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## Research into pile toe failure in Amazonehaven

### Recherche sur la défaillance des orteils en pieux à Amazonehaven

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**ABSTRACT:** Extreme folding damage of open-ended tubular piles could occur during piling in onshore practices. The Amazonehaven unique quay wall removal provided the opportunity to study pile toe failure. The quay wall had a combined-wall system with open-ended tubular piles as its primary elements exposed to both static and dynamic load. The static load regards the asset's technical lifetime, whereas the dynamic load regards the hammer-induced load during installation. In Amazonehaven, the mysterious pile toe failure is argued to be caused by the hammer-induced stresses due to uniaxial direction of the extreme deformations close to pile toe. However, research into pile toe failure in Amazonehaven shows that the stresses close to the pile toe are significantly lower than the material's yield stress. Therefore, the pile toe integrity is not solely influenced by dynamic load. The main reasons for pile toe failure are discussed to be (1) the initial dent close to pile toe and (2) the pile inclination.

**RÉSUMÉ:** Des dommages de pliage extrêmes des pieux tubulaires ouverts pourraient se produire lors de l'empilage dans les pratiques à terre. L'enlèvement unique du mur de quai d'Amazonehaven a permis d'étudier la rupture du pied de pieux. Le mur du quai avait un système de murs combinés avec des pieux tubulaires ouverts en tant qu'éléments principaux exposés à la fois à des charges statiques et dynamiques. La charge statique concerne la durée de vie technique de l'actif, tandis que la charge dynamique concerne la charge induite par le marteau lors de l'installation. À Amazonehaven, la mystérieuse rupture du pied du pieu est supposée être causée par les contraintes induites par le marteau dues à la direction uniaxiale des déformations extrêmes près du pied du pieu. Cependant, les recherches sur la rupture de la pointe du pieu à Amazonehaven montrent que les contraintes proches de la pointe du pieu sont nettement inférieures à la limite d'élasticité du matériau. Par conséquent, l'intégrité de la pointe du pieu n'est pas uniquement influencée par la charge dynamique. Les principales raisons de la rupture du pied de pieux sont (1) la bosselure initiale près du pied de pieux et (2) l'inclinaison du pieu.

**KEYWORDS:** open ended piles, pile driving prediction, Amazonehaven quay wall

## 1 INTRODUCTION

After removal of Amazonehaven quay wall in Maasvlakte II Rotterdam, it was observed that the open-ended piles, the primary elements in a combined wall system, were significantly damaged. The open-ended piles were damaged close to the pile toe, as depicted in Figure 1. This paper aims to study both technical- and management-aspects of pile toe failure.



Figure 1. Extreme folding damage

## 2 BACKGROUND

### 2.1 Relieving platform quay wall structure

A relieving platform quay wall structure is a frequently applied construction type in the Netherlands. This type of structure is applied to reduce the forces on the underlying retaining wall as well as the tensile forces in the foundation. The relieving platform quay wall structure consists of primary open-ended piles which transfer the forces to the subsoil and anchors the system with the tension piles; the secondary intermediate sheet piles are placed between the primary piles (Quay walls, 2013). Figure 2 gives an impression of the Amazonehaven quay wall. The concrete bearing piles transfer the forces from the relieving platform into subsoil with sufficient bearing capacity.

