Penetration of driven piles into pre-crushed blasted rock: Case Jätkäsaari

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Abstract. This paper deals with the ability of three driven pile types to penetrate a 0/300 mm pre-crushed blasted rock used as a fill material in the area of Jätkäsaari, Helsinki. The aim of this study was to test whether driven piles can be used as a foundation method in this fill instead of the more expensive drilled piles. In order to achieve that, a test area was created in Ahdinallas, Jätkäsaari. Piles with similar capacities of 300x300 reinforced concrete, RR170/12,5 steel pipe and TRM170/13 ductile iron were driven. The ground conditions in the test-piling area comprised of a 25-30 meter pre-crushed blasted rock layer, underneath of which was a 2-5 meter moraine layer. Thirty-three piles were driven in total, all equipped with a rock shoe. The area was laser-scanned prior and after piling. A pile driving record was kept, and inclinometer, torch, and PDA/CAPWAP measurements were made on the piles. All the piles that penetrated only the pre-crushed blasted rock stayed intact and were successful. Steel pipe and ductile iron piles however, penetrated the material with more ease and less hits/meter. As long as a pile would surely penetrate only a pre-crushed blasted rock layer, all of the tested pile types would be suitable for use as a foundation method. If there is a chance, however, that larger rock pieces are present, steel pipe piles or ductile iron piles would be a safer choice.

1. Introduction
The area of Jätkäsaari, Helsinki has been under constant evolution throughout the last 100 years. It started as four separate islands that housed a few summer cottages and then became the biggest port of Finland. Nowadays, it is developing into a new cultural and residential area. Sea fills have played a large role in the development of Jätkäsaari; from turning the four islands to a land area for the port, to expanding the land for the upcoming residential area.

Blasted rock is one of the main fill materials that has been used for the newer land expansions in Jätkäsaari. One of the main differences of this man-made material to natural ones is that it can contain pieces of larger than 600 mm to lower than 25 mm. This variation in grain sizes, as well as the existence of the large pieces, makes drilled piles the only deep foundation method that can penetrate it. Drilled piles are about three-four times more expensive than driven piles [1] and thus increase the piling costs significantly.

The City of Helsinki decided to test the pre-crushing of the blasted rock and use that 0/300 mm material as a fill in Ahdinallas, Jätkäsaari. This paper deals with the ability of three driven pile types to penetrate this pre-crushed blasted rock fill, and whether they can be used as a foundation method instead of the more expensive drilled piles. In order to achieve the aforementioned, a test site was created in
Ahdinallas, and three piles types of about equal capacity were chosen to be driven; 300x300 mm reinforced concrete piles, RR170/12,5 steel pipe piles and TRM170/13 ductile iron piles. Thirty-three piles were driven in total out of which three were inclined, six 15-meter long, twenty-seven 30-meter long and some were installed in a tighter pattern than the rest. Furthermore, the area was laser scanned prior to and after piling to check for displacements. A pile driving record was kept during the driving of the piles and different types of pile measurements were made to check their integrity, bearing capacity, straightness and movements after driving including inclinometer, torch, PDA and CAPWAP measurements.

2. Site description

The area of focus for this study is Ahdinallas, located in Jätkäsaari, Helsinki (Figure 1). The first fills in Ahdinallas were done around the years 1960-1980. Construction of this area has been planned to start in 2020, and pre-construction phases have started since 2016 and are currently underway. Preconstruction has involved dredging of clay layers in many stages and peeling off contaminated sediments. The dredged areas have been mainly filled with pre-crushed blasted rock with a visually evaluated grain size of 0/30 0 mm, and the area has been deep-compacted by dynamic compaction. [3].

2.1. Ground conditions

The test site was divided into three areas, A, B and C (Figure 4). The ground conditions underneath the test piling areas B and C (Figure 2) comprise of a 25-30-meter pre-crushed blasted rock layer, underneath of which there is a 2-5-meter moraine layer. The ground conditions underneath area A (Figure 3) differ. On the south side of the test site there is a blasted rock layer which starts at the rear gate from ground level until approximately level -25...-26. The layer falls towards the north with an inclination of 1:1,6. As such, in area A, underneath the pre-crushed blasted rock layer there is a blasted rock layer, underneath of which is the moraine layer.

