USE OF HIGH-STRENGTH STEEL IN STEEL PIPE PILES

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ABSTRACT

The aim of this Bachelor's thesis was to investigate the influence of higher steel grades on resistance factor in steel micro pipe piles to subsequently achieve more economical solutions using smaller pile diameter, but bigger structural limits. Buckling calculations were used as the main tool for this research.

The calculations were done according to the Eurocodes and Finnish Piling Manual –PO-2016. For convenience purposes calculations were done in Excel, to provide a comparison between graphs of steel pipe sizes allowing to see the degree of benefits in the use of the pile. Graphs reflect the interrelation between structural resistance and undrained shear strength in piles. Before making the calculations, the Eurocode was used to determine the characteristic structural resistance of each pile using higher steel grades. PO-2016 was used to determine the buckling factor of driven piles. Tables of structural resistance in correlation with undrained shear strength were made for ease of use.

The results of the thesis show that eleven steel piles with a smaller size in tandem with a higher steel grade can be used to achieve higher structural and geotechnical resistance.

Keywords High strength steel, Pile Buckling, Driven Pile, RR Pile.

Pages 31 pages including appendices 10 pages

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1 INTRODUCTION

1.1 Basis for research

This Bachelor's thesis was commissioned by SSAB Europe Oy. SSAB is a Nordic and US-based international steel company. On the global market SSAB is the leading producer for Advanced High-Strength Steels (AHSS) and Quenched & Tempered Steels (Q&T), strip, plate and tubular products. SSAB is aiming to create a stronger, lighter and more sustainable world. (SSAB Oy)

The soil in Northern Europe is extremely challenging for all types of groundwork construction, because it is composed of clay, gravel, moraine layers and the world's hardest bedrock. Consequently, drilled and driven piles are used to reach the bedrock. (Sotkamon PP). Piles in general are elements that are pushed into the ground and even bedrock to act as solid support elements for super-structures, which directly or indirectly transmit loads and limit deformation. Pile foundation is a vertical slender structure; therefore, buckling instability in structural design cannot be underestimated. (Bhattacharya, 2005, 815)

Over the last years engineers have been designing, installing and improving piling technologies. The need for high-strength and high-rigidity pipe piles has been rising due to the need for greater bearing capacity, implementation of advanced design methods and overall larger loadings. The major advantages of using high strength steel stem from reduced weight and smaller cross-sectional dimensions. Design stresses can be increased, while thickness is reduced, which leads to significant weight savings. (Tanaka, 2016, 24)

The study is concentrated on geotechnical resistance and buckling resistance of "micropiles" when high grade steel is used. Today there is a need to know what effect even higher steel grades have on steel pipe piles, in order to reduce environmental impacts of manufacturing, transporting and installing foundation parts, and to reach an even higher level of efficiency and capacity utilisation of steel structures.
In this study, High Strength Steels are defined as steel with yield limits of 600MPa, 630Mpa, 650MPa, 680MPa and 700 MPa.

1.2 Objectives

The main goals of this study are examine how higher steel grades affect resistance of steel pipe piles, calculate geotechnical and buckling resistance according to the Finnish piling manual PO-2016, create comparison graphs for selected pile sizes and steel grades, calculate local-buckling resistance (compression and bending resistances).

1.3 Implementation

This investigation takes the form of a quantitative research. Based on calculations of geotechnical resistance and buckling resistance the data will be collected and compared. The main interest of the study is to find more economic solutions and reduce the number of piles by improving their load-bearing capacity without increasing the size, or instead, for ease of installation, reduce their size without decreasing the load-bearing capacity.

1.4 Work limits

The work is limited to calculations of micropiles (RR75 => RR/RD320), empty steel pipe piles (no composite effect with concrete), use of Finnish national piling norms (buckling, etc.) and steel grades S600, S650 and S700.

2 HIGH-STRENGTH STEEL

2.1 General information

Primarily, high-strength steels are used in products where it is important to reduce mass while maintaining a high level of strength. Utilizing high-strength steels inevitably leads to a decrease in ductility characteristics, and, above all, to a decrease of brittle fracture resistance. That is why the emphasis during the development of manufacturing technology for high-strength steels is made on strength properties of the final product, as well as ductility, weldability and viscosity at negative temperatures, which is provided by low carbon content. This makes it possible to manufacture products of complex shapes with guaranteed durability.

As a rule, high-strength state is directly linked to achievement of a metastable structure that has a high level of micro-distortions, a high density of crystalline structure defects and, consequently, an enhanced diffusion predisposition. (Metalolom)

The use of high-strength steel is an eco-friendly solution. If high strength steel is utilised during the stage of foundation construction, the total energy requirement is reduced. Some of the typical qualities that these types of steel have include great yield strength, excellent impact toughness, exceptional weldability and high fatigue strength which are all significant for mechanical pile joints. (Uotinen, 2013, 1179)

2.2 **Corrosion**

Electrochemical corrosion of metal structures is a significant issue that impacts a number of industries, especially those that depend to a great extent on the use of buried metal structures. Corrosion in steel pipe piles can cause reduction of cross-section area, subsequently decreasing axial and lateral capacity. If corrosion reaches crucial limits, durability and security may be jeopardized. It is important to consider corrosion during design steps, as it is not easy to repair or investigate an already installed pile. (Steelcast)

The main factors that influences corrosion appearance are moisture content, degree of aeration, pH, resistance of soil, chlorides and microbiological activity of the on-site soil. If piles are installed in soils rich with oxygen where sulphate-reducing bacteria and other microbes are present, the rate of corrosion is significantly boosted. Oxygen levels decrease at a greater soil depth, which means that corrosion levels are reduced too. (Steelcast)

When such components as iron and chromium are present in steel, they help combat corrosion. Pure chromium has a high chemical resistance due to a thin layer of protective oxide forming on its surface. (Steelcast)

2.3 **Benefits of using high strength steel in driven and drilled pipe piles**

Structural bearing resistance in compression and moment resistance increase linearly as yield strength rises. For example, resistance increases up to 23-27% when a switch is made from S550MC to S700MC. Such a change will provide favourable mechanical properties and higher corrosion resistance in comparison to conventional carbon steel grades.

The use of high-strength steel in RRs piles will help gain a cost-efficient foundation solution for a wide range of building projects, diminish rates of displacement and soil disturbance, reduce vibration, ease installation and facilitate the use of lighter installation equipment. The use of high-strength steel in RDs piles will bring the same benefits and additionally the opportunity to use smaller pilot and ring bits. (Rautaruukki Corporation, 2010)

2.4 **Design rules for application of high strength steels**

The European Standard EN 1993-1-12, "Eurocode 3: Design of steel structures: Part 1-12" covers the rules permitting steel structures to be designed with steel up to S700.
The national annex of EN1993-1-12 standard of the country in question should also be used for reference. The additional part of EN 1993-1-12 provides tables with recommended steel grades and their nominal yield strength. Table 1 and Table 2 represent nominal values of yield strength f_y and ultimate tensile strength f_u according to different thicknesses and type of products.