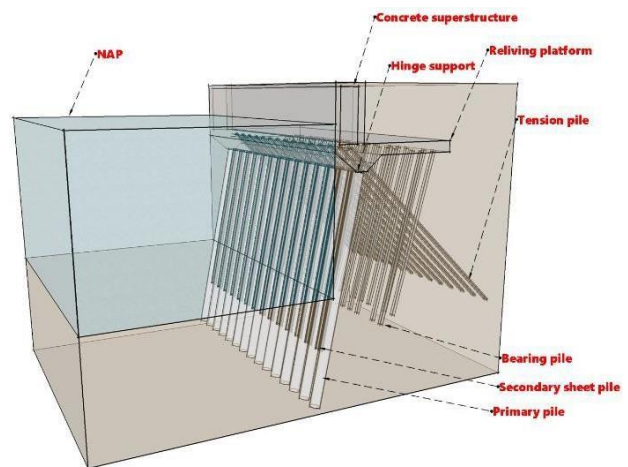


Figure 2. Amazonehaven relieving platform structure

### 2.2 Removal

The partial removal of the Amazonehaven deep seaport in Port of Rotterdam occurred mainly due to expansion of the port. The widening of the port entrance was not due to a technical failure. It was rather based on enabling a continuous facilitation for ultra large vessels, according to new safety regulations imposed by the Port of Rotterdam Authority (Broos & de Gijt 2013).

### 2.3 Observations

After removal of open-ended piles and the intermediate sheet piles, throughout 2011-2013, the mystery (pile toe failure) of Amazonehaven was brought forward. Both elements, primary open piles and secondary sheet piles, were significantly damaged close to pile toe. The damages

could be identified as (1) extreme folding of pile toe, (2) completely closed pile toe, ovalisation at pile toe. The damage in axial direction is estimated to be about 15% to 20% of the total numbers of primary elements. For secondary elements, the damage is estimated to be about 50% of the total numbers (Broos & de Gijt 2014). Moreover, scorched sand at pile toe was observed which reveals the occurrence of an Extremely High Temperature of about 400<sup>0</sup>-500<sup>0</sup> (Broos & de Gijt 2014). The heat is possibly generated by the high friction between soil and pile which could only occur during (pile) driving activity.

#### 2.4 Execution work

The primary elements were partly vibrated and partly driven with an inclination of 5:1 (11.3<sup>0</sup>). It is common to firstly vibrate the elements up to the Pleistocene layer and secondly to drive the elements up to the required depth. A combination of vibratory drivers and impact hammer driving is more practical, saves time and effort and enables obtaining an adequate soil bearing capacity (de Gijt & van Schaik 1991). The vibration of the piles occurred with an RBH 160 vibrator, with the centrifugal force of 1600 [kN]. The driving of the elements commenced with a diesel hammer D62 and in some cases a D100 diesel hammer is used (van Schaik 1990). The pile driving has been performed for the last, more or less, 10 m of the embedded length. In 1990, a driveability analysis is carried out to safeguard the driveability of the elements. The analysis showed that a D/t (1420 mm x 15 mm) ratio of 93, is driveable with a diesel hammer D100 as well as D82, given the Amazonehaven soil condition.

The number of blows during pile driving was up to 400 per 25 cm. After using a D100 the blows per 25 cm reduced to a value of 300 per 25 cm. The number of blows per 25 cm, the refusal-value, is set to minimize the damage to both hammer and pile. Accordingly, the driving time reduced from 8 hours, given a D62, to 1 to 2 hours with a D100. The blow counts remained lower, using a diesel hammer D100, driving time reduced to 1 to 2 hours and blow counts remained between 70 to

120 strikes per 25 [cm] (de Gijt & van Schaik 1991). The drawback of hammer alternation during execution work was apparently both a halt in execution work for nearly two weeks and a probable soil set-up occurrence. Soil set-up refers to soil reaching its full capacity which makes re-driving troublesome.

Furthermore, it was mentioned that in 1990 when pile advancement stopped with a diesel hammer D62; the contractor was forced to pull out the pile. In that specific event, the pile had a complete harmonic shape close to pile toe.

Also, due to pressure to realize the project as fast as possible, the old quay wall, many miscommunications did occur (Parent 1990). Other than this, no driving difficulties were reported during pile installation.

#### 2.5 Major events

Two major events occurred during the technical lifetime of the asset. First, immediately after construction interlock openings were discovered. Second, one out of 20 sections had a settlement of around 50 mm due to overloading (Mourillon 2015).

