand, namely driven piles, cast-in-situ piles and screw displacement piles.

In parallel with field testing, calibration chamber tests have focused on the influence of thin weak zones during the penetration and static loading of jacked piles (de Lange, Terwindt and van der Linden, 2018; van der Linden, de Lange and Korff, 2018), corroborrated by finite element models (FEM) and discrete element models (DEM), as presented in Chai et al. (2022). The research focussed on so-called "averaging methods". In short, averaging methods aim to describe the proportion of soil that a penetrometer or a pile can sense, culminating in a design cone resistance $q_{c,avg}$. With the 2 cm resolution of the CPT, very thin laminations can be detected and incorporated into an accurate prediction of installation resistance for press-in piles.

Fig. 6 shows the results of three common averaging methods applied to the CPT from the GYRO PRESS demonstration case, where the pile diameter D is 508 mm. The averaging methods can be summarised as follows:

- The **Dutch 4D/8D method** (van Mierlo and Koppejan, 1952) accounts for a zone four pile diameters below the pile tip and eight pile diameters above the pile tip, combining a weighted average with a minimum path rule when deriving $q_{c,avg}$.
- The **LCPC 1.5D method** (Bustamente and Gianeselli, 1982) averages the q_c values in a zone 1.5 pile diameters above and below the pile tip, limiting the q_c values to ±30% of the arithmetic average.
- The **filter method** (Boulanger and DeJong, 2018) applies a depth-dependent sinusoidal filter to derive $q_{c,avg}$ and has been shown to improve on existing averaging methods when analysed in laboratory and field tests (Bittar, Tian and Lehane, 2022). The filter method presented has been calibrated based on scaled penetrometer tests in interlayered soils (de Boorder, de Lange and Gavin, 2022),

With increasing embedment into the lower sand layer at 18 m (**Fig. 6**), the three methods slowly converge to one another as the influence of the softer overlying layer slowly reduces. Nevertheless, the Dutch 4D/8D method returns a $q_{c,avg}$ that is generally much lower than the two other methods, redolent of the conservative minimum path rule used in the method. Divergence between the LCPC 1.5D and filter methods is evident in the upper sand layer at 13 m depth, giving a peak $q_{c,avg}$ of 22 MPa and 13 MPa respectively. The filter method, in this case, has a much larger influence zone compared to the LCPC method because of the depth-dependent weighting it applies across this zone, as opposed to the simple arithmetic average in the LCPC method.

While laboratory and numerical models have given credence to the newer filter-based averaging method, installation data from press-in piling provides a means of validating these methods at full-scale. By fully instrumenting press-in piles during installation, the pile base and shaft resistance can be accurately determined, allowing for a direct comparison with CPT data and helping to improve installation forecasting and capacity assessment. This in turn can be used to improve existing ground models, validated based on realised pile installation data.

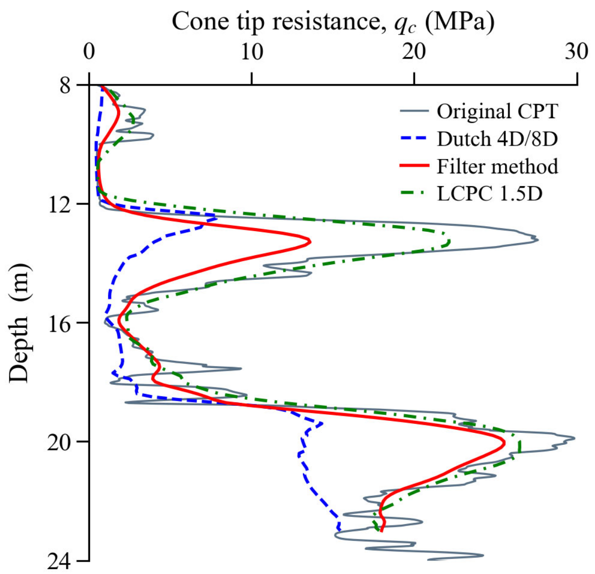

Fig. 6. Three different averaging methods applied to a CPT at the GYRO PRESS demonstration case, taking a pile diameter of 508 mm

6. Conclusion

After successful demonstration cases in the Netherlands, press-in piling has proven to be a viable solution for rehabilitating and renovating urban quay walls. As the technology increases in popularity, several research areas are being focussed on in particular:

- Improving CPT-based correlations for forecasting press-in pile response during installation and under static loading
- Validation of newly developed CPT averaging methods at full-scale
- Incorporation of installation data into ground models and digital twin technologies

This research is ongoing at TU Delft and InGEO and the findings will be disseminated over the coming years.

7. Acknowledgements

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