Table 1. Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel(EN1993-1-12 Table 1/2007, s. 5)

EN10025-6 Steel grade and qualities	Nominal thickness of the element t mm					
	t≤50mm		50mm<t≤100m		100mm<t≤150mm	
	f_y[N/mm^2]	f_u[N/mm^2]	f_y[N/mm^2]	f_u[N/mm^2]	f_y[N/mm^2]	f_u[N/mm^2]
S 500Q/QL/QL 1	500	590	480	590	440	540
S 550Q/QL/QL 1	550	640	530	640	490	590
S 620Q/QL/QL 1	620	700	580	700	560	650
S 690Q/QL/QL 1	690	770	650	760	630	710

Table 2. Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled flat products (EN1993-1-12 Table 2/2007,5)

EN 10149 – 2[a)]	1.5 mm ≤ t ≤ 8 mm		8 mm < t ≤ 16 mm	
	f_y[N/mm^2]	f_u[N/mm^2]	f_y[N/mm^2]	f_u[N/mm^2]
S 500MC	500	550	500	550
S 550MC	550	600	550	600
S 600MC	600	650	600	650
S 650MC	650	700	630	700
S 700MC	700	750	680	750
Verification of the impact energy in accordance with EN 10149-1 Clause 11, 5 should be specified				

Eurocode claims that the steel material to be used should have sufficient ductility. The ductility is given by setting limits for the following characteristics. The requirements for ductility of the material are given in part 3.2.2.(1) EN 1993-1-12 along with recommended values. From there follows:

$$f_u/f_y \geq 1{,}05 \qquad (1)$$

elongation at failure not less than 10 %;

$$\varepsilon_u \geq f_y/E \qquad (2)$$

where:

f_u - ultimate tensile strength
f_y - nominal values of yield strength
ε_u - the elongation at failure
E -elastic modulus

3 GEOTECHNICAL AND STRUCTURAL DESIGN

3.1 Basics of design

Design process is the most important stage of transferring an idea into a product. EN 1997 Eurocode 7 must be used for doing geotechnical and pile design, but unfortunately, it does not cover pile buckling in detail. In this case in Finland RIL 254-2016 Piling Manual PO 2016 must be used. PO 2016 describes the general principles of ground planning and pile designing.

According to PO-2016 all drilled piles are drilled into solid bedrock. Based on this the geotechnical resistance (resistance of bedrock below pile toe) is always adequate and there is no need to check it either by calculations or by load tests (PO-2016 clause 4.5.2.3 page 71).

3.2 Limits

When undertaking a construction project, the following boundary conditions should be checked, if they are relevant to the project:

- overall regional stability
- geotechnical resistance of the pile foundation
- tension resistance of the pile foundation
- rise of pile foundation
- ground failure caused by transversal load of the pile foundation
- structure failure of pile foundation caused by compression, tension, bending and shear load
- pile buckling
- combined fracture of the pile foundation and ground
- displacements: too much pressure or rise, too big transversal load

Among other limits, special attention has to be paid to the following environmental impacts:

- vibration
- environmental displacement
- water pressure change

(RIL 254-1-2016, 2016)

3.3 Geotechnical bearing capacity

Geotechnical bearing capacity of the ground is the capability of the structure to transfer the load from the pile to soil while settlements and lateral displacements persist within the allowable bounds, and it is determined in accordance with soil conditions and piling class. (Fenton, 2007, 2)

The geotechnical resistance of a pile is a combination of side friction, where load is transmitted to the soil through friction along the sides of the pile, and end bearing, where load is transmitted to the soil or rock through the tip of the pile. If the pile rests on the bedrock, its ultimate capacity depends mainly on the load bearing properties of the underlying material; these piles are called end bearing piles. When piles become very long, they are specified as friction piles, because most of the resistance is derived from skin friction. (Fenton, 2007, 2)

According to the Finnish norms, geotechnical resistance is calculated only for RR and RRs piles. RD and RDs piles are always drilled into firm and solid bedrock, which is assumed to have a sufficient resistance in every case. (RRPileCalc)

3.4 Piling class

The structure of the pile is classified by standard pile class that takes into account load and strain conditions. There are three types of piling classes: PTL1, PTL2 and PTL3. In piling class PTL3, 100% of the impact resistance can be used, in piling class PTL2 the value is 80% of the characteristic resistance and in piling class PTL1 only 60%.

As steel is able to withstand bending and compression, the damage caused by eccentricity of the stroke is smaller than in reinforced concrete piles. Consequently, the eccentricity caused by the hit does not need to be taken into account separately. (RIL 254-1-2016, 2016)

The maximum value for the compression resistance of the pile structure for different pile classes can be obtained from RIL 254-1-2016, PO-2016:

PTL3: $R_{c.max} = 0,9 f_y A_s$

PTL2: $R_{c.max} = 0,8 * 0,9\ f_y A_s$

PTL1: $R_{c.max} = 0,6 * 0,9\ f_y A_s$

where:

f_y-nominal values of yield strength
A_s - cross-section area

3.5 Geotechnical resistance based on end-of-driving instructions

When end-of-driving instructions are used, geotechnical design resistance $R_{c:d}$ of a pile is obtained from the characteristic value of geotechnical resistance by the following formula (PO-2016, 4.5.2.4):

$$R_{c;d} = \frac{R_{c.max}}{\gamma \cdot \xi}$$

where:

ξ- correlation coefficient, ξ = 1.47/1.1 ≈ 1.336 (PO-2016, 4.5.2.4 and 4.5.2.6), if the structure supported on the piles is sufficiently rigid and strong to transmit loads from ”weak” piles to ”strong” piles. Otherwise the value of the correlation coefficient is ξ = 1.47.
γ- partial safety factor of pile resistance for compression, γ = 1.2 (PO-2016, Table 4.3)

3.6 **Structural bearing resistance**

The structural resistance of a pile is verified in terms of both pile structure and soil failure according to Piling Manual PO-2016. Structural bearing resistance of a driven pile is the capability of the structure to transfer the load from the superstructure to the pile toe while settlements and lateral displacements persist within the allowable bounds. (Bhattacharya, 2005, 816)

Pile is a structure that is designed against bending failure due to lateral loads. If there is a lack of lateral support, then the pile may buckle. Piles are even more vulnerable to buckling because of eccentricities during installation which are inevitable even under the best of monitoring and instrumentation conditions. (Bhattacharya, 2005, 818)

The ultimate buckling resistance of an axially loaded pile is calculated by the method presented in PO-2016, Sec. 4.7.5, where the pile is assumed to be surrounded by a fine-grained soil layer over its entire unbraced length.