#### 2.6 Stability of the quay wall

A recent study showed that the stability of the quay wall was untouched even though the damage close to pile toe has been significant (Mourillon 2015). In Mourillon study, the open-ended piles were modelled into PLAXIS. It shows that the moment (due to lateral soil load) on the combined wall increases by 1.4 and the anchor force reduces by 0.8 due to extreme folding damage (which was observed after removal). Also, the soil displacement increases by a factor 3. Nevertheless, the entire structure would have remained stable for a certain period (Mourillon 2015). The main reasons that the quay remained stable are: (1) the quay wall's design was based on a deterministic (conservative) approach, (2) in front of the quay wall the contract depth was reached and not the designed (deeper) depth, (3) the quay wall was not fully

utilized during its technical lifetime and the quay wall was strategically designed for a higher static load than it was intended to be used for (Gemeente werken Rotterdam 1989).

#### 2.6 Failure modes

The modes of failure are introduced by analyzing the available data, photos and the measurements on the extreme folding damage of the piles. Figure 3 depicts the pile toe cross section of the four popular failure modes, as observed in Amazonehaven. In total 12 failure modes have been identified.

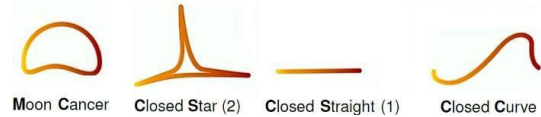


Figure 3. Cross-section of deformed pile toe

#### 2.7 Loads

The main loads on a quay wall are: structural- and installation-loads. The first refers to the static loads which are present during the technical lifetime of the asset. The latter refers to the dynamic loads being applied on the pile during piling (pile driving activity). In this paper, the main focus is on the dynamic load, due to the uniaxial direction of the extreme folding damage close to pile toe.

### 3 RESEARCH METHODOLOGY

#### 3.1 Introduction

The research methodology of pile toe failure focuses on the technical aspects of the failure.

#### 3.2 Technical part

For the technical aspect both Pile Driving Prediction (PDP) and SCIA Engineer are used. PDP is a one-dimensional program where the hammer-pile-soil interaction is studied. Therefore, the general reasons of pile toe failure within the hammer-pile-soil system, are clustered and categorized. Then, the study with a Finite Element Analysis (FEA) program, SCIA, is carried out. In the SCIA model, a sensitivity analysis is carried out on the (static) load-pile-soil interaction.

##### 3.2.1 PDP

AllWave PDP is a prediction program to study the driveability of the primary pile within the hammer-pile-soil system. To this end, the program uses the stress wave theory, to simulate the pile behavior during driving (Middendorp 2004). Therefore, displacements and forces of the hammer, the pile, and the soil during pile installation are determined. The inputs are: hammer characteristics, pile dimensions, and soil characteristics (Kooistra 2008). The outputs are: Soil Resistance to Driving (SRD), driving time, soil fatigue, stress development along the pile and the number of blows required to bring the pile into its designed required depth. The program, therefore, helps the designer to select a suitable hammer with hammer-induced driving stresses below material's yield stress and the number of blows below the refusal threshold. In this fashion, the pile toe integrity during piling is maintained, as well as both the hammer and pile head are not damaged.

##### 3.2.2 SCIA Engineer

SCIA Engineer is an integrated, multi-material structural analysis and design software for various types of structures. In SCIA, it is possible to carry out a calculation which takes into account the (non-linear) plastic behavior of the steel. It is assumed that extreme folding damage has occurred due to development of high stresses, exceeding the material's yield stress. Moreover, SCIA enables studying pile's behavior taking into account geometrically non-linearity.

## 4 ANALYSIS

### 4.1 Introduction

The analysis of pile toe failure includes the technical aspects of the piling disease.

### 4.2 Technical part

The technical part, includes both PDP and SCIA. The failure sources are studied within a hammer-pile-soil system. Therefore, the pile toe failure has a dynamic-, geometric- or geologic- nature.