![Figure 1](image-url): Location of the area of focus Ahdinallas. [2, modified]
2.2. Pre crushed blasted rock
Blasted rock is a material that is detached from the intact rock by blasting, and it can contain pieces of over 600 mm in diameter to lower than 25 mm. The most common sources of blasted rock in Finland are granite, pegmatite, schist, diabase, and gneiss [4]. For blasted rock to become pre-crushed blasted rock, it has to undergo a crushing process. During crushing, the material is subjected to forces higher than its strength limit, and thus breaks to smaller pieces [5]. In order to reach the desired grain size, there can be two or three stages of crushing; pre-crushing, secondary and/or tertiary crushing. As suggested by its name, pre-crushed blasted rock is the end result of the pre-crushing of blasted rock. Pre-crushing is mainly used to reduce the initial grain size of the blasted material, after which it can be fed to other crushers or it can be used as it is [6]. The pre-crushing of the blasted rock used in Ahdinallas was made using the Metso C130 jaw crusher. The end result of the pre-crushing was 0/300 mm.

3. Test piling
The testing of the penetration of the selected driven piles into the pre-crushed blasted rock started on 7.10.2019 and ended on 11.10.2019. On 10.10 the final pile was installed and on 11.10 the protruding pile parts were cut. A 5-ton Junttan Hydraulic Impact hammer was used on a Junttan PM25 piling machine. The following piles were used: 170/12.5 steel pipe piles, 170/13 ductile iron piles and 300x300 reinforced concrete piles. Ductile iron pile units had a length of 5 m, steel pipe pile units 10 m, and reinforced concrete pile units 15 m. Thirty-three piles were driven in total (Figure 4); seven were 15-meter reinforced concrete piles, eight were 30-meter reinforced concrete piles, nine were 30-meter steel pipe piles and nine 30-meter ductile iron piles.
During the driving of the piles, it was obvious that the effects of deep compaction were apparent on the first 4-5 meters, where more hits were needed for the piles to penetrate. After that the material seemed to be no longer compacted and the piles penetrated it with a relative ease. The 30-meter reinforced concrete piles that were driven in area A broke while trying to penetrate the blasted rock layer. Moreover, due to lack of safety cushion on the driving of some reinforced concrete piles, damages were also visible on the top parts of the piles. One 30-meter ductile iron pile (nr 7) also broke during its installation in area A, probably due to coming across a very large rock piece (Figure 3). Ductile iron pile 8 and steel pipe pile 9 installed next to it did not face that problem. The 15-meter reinforced concrete piles and the ductile iron and steel pipe piles (except for pile 7) were installed successfully in area A. In areas B and C all the pile types managed to penetrate the material and remain unbroken.

4. Pile measurements

4.1. Laser scanning
The ground surface of the test piling area (Figure 4) and around 20 meters outside of it were laser-scanned prior to the piling and after it, in order to define the displacements of the ground surface. The accuracy of the scanning was set to under 10 mm. From the surfaces prior to and after piling a new surface was created, showing the difference between them. Based on that, the settlements in the piling area were between 20-90 mm, with the highest values being around the reinforced concrete piles in areas A and C.

4.2. Straightness measurements
In order to define the straightness of the driven piles, the torch method was used. A torch was taped to a measuring tape and lowered inside the steel pipe and ductile iron piles, and the depth at which the light stopped being visible was taken down. This measurement could be performed successfully because all the steel pipe and ductile iron piles (except nr 7) had remained unbroken and thus dry on the inside. This method was not used in reinforced concrete piles because even though most units had an approximately 60 mm hole in the middle, the hole was too small for the available torch. In addition to the torch method, the inclination of the parts of the piles that were above surface was defined through the laser scanning data. For the ductile iron piles and steel pipe piles, the laser scanning data and the pile curvatures through the torch method were combined, and the profiles of the piles were created (Figure 6). Moreover, assuming that the rest of the piles moved in accordance to the top parts, a first image of the pile profiles of reinforced concrete piles could also be made (Figure 5).
Most of the piles had a direction towards the sea, as expected. This direction is towards the left in figures 5 and 6. Furthermore, 86.6% of the straight piles had a deviation less than 2° from the straight line and 46.6% a deviation less than 1°, showing that the piles managed to remain quite straight after penetrating this material.

4.3. Inclinometers
Three automatic inclinometers were installed inside three different test piles. Those piles were straight ductile iron pile 31, inclined steel pipe pile 20 and straight reinforced concrete pile 23. The inclinometers installed in piles 31 and 23 were the same length as the piles. The inclinometer installed in pile 20 was 15-meter long, and the measurements started at -18, with 0 being the top of the pile. In all the piles, direction +A was towards the sea front and –A away from it, and direction –B towards the city and +B away from the city.