3.7 **Buckling**

Buckling is one of the dominating causes of failure in pile structure in soft soil. Buckling failure of slender structure may happen if the pile is subjected to axial force, loss of side ground pressure or loss of pile strength caused by corrosion. Buckling may also facilitate plastic hinges in the pile, causing failure of the whole structure.

During design stage it is hard to predict how steel structures will act in different circumstances. It is important to determine the upperlimit of ability of the structures in order to be on the safe side. Initial imperfection of the pile should always be considered during the installation of the structure to the ground. The curvature of the pile increases under axial load, resulting in bending stresses in the pile and lateral stresses in the soil. Bucklingcan appear before or after maximum stresses are reached. (Bhattacharya, 2005)

According to the Finnish Piling Manual when small diameter piles (d<300 mm) are used under difficult conditions, the radius of curvature of short pile elements is 1000 x ‘d’,

where ‘d’ is the diameter of the pile. When using long pile elements the curvature radius is 2000-25000 x ‘d’.
In order to calculate the initial deflection of thepile, critical buckling lengthis required. It can be obtained from (RIL 254-1-2016, 2016):

$$L_{cr}= \pi \sqrt[4]{\frac{EI}{k_s \cdot d_{eff}}}$$

where:

k_s-subgrade reaction of the soil
E-the Young’s modulus of elasticity for steel
I - second moment of area
d_{eff}- effective diameter of pile for buckling, where corrosion is taken into account

The initial geometric deflection of a pile can be inserted as a table value from $L_{cr}/200$ … $L_{cr}/800$. Values of the larger divisor, which is also the larger radius of curvature in Table 3, can be used in easy installation conditions. Values of the smaller divisor can be used when installation conditions are expected to be demanding.

Table 3. Initial deflection of the pile, RIL 254-1-2016, PO-2016

	Unspliced pile	Spliced pile
Initial deflection δ_g [m], RR and RRs-piles	$L_{cr}/300 – L_{cr}/600$	$L_{cr}/200 – L_{cr}/400$
Initial deflection δ_g [m], RR and RRs-piles	$L_{cr}/500$ - $L_{cr}/800$	$L_{cr}/300$ - $L_{cr}/600$

3.8 Resistance of the soil

When a pile is driven into cohesive soil, frequent hammer impacts cause a sharp local compaction under the pile toe. As a result, pea-shaped zones (Figure 1) of sealing soil are formed, preventing the pile from going further. After the cessation of hitting, the pear-shaped zone is unsealed, and the pile can be driven further. (Airhart, 1967, 2)

Pear-shaped sealed zones are formed in soils with low filtration coefficient. Resorption in such zones depends on the rate of water release: the smaller the filtration coefficient is, the slower the water is removed when the soil is sealed. Frequent hammer hits create a store of potential energy, making the water slowly leak out. (Airhart, 1967, 2)

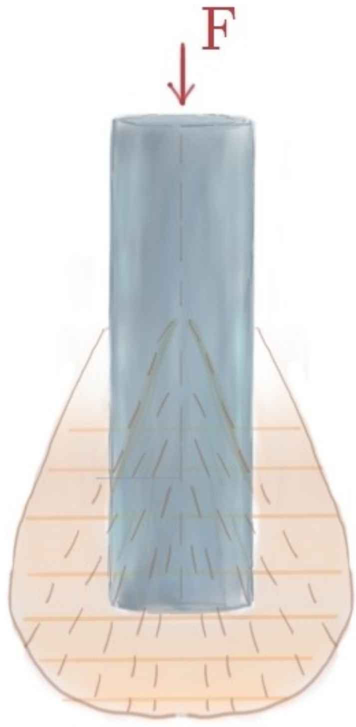

Figure 1. Pear-shaped zone

Within a certain time, the store of potential energy is consumed, the pressure in the pear-shaped zone and in the surrounding ground is leveled, and the soil can be left to harden. (Airhart, 1967, 4)

In cohesive soils, encouraged by the installation of piles dynamic impact causes a disturbance of the soil structure and its subsequent liquification. The change in soil structure triggers the water to lift along the pile stem. The hydrodynamic pressure of water moving upwards also reduces the bearing capacity of soil. Within a few days, the soil structure is restored and it leads to an increase in the bearing capacity of the pile. Undrained shear strength, C_{uk}, frequently increases with depth. (Airhart, 1967, 4). The value used for undrained shear strength is the reduced characteristic value of undrained shear strength, e.g.is based on yield point. A very typical characteristic value of undrained shear strength would be 10 kPa when weight sounding resistance occurs under rotation and the drill rods are not subjected to significant skin friction, for instance, from earth fill layers. (RRPileCalc) Thus, the smaller undrained shear strength factor is, the more average soil conditions are.

The resistance of the soil to lateral movement of the pile is limited. In the case of cohesive soils, the ultimate earth pressure ρ_m is calculated according to the following formula (RIL 254-1-2016, 2016):

$$\rho_{m=6\ldots9\cdot C_u}$$

where:

C_u- undrained shear strength

One of the factors that need to be considered in order to determine the capacity of the pile is the lateral subgrade reaction exclusive to cohesive soils. The soil stiffness is the linear ratio between the pressure and the associated vertical displacement. The coefficient of subgrade reaction, e.g spring stiffness, is the initial slope of the curve under the limit pressure. (RIL 254-1-2016, 2016)