#### 4.2.1 PDP

(a) soil compaction due vibration; more soil resistance to pile driving is generated, which reduces the downward wave stresses. Therefore, the hammer-induced driving stresses close to pile toe are less than material's yield stress. Figure 4 shows (B) the number of blows over the entire driving depth, given the threshold (R), for both virgin or compacted (15%) soil. The Fatigue Factor (FF) due piling, degradation of the soil resistance, is 0.2. Due to compaction, the piling becomes troublesome (heavy piling), if not impossible.

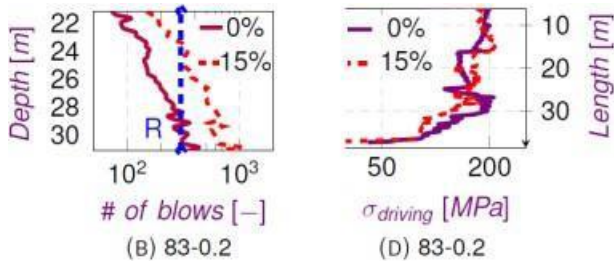


Figure 4. Piling prediction for a D/t-83, Fatigue Factor-0.2

Figure 4 shows (D) the hammer-induced driving stresses over the entire length of the pile. The compaction does not affect stress- development along the pile, significantly.

- (b) pile inclination could cause unequal load distribution due to eccentric impact force at pile head. Therefore, another stress-development is to be expected along the pile.
- (c) Zero Shaft Friction (ZSF) simulates piling while shaft friction is completely eliminated. A ZSF circumstance could happen in case of (pile) stagnation & continuous driving.
- (d) Hammer selection is quite important to ensure sustained driving. For Amazonehaven, a D62 hammer did not comply within the ranges of minimum and maximum hammer energy (Tara 2016).
- (e) Driving stresses are about 60% lower than the material's yield stress (483 MPa) close to pile toe, for Amazonehaven Standard to Normal Soil Condition (SNSC). However, in case of Medium to Hard Soil Condition (MHSC), the stresses are extremely high close to pile toe as depicted in Figure 5.

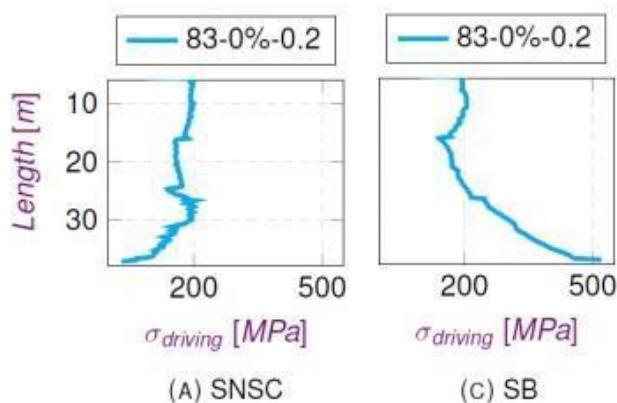


Figure 5. Piling prediction for a D/t-83, Fatigue Factor-0.2

- (f) Temperature reduces both strength and stiffness of the steel which makes it less resilient to folding. The temperature elevation is argued to be caused by a high friction between soil and pile. A local Temperature Elevation (TE) together with, e.g., an initial imperfection will be detrimental to maintain pile toe integrity during piling.
- (g) Initial imperfection leads to pile toe failure, in terms of extreme folding damage when it is accompanied with a Locally Extremely Hard Spot (LEHS). In case of sustained driving, unequal soil distribution inside & outside occurs, which leads to a gradual inwards deformation due to clamped solid soil next to pile toe. Figure 6 shows, the imperfection as modeled in SCIA and its final deformation.