For the duration of the test piling week the movements of all three piles remained quite small, under 13 mm. Ductile iron pile 31 had the biggest displacements in both A and B directions, +11.4 and -12.6 mm respectively. The biggest displacements for all the piles happened at times when there was no pile installation going on. The installation of nearby piles affected the piles with displacements lower than 10 mm, and only caused changes in the direction of the movements in the A direction. Moreover, it was obvious that displacements were bigger a few weeks after the end of the test site due to the fact that pre-construction phases for nearby works such as bridge foundations or an upcoming pile slab had started. However, even then, the biggest displacement was 30 mm. As a result, even though only the top was compacted, still this material does not allow for big movements in the piles.

4.4. Pile driving record
A pile driving record was kept for all the piles, consisting of the hits/meter for each pile and the dropping height of the weight. A Junttan PM 25 piling machine was used for piling, with a 5-ton hydraulic drop weight. The weight was dropped from a height of 200 mm.

Figures 7, 8 and 9 show the hits/meter corresponding to the installation depth of four representative piles from each piling area. In all the areas reinforced concrete piles (RTB) had bigger values of hits/meter and consequently they had the highest average of hits/meter, which was 155. Steel pipe piles (RR) had an average of 88 hits/meter and ductile iron piles (TRM) of 92.5. However, the cross-sectional area of reinforced concrete piles was almost 4 times bigger than that of steel pipe and ductile iron piles. As such, steel pipe and ductile iron piles had an approximately 2 times higher result of hits/m². The average maximum amount of hits/meter for steel pipe piles and ductile iron piles was quite close and
for both in the final meters, with steel pipe piles having a little smaller number and depth. It must be noted however, that most of the ductile iron piles were driven until they reached the hard bottom. The hits/meter were higher in the initial meters for all the piles, due to the compacted layers. However, the majority of reinforced concrete piles reached their maximum amount of hits during the first meters of piling, showing that they had the most difficulty in penetrating the compacted layers. In area A (Figure 7), there was a big increase in the values of hits/meter after depth -15 for reinforced concrete piles, corresponding to both their splicing and reaching the blasted rock layer. The lower values after that represent the breaking of the piles. In all the areas, the hits/meter were higher again in the bottom meters, due to reaching the moraine layer.

![Figure 7. Hits/meter-depth graph for piles in area A.](image1)

![Figure 8. Hits/meter-depth graph for piles in area B.](image2)

![Figure 9. Hits/meter-depth graph for piles in area C.](image3)

4.5. PDA measurements
Pile Driving Analyzer measurements were conducted in thirteen piles as part of this study. Those measurements were done with the Pile Driving Analyzer®-Model 8G, and the loading was done using the Junttan HHK 5A hydraulic piling machine. The mobilizing static resistance was estimated with the CASE-method by using the RMX estimator and the damping factor $J_c=0.5$. The following graph (Figure 10) shows the measured RMX-values from the measured piles, the calculated mean and minimum values, as well as the geotechnical compression capacity $R_{c;d}$. $R_{c;d}$ was calculated for each of the pile materials using the following equations (1) and (2). 44.4% of steel pipe and ductile iron piles were measured, and 55.5% of 30-meter reinforced concrete piles. As such, based on Table 4.10 of RIL254-2016 [12], the correlation factors $\xi_s=1.45$ and $\xi_e=1.3$ were used, and since signal matching was used, they were also multiplied by 0.9.

$$R_{c;d}=\frac{R_{c;k}}{\gamma_t}$$  (1)
\[
R_{c,k} = \min \left\{ \frac{R_{c,m}}{\xi_5} ; \frac{(R_{c,m})_{\text{mean}}}{\xi_6} ; \frac{(R_{c,m})_{\text{min}}}{\xi_6} \right\}
\] (2)

Figure 10: Measured RMX values as well as calculated \( R_{c;m;\text{mean}} \), \( R_{c;m;\text{min}} \) and \( R_{c;d} \) values from the PDA-measured piles. The blue color depicts ductile iron piles (left), the red steel pipe piles (middle) and the grey reinforced concrete piles (right).