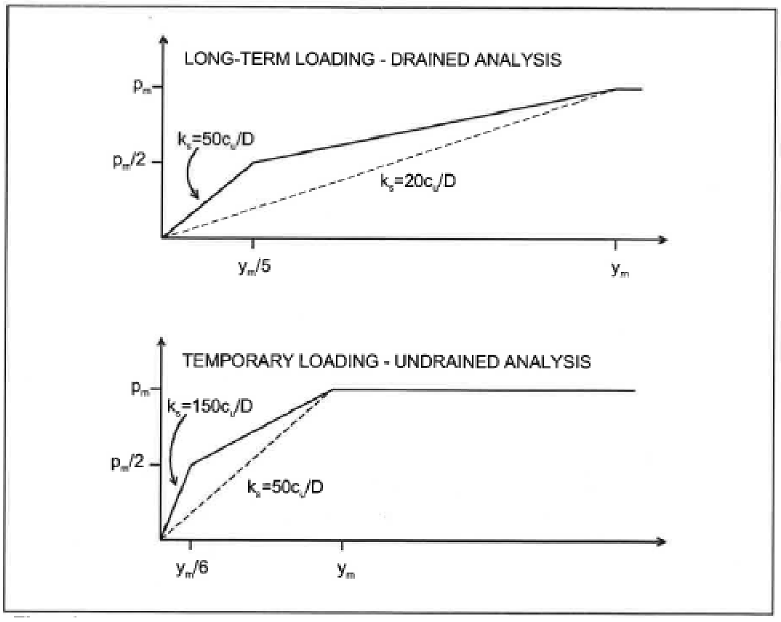

Figure 2. Divination of the subgrade reaction in cohesive soil

In the long-term loading, the subgrade reaction k_s is obtained from (RIL 254-1-2016, 2016):

$$k_s = 20 \dots 50 \frac{C_u}{d_{eff}}$$

whereas for temporary loading, subgrade reaction k_s is calculated from the following formula (RIL 254-1-2016, 2016):

$$k_s = 50 \dots 150 \frac{C_u}{d_{eff}}$$

where:

C_u - undrained shear strength
d_{eff} - effective diameter of pile for buckling, where corrosion is taken into account

3.9 Buckling resistance

The zone of local shear failure emerging inadjacency to the pile is the result of horizontal pressures and displacements, appearing due to the pile adopting a position previously occupied by a volume of soil. Worsened with each hammer hit,the displacement occurs as the pile is driven through the soil and disturbance is created from vertical shear. It is anticipated that complete plastic failure of soil is caused by horizontal forces, whereas displacement in this state is caused by vertical forces. (Bhattacharya, 2005)

Critical buckling resistance of an initially straight pile Fcr, when soil around pile is failing, can be obtained from (RIL 254-1-2016, 2016):

$$F_{cr} = 2 \cdot \sqrt{k_s \cdot d_{eff} \cdot EI}$$

where:

k_s-subgrade reaction of soil
d_{eff}- effective diameter of pile for buckling
EI- bending stiffness

Buckling resistance of an initially curved pile $F_{d;s}$, when soil around pile is failing, is calculated with the following formula (RIL 254-1-2016, 2016):

$$F_{d;s} = \frac{F_{cr}}{1 + \frac{k_s \cdot \delta_g}{\rho_m}}$$

where:

k_s-subgrade reaction of soil
δ_g-initial deflection of pile
ρ_m- ultimate earth pressure

3.10 **Resistance of the pile**

Bearing capacity of a single pile is defined by the smallest bearing capacity value obtained under the following two factors: the condition of soil resistanceand the condition of the pile material resistance. (Stroitelstvo-New)

Design resistance of a pile taking a compressive vertical load and supported at the lower end by the bedrock or by the cohesive soils with solid consistency is determined from the bearing capacity of the pile. (Stroitelstvo-New)

Buckling is extremely susceptible to imperfections and lateral loads. Buckling also marks a transition point from elastic to plastic mode of failure. Lateral loads and geometrical imperfections both contribute to the appearance of bending moments in addition to axial loads. Bending moments have to be accompanied by stress resultants that reduce the cross-sectional area for carrying the axial load. (Bhattacharya, 2005, s. 817). Due to different ways of manufacturing, steel piles have some residual stresses. This is taken into account applying a so-called fictive initial deflection δ_f..

The fictive initial deflection $\delta 0_f$ is presented as follow (RIL 254-1-2016, 2016):

$$\text{group a: } \delta_f = 0.0003 \cdot L_{cr}$$
$$\text{group b: } \delta_f = 0.0013 \cdot L_{cr}$$
$$\text{group c: } \delta_f = 0.0025 \cdot L_{cr}$$

Long steel pipe piles with longitudinal welding belong to group b, whereas large diameter piles belong to group c.

The initial geometrical deflection used in calculations is comprised of δ_g and δ_f. The initial deflection δ_0 to be used in calculations is:

$$\delta_0 = \delta_g + \delta_f$$

where:

δ_g-initial deflection of pile
δ_f-fictive initial deflection

(RIL 254-1-2016, 2016)

3.11 **Resistance of steel structure**

Compression resistance Fd;s of pile cross-section in ultimate limit state is calculated with the following formula:

$$\mathrm{F_{c;u}} = \mathrm{A_s} \cdot \mathrm{f_{yd}}$$

where:

A_s- the cross-section area
f_{yd}-design yield strength

Bending resistance of pile cross-section in ultimate limit state is obtained from:

$$\mathrm{M_u} = \eta \cdot \mathrm{W_{el}} \cdot \mathrm{f_{yd}}$$

where:

η -the shape factor dependent on classification of cross-section classes
W_{el} -elastic section modulus
f_{yd} -design yield strength

(RIL 254-1-2016, 2016)

3.12 Resistance of cross-section in combined compression and bending

It is important that the ultimate load Pd;p of the pile can be achieved in a situation where integrated compression and bending actions do not exceed the structural capacity Fc;u and Mu of the pile cross-section. Structural resistance of the pile needs to be taken into account when the ultimate load is derived. (U.S. Department of Transportation Federal Highway Administration, 2016)

Bending resistance of the pile's cross-section can be obtained from (RIL 254-1-2016, 2016):

$$P_{d;p} = \frac{B}{2} - \sqrt{\frac{B^2}{4} - C}$$

where:

$$B = F_{cr} + F_{c;u} + 0{,}5 \cdot F_{cr} \cdot \delta_0 \cdot F_{c;u}/M_u$$

$$C = F_{cr} \cdot F_{c;u}$$

4 LOCAL BUCKLING RESISTANCE

4.1 Main principles

Cross-section classification relies on diameter-to-thickness ratio, $d/_t$ ratio. This d/t ratio of pile pipes refers to cross-section. Class 4 is high (large outer diameter of pile pipe, small wall thickness); implies that cross-sections are slender. Due to this slenderness there is an opportunity for local buckling with smaller stress levels than yield strength of the material. For this reason, the resistance of cross-sections belonging to class 4 is reduced by limiting the highest possible compression stress level to the level of so-called local buckling stress. Besides limiting the compression stress level, calculations of class 4 cross-sections are always done in elastic state. Local buckling is related to equilibrium limit state. Respectively, the material safety factor γ_{M1} is used for pile pipe. (RRPileCalc) For pile pipes this partial safety factor is taken from EN 1993-1-6 clause 8.5.2(2), where its recommended value is 1.1. The partial safety factor can also be found in National Annex. In case of Finland, the partial safety factor is 1.1.