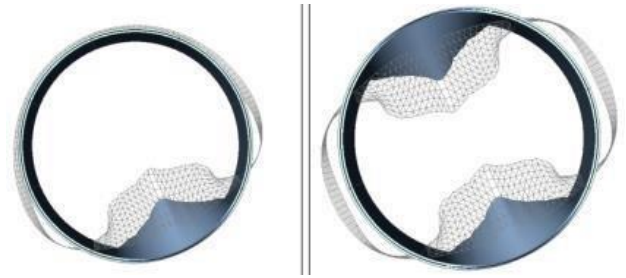


Figure 6. Top view pile, initial dent and its final deformation

- (h) Plugging refers to the dimension of the pile which fosters a plugged response of the pile. The dimension of Amazonehaven's piles is evaluated to be significantly large which does not facilitate plugging. Plugging is, therefore, not taken into account.
- (i) Steel fatigue appears when the number of blows become extremely high. However, the head of the pile is more sensitive to fatigue rather than the toe, because the driving stresses at the toe are shown to be less than at head in Standard to Normal Soil Condition (SNSC). Therefore, it is argued that the steel fatigue not led to pile toe failure as there is no documentation of extreme deformation at pile head. Fatigue of the material is not taken into account.
- (j) Fabrication of the piles could affect material's response to unevenly distributed stresses. This study does not take fabrication into account.
- (k) Plugging becomes problematic in cohesive soil properties, where the soil inside the pile acts as a rigid body. Amazonehaven, sandy soil, does not foster the plug phenomenon.
- (l) Locally Extremely Hard Spot (LEHS) is detrimental to pile toe and could have caused pile toe failure. A combination of LEHS and initial (dent) imperfection will worsen the extent in which pile toe failure occurs.
- (m) Steel fatigue appears when the number of blows become extremely high. However, the head of the pile is more sensitive to fatigue rather than the toe, because the driving stresses at the toe are shown to be less than at head in Standard to Normal Soil Condition (SNSC). Therefore, it is argued that the steel fatigue not led to pile toe failure as there is no documentation of extreme deformation at pile head. Fatigue of the material is not taken into account.
- (n) Fabrication of the piles could affect material's response to unevenly distributed stresses. This study does not take fabrication into account.
- (o) Plugging becomes problematic in cohesive soil properties, where the soil inside the pile acts as a rigid body. Amazonehaven, sandy soil, does not foster the plug phenomenon.

- (p) Locally Extremely Hard Spot (LEHS) is detrimental to pile toe and could have caused pile toe failure. A combination of LEHS and initial (dent) imperfection will worsen the extent in which pile toe failure occurs.
- (q) Pile inclination refers to a non-uniform soil property (stiff and weak) at the toe as depicted in Figure 7. Pile inclination is assumed to exacerbate the occurrence of such non-uniform soil properties. Therefore, pile toe experiences at one edge higher stresses whereas at the other edge the stresses are limited to impact stresses at the head.

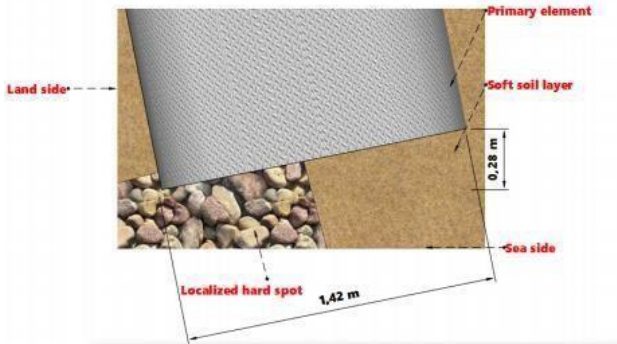


Figure 7. Pile inclination, non-uniform bed

- (r) Zero Shaft Friction (ZSF) plays a role, in case of Soft Rock (SR) phenomenon. In this situation, the overlying layers have poor properties whereas the bed enjoys stiff-rock-ish soil properties. Therefore, the stresses at the toe are much higher than the impact stresses at the head.
- (s) Soil fatigue affects the driveability. Due to piling, soil degradation occurs, which means that due to vicious blows the soil loses its strength. Therefore, impact driving becomes easier. A soil Fatigue Factor (FF) -value of 0.2 reduces the Soil Resistance to Driving (SRD) considerably, where theoretically stress wave travels through the pile almost freely.
- (t) Soil set-up affects the driveability. In this fashion, mainly clayish soil regains its initial strength for re-driving after a delay. Therefore, soil set-up has more or less the same effect as soil compaction or a situation without accounting for soil fatigue.