Reinforced concrete piles had the lowest resistance values. It must be noted however that only one of the reinforced concrete piles reached the hard bottom layer. Between steel pipe and ductile iron piles, steel pipe piles had a higher \( R_{c;m;\text{mean}} \) value, but their \( R_{c;m;\text{min}} \) values were really close. In all the intact piles the stresses did not exceed the maximum allowed limits. In all the materials some piles were measured one day after their installation and they did not show any significant changes in their RMX values. For Piling Classes (PTL) 1 and 2, as defined by the Finnish Piling Manual PO-2016 [12], the calculated \( R_{c;d} \) values of the piles were compared to the maximum recommended \( R_d \) values for the design phase by SSAB [10] for steel pipe and ductile iron piles, and by the Finnish Piling Manual PO-2016 [12] for reinforced concrete piles. The \( R_{c;d} \) values of steel pipe piles and ductile iron piles, 937,3 kN and 968,7 kN respectively, were higher than the recommended \( R_d \) values for PTL1, but around 18% smaller than the recommended ones for PTL2. The \( R_{c;d} \) of reinforced concrete piles, 827,6 kN, was 9% lower for PTL1 and 18,4% lower for PTL2 compared to the recommended values for the design phase. As such, if these piles were to be used as foundations in an upcoming building, in which case PTL2 would be selected, the maximum allowed \( R_d \) values for the piles should be lowered in the design to fit the measured and calculated ones.

4.6. CAPWAP analysis
A CAPWAP analysis was made in two reinforced concrete piles, one ductile iron pile and one steel pipe pile. The results can be seen in the following table (Table 1). The measurements in P21 were done one day after installation of the pile whereas the rest were done exactly after the installation of the piles.

![Results from PDA measurements](image)

Based on Table 1, steel pipe pile P26 had the highest total resistance (RU). However, not all of those piles reached the hard bottom layer, and as such their total resistances cannot be compared directly. The piles that reached the hard bottom layer (P23, P26, P27) had most of their resistance coming from the toe resistance (EB) and had higher resistance values the more securely they were on the harder layer. Reinforced concrete piles had higher values of shaft resistance compared to the two other pile types.
5. Cost and environmental effects

Upon the completion of the test piling week, 345 meters of reinforced concrete piles, 269 meters of steel pipe piles and 280 meters of ductile iron piles were used. The drilling machine was used for four days to complete the test site. In order to make a comparison, we could assume that the same test site would have been done using drilled piles. The selected drilled pile would have been an RD170/10 pile, being of similar capacity as the used driven ones. According to the thesis of Juha Häkkänen [4], the amount of time spent for the driving of a 40-meter RD220 pile to a blasted rock layer was about 2 piles per working shift. By making an approximation that 33-meter RD170/10 piles would be used, and in somewhat easier ground conditions, we could double the amount, and say 4 piles per shift could be installed in the conditions of the test site. Having 33 piles in total, it would take 8,25 days to only install the piles, which is twice the amount of days that the installation of the driven piles took.

Apart from the piling execution costs, there is a significant difference in the prices of the driven piles compared to the drilled ones. According to interviews with contractors in 2019 the price of steel pipe piles is 48€-57€/m, of reinforced concrete piles 16€-33€/m and of ductile iron piles around 50€/m. The price of an RD170/10 pile is about 210€/m [4]. Taking a middle price for steel pipe and ductile iron piles of 52€/m and 25€/m respectively, the following table (Table 2) shows the costs for each of the driven piles in this project and their total cost. Moreover, the table presents the cost in the scenario where only 33-meter drilled piles would have been used, excluding the six 15-meter piles from the calculations of the drilled piles. Based on Table 2, the cost of the drilled piles is 5,1 times higher compared to the cost of the used driven piles, without taking into account the piling execution costs and the 15-meter piles.

In addition, the price for the pre-crushing of the blasted rock is 2,5 €/t [7], and with a density of 1,6 t/m³ [8] the cost is 4 €/m³. As such, the price to fill just the area of the test piling, which is 29467 m³ (assuming that the area which consisted of blasted rock in area A would also be filled with the pre-crushed rock, and the pre-crushed rock would be from levels 0…-28) is 117868€. Adding to that the cost of the used driven piles in the test site (Table 2), the cost is still 17,4% lower than only the cost for the drilled piles. It is hence obvious, that pre-crushing the blasted rock and using driven piles as a foundation method is more economical than the combination of uncrushed blasted rock and drilled piles.