4.2 Determination of cross-section class

The cross-section class of pile pipe is defined according to (EN 1993-1-1 , 2005), Table 5.2, Sheet 3. Limit value between cross-section classes 3 and 4 is:

$$d_{eff}/t_{eff} = 90 \cdot \varepsilon^2$$

where:

d_{eff} is the effective outside diameter of pipe pile with corrosion allowance considered
t_{eff} is the wall thickness of pipe pile with corrosion allowance considered
ε is the factor dependent on the yield strength f_y of the pile pipe material:

$$\varepsilon = \sqrt{235/f_y}$$

Cross-sections with slenderness exceeding thelimit value above belong to cross-section class 4.

4.3 Compression resistance of cross-section (buckling excluded)

Compression resistance $N_{c,Rd}$of pile pipe belonging to cross-section class 4 is based on the reduction factor χx for elastic-plastic local buckling of a shell, like described in (EN 1993-1-6 , 2007):

$$N_{c;Rd} = \frac{\chi_\chi \cdot A \cdot f_y}{\gamma_{M1}}$$

where:

$N_{c,Rd}$ is the design compression resistance of the cross-section
χ_x is the reduction factor for elastic-plastic local buckling of a shell
A is the gross cross-section area of the pile pipe (possible corrosion allowance considered)
f_y is the nominal yield strength of the pile pipe material
$\gamma_{M1}$is the partial safety factor for resistance in equilibrium limit state like described above.

The reduction factor χ_x for elastic-plastic local buckling is calculated as follows (EN 1993-1-6, clause 8.5.2(4)):

$$\chi_\chi = 1{,}0$$

for$\lambda_x \leq \lambda_{x0}$

$$\chi_\chi = 1 - \beta\left(\frac{\lambda_x - \lambda_{x0}}{\lambda_{px} - \lambda_{x0}}\right)^\eta$$

for$\lambda_{x0} < \lambda_x < \lambda_{px}$

$$\chi_\chi = \frac{a_x}{\lambda_x^2}$$

for$\lambda_{px} \leq \lambda_x$

where:

λ_x	is the non-dimensional slenderness
λ_{x0}	is the squash limit relative slenderness (EN 1993-1-6, clause D.1.2.2(3): $\lambda_{x0} = 0.20$)
β	is the plastic range factor (EN 1993-1-6, clause D.1.2.2(3): $\beta = 0.60$)
η	is the interaction exponent (EN 1993-1-6, clause D.1.2.2(3): $\eta = 1.0$)
λ_{px}	is the plastic limit relative slenderness
a_x	is the elastic imperfection reduction factor

Subscript x of all of the above variables refers to meridional (axial) compression of the pile pipe.
The elastic imperfection reduction factor $\alpha_x$is obtained from (EN 1993-1-6, equation D.14):

$$a_x = \frac{0,62}{1 + 1,91 \cdot \left(\triangle \omega_k / t\right)^{1,44}}$$

where:

$\triangle \omega_k$ is the characteristic imperfection amplitude

t is the wall thickness of the pile pipe (possible corrosion allowance considered).

Characteristic imperfection amplitude $\triangle \omega_k$ is calculated as follows (EN 1993-1-6, equation D.15):

$$\triangle \omega_k = \frac{1}{Q} \cdot \sqrt{\frac{r}{t}} \cdot t$$

where:

r	is the radius of the centerline of the pile pipe wall thickness (possible corrosion allowance considered) (EN 1993-1-6, clause D.1.1(1)).
t	is the wall thickness of the pile pipe (possible corrosion allowance considered)
Q	is the fabrication quality parameter according to the tolerances of the pile pipe.

The fabrication quality parameter Q is defined according to the fabrication tolerance quality classes given in EN 1090-2. Steel pipe piles produced by SSAB meet the quality class B. Thereby, from Table D.2 in EN 1993-1-6 the parameter Q obtains the value Q = 25.
The plastic limit non-dimensional slenderness λ_{px} is calculated as follows (EN 1993-1-6, equation 8.16):

$$\lambda_{px} = \sqrt{\frac{a_x}{1 - \beta}}$$

where

α_x	is the elastic imperfection reduction factor
β	is the plastic range factor (EN 1993-1-6, clause D.1.2.2(3): β = 0.60).

The non-dimensional slenderness λ_x is obtained from(EN 1993-1-6, equation 8.17):

$$\lambda_x = \sqrt{\frac{f_y}{\sigma_{x;Rcr}}}$$

where

f_y is the nominal yield strength of the pile pipe material
$\sigma_{x;Rcr}$ is the elastic critical local buckling stress

The elastic critical local buckling stress of a circular hollow section $\sigma_{x;Rcr}$ is calculated as follows (EN 1993-1-6, equation D.2):

$$\sigma_{x;Rcr} = 0.605 \cdot E \cdot C_x \cdot \frac{t}{r}$$

where:

E is the Young's modulus of elasticity
C_x is defined in EN 1993-1-6 clause D.1.2.1 as a function of the length of the cylinder-like structure considered. In practice, the lengths of piles are usually greater than 1…2 x d. In such case, the value obtained from EN 1993-1-6 is C_x = 0.6. This value may be used also for shorter lengths as a conservative simplification.
t is the wall thickness of the pile pipe (possible corrosion allowance considered)
r is the radius of the centerline of the pile pipe wall thickness (possible corrosion allowance considered) (EN 1993-1-6, clause D.1.1(1)).

4.4 Bending resistance of cross-section

Bending resistance $M_{c,Rd}$ of pile pipe belonging to cross-section class 4 is based on the reduction factor χ_x for elastic-plastic local buckling of a shell, like described in EN 1993-1-6:

$$M_{c;Rd} = \frac{\chi_\chi \cdot W_{el} \cdot f_y}{\gamma_{M1}}$$

where:

χ_x is the reduction factor for elastic-plastic local buckling of a shell
W_{el} is the elastic section modulus of the cross-section (possible corrosion allowance considered)
f_y is the nominal yield strength of the pile pipe material
γ_{M1} is the partial safety factor for resistance in equilibrium limit state like described above

4.5 **Resistance of the cross-section for combined actions, normal force and bending**

Usually piles are facing normal forces from external loads and bending moments from curvature of the pile (initial deflection of the pile and added deflection attributed to the loading). The resistance of the pile pipe cross-section for these combined actions is calculated as described below:

$$\sigma_{x,Ed} = \frac{N_{Ed}}{A} \pm \frac{M_{Ed}}{W_{el}}$$

$\sigma_{x,Ed} \leq \frac{f_y}{\gamma_{M0}}$, when $\sigma_{x,Ed}$ is in tension

$\sigma_{x,Ed} \leq \frac{\chi_\chi \cdot f_y}{\gamma_{M1}}$, when $\sigma_{x,Ed}$ in compression

where:

$\sigma_{x,Ed}$ is the design value of axial stress at the point to be considered
N_{Ed} is the design value of normal force at ultimate limit state
A is the gross cross-section area of the pile pipe (possible corrosion allowance considered)
M_{Ed} is the design value of bending moment at ultimate limit state
W_{el} is the elastic section modulus of the cross-section (possible corrosion allowance considered)
χ_x is the reduction factor for elastic-plastic local buckling of a shell
f_y is the nominal yield strength of the pile pipe material
γ_{Mo} is the partial safety factor for resistance of pile pipe material. Taken from EN 1993-1-1, clause 6.1(1), where 1.00 is given for recommended value. The partial safety factorfound in the National Annex of Finland equals 1.00.