#### 4.2.2 SCIA Engineer

The main reasons to pile toe failure in Amazonehaven are shown to be: initial imperfection and pile inclination. The pile is modeled in SCIA to carry a sensitivity analysis regarding the above mentioned causes to pile toe failure. Figure 8 and 9 show the Yield Stress Momentum (YSM) with (A) increasing initial dent and (B) a decreasing soil homogeneity at pile toe, given various  $D/t$  ratios, for respectively centric and eccentric loading. The Yield Stress Momentum (YSM) is the point in which the material's yield stress reaches for the first time. Therefore, it could be argued that a pile with a lower YSM-value be locally more prone to extreme folding damage.

The YSM decreases drastically in case of decreasing Imperfection Ratio (IR), where  $IR = 1$  means a perfectly rounded pile. However, it decreases less drastically for Homogeneity Ratio (HR) at pile toe, where a  $HR = 1$  means a uniform (stiff) soil-bed. A decreasing HR means a non-uniform (stiff and weak) soil-bed.

Also, due to eccentric loading, YSM-value is lower which pinpoints inclined piling could be detrimental for maintaining pile toe integrity during piling.

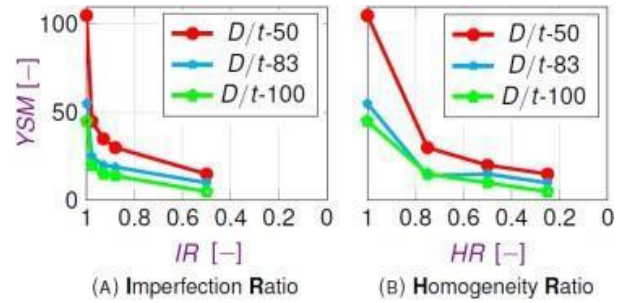


Figure 8. Yield Stress Momentum for centric loading

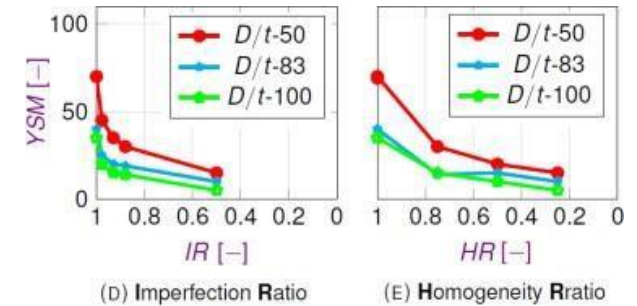


Figure 9. Yield Stress Momentum for eccentric loading

## 5 CONCLUSIONS

In this paper a variety of causes to pile toe failure are discussed. The main reasons for such a failure are shown to be (1) initial (dent) imperfection and (2) pile inclination. The research showed that given a Standard to Normal Soil Condition (SNSC), the hammer-induced driving stresses are lower than material's yield stress close to pile toe. However, given a Medium to Hard Soil Condition (MHSC) the stresses become extremely high close to pile toe. The latter is very doubtful to be the case given Amazonehaven soil conditions. The finding is valid given a diesel hammer D100-13 and a range of  $D/t$  ratios of 20 to 100. Furthermore, sensitivity analysis shows that the initial dent fosters development of extreme folding damage during piling more than a non-uniform soil layer at pile toe.

The research also discussed the need for remedies to piling disease (pile toe failure). To avoid such a risk, either pre-piling remedies must be implemented or post-piling remedies. It is apparent that post-piling remedies have a higher value of financial burden for the client. It is, therefore, very recommended to introduce creative and process-based remedies in the piling phase, next to conventional solutions.

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