Furthermore, concerning the environmental aspects of these piles, from manufacturing until they reach the construction site, Table 2 shows the CO₂ equivalent emissions of each pile type, as well as the total CO₂ eq. emissions for all the 30-meter driven piles. 300x300 reinforced concrete piles have 65 kg/m of CO₂ eq. emissions [9], steel pipe piles have about 2,47 kg/kg [10] and 170/13 ductile iron piles 59,71 kg/m [11]. Moreover, the CO₂ equivalent emissions were calculated for the case where the twenty-seven 30-meter driven piles would be replaced by twenty-seven 33-meter drilled piles. In steel pipe piles, the 2,47 kg/kg is converted to kg/m by multiplying it by the weight of steel pipe piles, 48 kg/m. If drilled piles were chosen, the CO₂ equivalent emissions would show an increase of 62%, compared to the CO₂ equivalent emissions from the used driven piles. Moreover, drilled piles require grouting, as well as use of water during their installation, increasing further their environmental effects.

### Table 1: Results from the CAPWAP analysis

| Number | Pile Type | LP [m] | Jc | SF [kN] | EB [kN] | RU [kN] |
|--------|-----------|--------|----|---------|---------|---------|
| P21    | RTB       | 28,5   | 0,59| 1243    | 177     | 1420    |
| P23    | RTB       | 29     | 0,41| 933     | 981     | 1914    |
| P26    | RR        | 30     | 0,41| 392     | 1708    | 2100    |
| P27    | TRM       | 30,6   | 0,46| 552     | 921     | 1473    |

*Numbers represent the order of pile installation.*

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[9] Jc, SF, EB, RU: Geotechnical resistance parameters.

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[2] Jc, SF, EB, RU: Geotechnical resistance parameters.
### Table 2: Cost and CO₂ calculations for driven and drilled piles

| Pile type                | Driven meters | Price per pile | Total cost | CO₂ eq. emissions | Total CO₂ eq. emissions / 30-m piles |
|--------------------------|---------------|----------------|------------|-------------------|--------------------------------------|
| Reinforced concrete      | 345 m         | 25 €/m         | 8625 €     | 65 kg/m           | 16575 kg                             |
| Ductile iron             | 280 m         | 50 €/m         | 14000 €    | 59.71 kg/m        | 16719 kg                             |
| Steel pipe               | 269 m         | 52 €/m         | 13988 €    | 2.47 kg/kg        | 31892.6 kg                           |
| Drilled pile             | 891 m         | 210 €/m        | 187110 €   | 2.47 kg/kg        | 105637 kg                            |
| Cost of all driven piles |               |                | 36613 €    |                   |                                       |
| Cost of driven piles and |               |                | 154481 €   |                   |                                       |
| pre-crushing             |               |                |            |                   | 65186.6 kg                           |

### 6. Conclusions

The aim of this study was to investigate whether driven piles can penetrate a pre-crushed blasted rock fill of 0/300 mm located in Ahdinallas, Jätkäsaari, Helsinki. This was made possible by the driving of 170/12.5 steel pipe piles, 170/13 ductile iron piles and 300x300 reinforced concrete piles on a test site in Ahdinallas.

Pre-crushed blasted rock proved to be a suitable fill material since it can be penetrated by all the three tested driven piles successfully, a compacted surface has small settlements (max 90 mm) after the driving of piles, and the piles are not affected by the installation of nearby piles, with 12.6 mm being the biggest movement during the test site. However, reinforced concrete piles had the highest average of hits/meter, but the biggest cross-section, and a harder time penetrating the first compacted meters compared to the other two pile types. Steel pipe piles and ductile iron piles had very similar behaviors when penetrating the pre-crushed blasted rock and did so more easily compared to reinforced concrete piles. In area A the average amount of hits/meter for all the piles was higher due to the penetration of the blasted rock layer, which also resulted in the breaking of the 30-meter reinforced concrete piles and of one ductile iron pile driven in that area. Furthermore, the pre-crushing of the blasted rock and the use of driven piles proved to be more economical (17.4% lower costs) than the use of driven piles on blasted rock. In addition, the use of driven piles was more environmentally friendly (62% less emissions) compared to drilled piles.

In conclusion, all the tested piles can be used as a foundation type in pre-crushed blasted rock fills, providing both economic and environmental benefits. Nevertheless, if there is a possibility of larger than approximately 300 mm rock pieces, or the piles have to be installed very close to each other, steel pipe piles or ductile iron piles should be used. In whatever pile type that will be used, in order to ensure the appropriate resistances, the piles should be driven to a harder bearing layer.

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