The axial tensile stress is not allowed at any point of the cross-section to exceed the design value of the yield strength, and the axial compression stress is not allowed to exceed the design value of the buckling strength. In this way, there is no possibility to form a buckling at the compressed edge of the cross-section. (RRPileCalc)

4.6 **Final resistance of the pile**

When dealing with cross-sections belonging to cross-section class 4, the calculation is done in elastic limit state, so that the compression stress at the edge is limited to the value:

$$\sigma_x = \frac{\chi_\chi \cdot f_y}{\gamma_{M1}}$$

where:

χ_x is the reduction factor for elastic-plastic local buckling of a shell
f_y is the nominal yield strength of the pile pipe material
γ_{M1} is the partial safety factor for resistance in equilibrium limit state like described above

The reduction factor is not used for tensile stress at the edge of cross-section. Compression and bending resistances of the cross-section calculated this way are used in buckling calculations in a similar way as with cross-sections belonging to cross-section classes 1, 2 and 3.

4.7 Local buckling with high strength steel piles

In this study there is only the RR320/10 pile that goes to cross-section class 4 and where local buckling has to be considered. Calculations are presented in Appendix 1.

5 COMPARISON GRAPHS

To help visualize and understand the aim of the study more clearly, comparison graphs of selected steel pipe sizes were done.
For convenience purposes two charts were made. Figure 3 below shows comparison charts where it is possible to choose different pile sizes and different yield strength in each one.

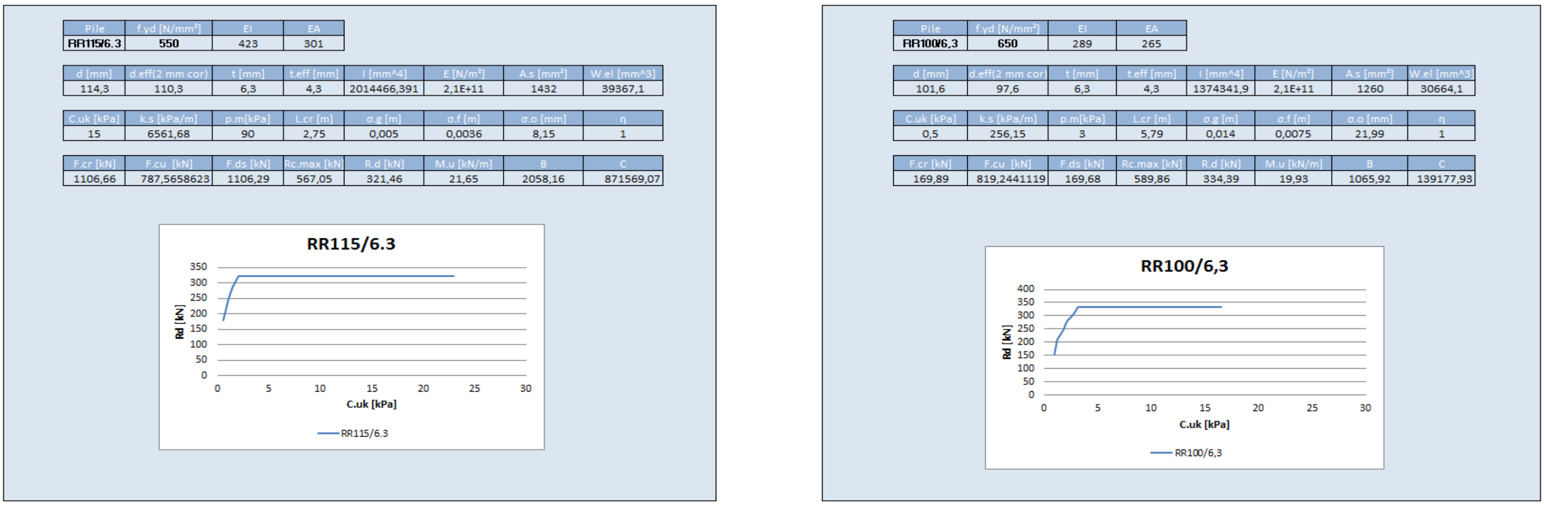

Figure 3. Charts for selection of pipe piles for comparison

When a pile is selected, relation graph of Structural Resistance and Undrained Shear strength appear. Additional graph was created for comparison of both steel pipe piles. The graph for one pile includes two indicators: Structural resistance and Geotechnical resistance diagrams. By combing them it is possible to deduce the window of benefit and see where the moment goes from elastic to plastic state. By increasing the capacity of a certain pile we can follow the limit value changes of geotechnical resistance and undrained shear strength, which will help conclude whether it is beneficial to use the pipe pile or not. Figure 4 represents the original pile graph that consists of Structural resistance of a pile and Geotechnical resistance of a pile. When load bearing capacity is increased, the graph defines the limit values. Point A represents where the range of pile benefit begins, whereas point B showswhere the pile benefit range ends. The percentage difference between these two geotechnical resistance limits serves as an indication of the pile's profitability. Another important factor to consider when estimating the pile's benefit is Cuk -Undrained Shear strength. The smaller undrained shear strength valueis, the more average soil conditions we have. The average limit value for Cuk in Finland is 10 kPa. This applies to driven piles, RR Piles, as RD piles installed right into bedrock, and the bedrock support can carry more weight that the pile, so the capacity of drilled piles is determined according to the structural capacity of their cross-sections.

Figure 5 shows us that RR100/6.3 S550 has a significantly lower geotechnical resistance than the RR90/6.3 S700, with the difference of 10%. Even though Cuk value of RR90/6.3 is a bit bigger that the one RR100 pile has, but the difference is only about 4 KPa, which is much less than 10 kPa. The most beneficial piles are presented in Appendix 2. The table of all examined “micropiles” with different resistances according to different CukPiling Class and buckling length is presented in Appendix 3.

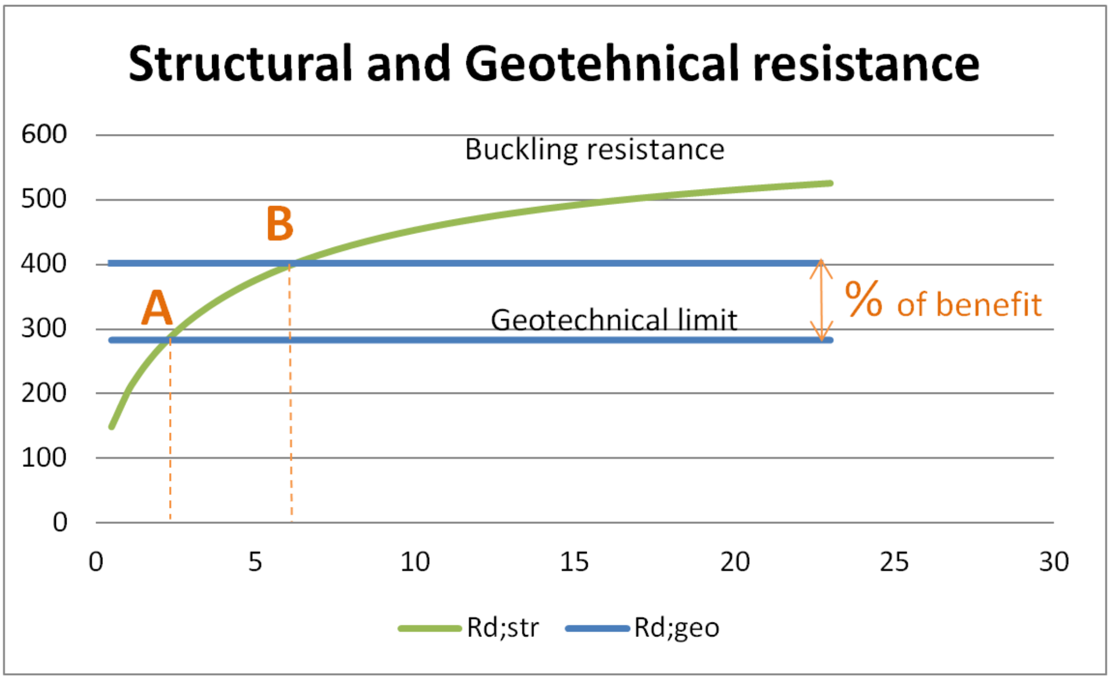

Figure 4. Graph explanation

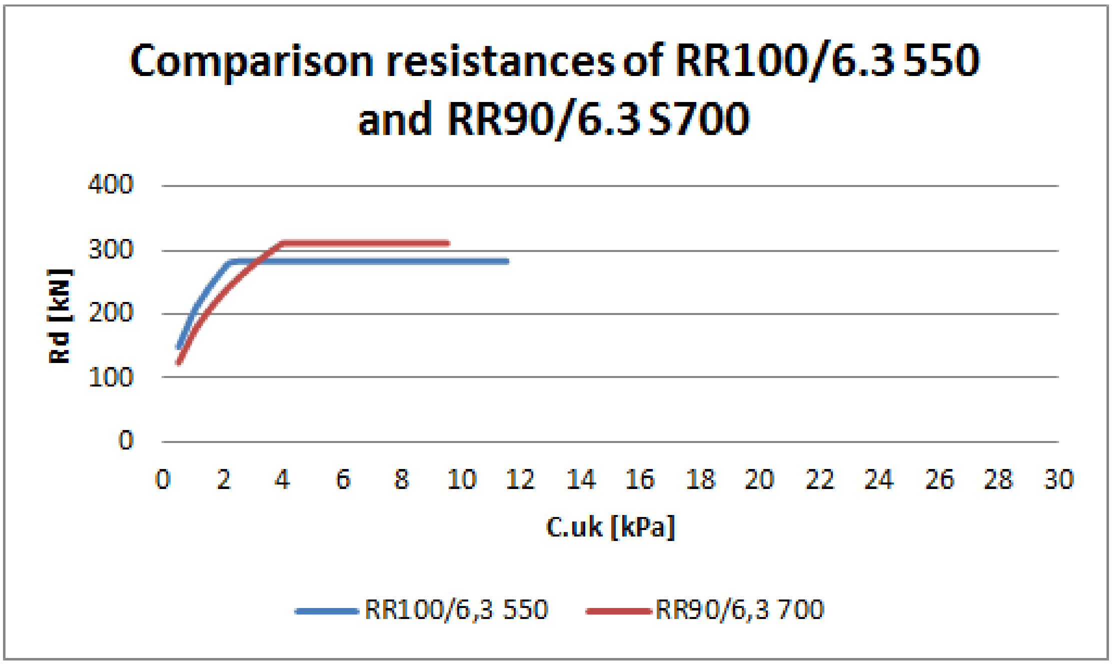

Figure 5. Comparison graph from excel calculation

6 CONCLUSION

Drilled and driven piles are extensively used in different settings for construction of foundations. However, pile installation methodsare applied more and more often due to increasing demand on the use of piles, so there is a need to improve this technology. The main goal to consume less material and make products more affordable and cheap can be achieved by using high-strength steel piles with improved load bearing capacity.

In Finland design of steel pipe piles is done according to the Eurocode, the Finnish Piling Manual PO 2016 and the National Annexes. The most important factor that defines the dynamics of buckling instability is whether the piles are partially exposed, driven into cohesive soils or installed under driving stresses. According to the Piling Manual PO-2016, RD piles are drilled into solid bedrock, which, considering the fact that bedrock resistance is always assumed as adequate, leads to the conclusion that no buckling calculations or load tests have to be done. Meanwhile, the resistance factor of RR piles, also known as driven piles, is calculated only through buckling.

During this study, resistance of steel pipe piles was examined using higher steel grades and new solutions were discovered. Pile strength is limited by geotechnical resistance and driving can be done up to 90% yield strength. The research has shown that it is possible to use eleven different pile sizes with smaller cross-sectional properties, but a bit bigger structural limits and higher geotechnical resistances.All new solutions are presented in Appendix 2.

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LOCAL BUCKLING OF RR320/10 S700 STEEL PIPE PILE

RR 320/10 S700

$d := 323.9 \cdot mm$

$d_{eff} := d - 4 \cdot mm = 0.32\,m$ outside diameter of pile pipe (possible corrosion allowance considered)

$t := 10 \cdot mm$

$t_{eff} := t - 2 \cdot mm = 8 \cdot mm$ wall thickness of pile pipe (possible corrosion allowance considered)

$f_y := 680 \cdot MPa$

$\varepsilon := \sqrt{\frac{235 \cdot MPa}{f_y}} = 0.588$ factor depending on the yield strength fy of the pile pipe material

$\frac{d}{t} = 32.39 \qquad 90 \cdot \varepsilon^2 = 31.103$

$32.39 > 31.103$ Class 4

$\gamma_{M1} := 1.0$ partial safety factor for resistance in equilibrium limit state

$A := 9861 \cdot mm^2$ cross-section area of the pile pipe

$A_{eff} := A \cdot \left(\frac{90}{\frac{d}{t}} \cdot \frac{235 \cdot MPa}{f_y} \right)^{0.5} = 9.663 \times 10^3 \cdot mm^2$ gross cross-section area of the pile pipe

$E := 210 \cdot MPa$ Young's modulus of elasticity

$R_2 := \frac{d}{2} = 0.162\,m$

$R_1 := \frac{d}{2} - t = 0.152\,m$

$W_{el} := \frac{\pi \cdot \left(R_2{}^4 - R_1{}^4 \right)}{4 \cdot R_2} = 7.507 \times 10^5 \cdot mm^3$ elastic section modulus of the cross-section

$W_{el.eff} := W_{el} \cdot \left(\frac{140}{\frac{d}{t}} \cdot \frac{235 \cdot MPa}{f_y} \right)^{0.25} = 8.3 \times 10^5 \cdot mm^3$

$r := \frac{d_{eff}}{2} = 0.16\,m$ radius of the centerline of the pile pipe wall thickness (possible corrosion allowance considered)

Compression resistance of cross-section (buckling excluded) and Bending resistance of the cross-section

$\beta := 0.60$ plastic range factor

$\eta := 1.0$ interaction exponent

$C_x := 0.6$ obtained from EN 1993-1-6 is Cx = 0.6

$$\sigma_{x.Rcr} := 0.605 \cdot E \cdot C_x \cdot \frac{t_{eff}}{r} = 3.813 \times 10^6 \, Pa$$ elastic critical local buckling stress of a circular hollow section

$Q := 25$

$$\Delta\omega_k := \frac{1}{Q} \cdot \sqrt{\frac{r}{t}} \cdot t = 1.6 \times 10^{-3} \, m$$ Characteristic imperfection amplitude

$$\alpha_x := \frac{0.62}{1 + 1.91 \cdot \left(\frac{\Delta\omega_k}{t_{eff}}\right)^{1.44}} = 0.522$$ elastic imperfection reduction factor αx

$$\lambda_{px} := \sqrt{\frac{\alpha_x}{1 - \beta}} = 1.142$$ plastic limit non-dimensional slenderness

$$\lambda_x := \frac{f_y}{\sigma_{x.Rcr}} = 178.352$$ non-dimensional slenderness

$\lambda_{x0} := 0.20$ squash limit relative slenderness

$\lambda_{px} \le \lambda_x$ therefore $$\chi_x := \frac{\alpha_x}{\lambda_x^{\,2}} = 1.641 \times 10^{-5}$$ reduction factor for elastic-plastic local buckling of a shell

$$N_{c.Rd} := \frac{\chi_x \cdot A \cdot f_y}{\gamma_{M1}} = 110.004 \, N$$ Compression resistance

$$M_{c.Rd} := \frac{\chi_x \cdot W_{el} \cdot f_y}{\gamma_{M1}} = 8.375 \cdot N \cdot m$$ Bending resistance

BENEFICIAL PILES

Figure 6 represents that RR75/6.3 S 700 benefits in geotechnical resistance for 7 %. Limit of undrained shear strength of RR75/6.3 is 4.7 kPa.

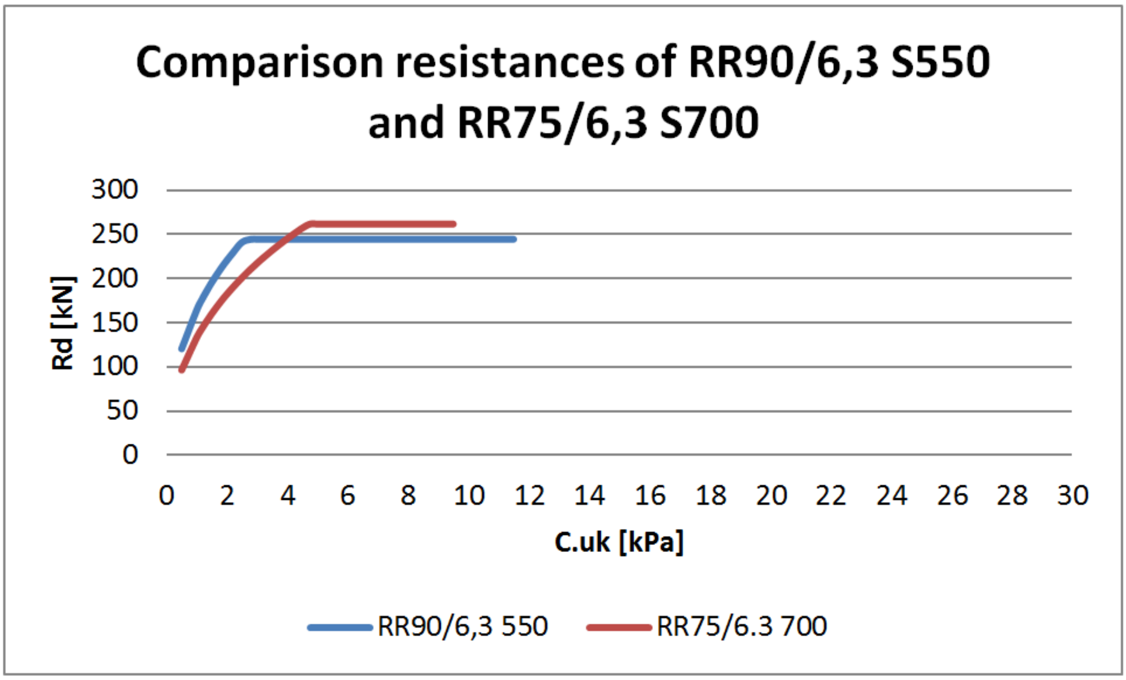

Figure 6. Comparison resistances of RR90/6,3 S550 and RR75/6,3 S700

Figure 7 represents that RR90/6.3 S 700 benefits in geotechnical resistance for 10 %. Limit of undrained shear strength of RR90/6.3 is 3,95kPa.

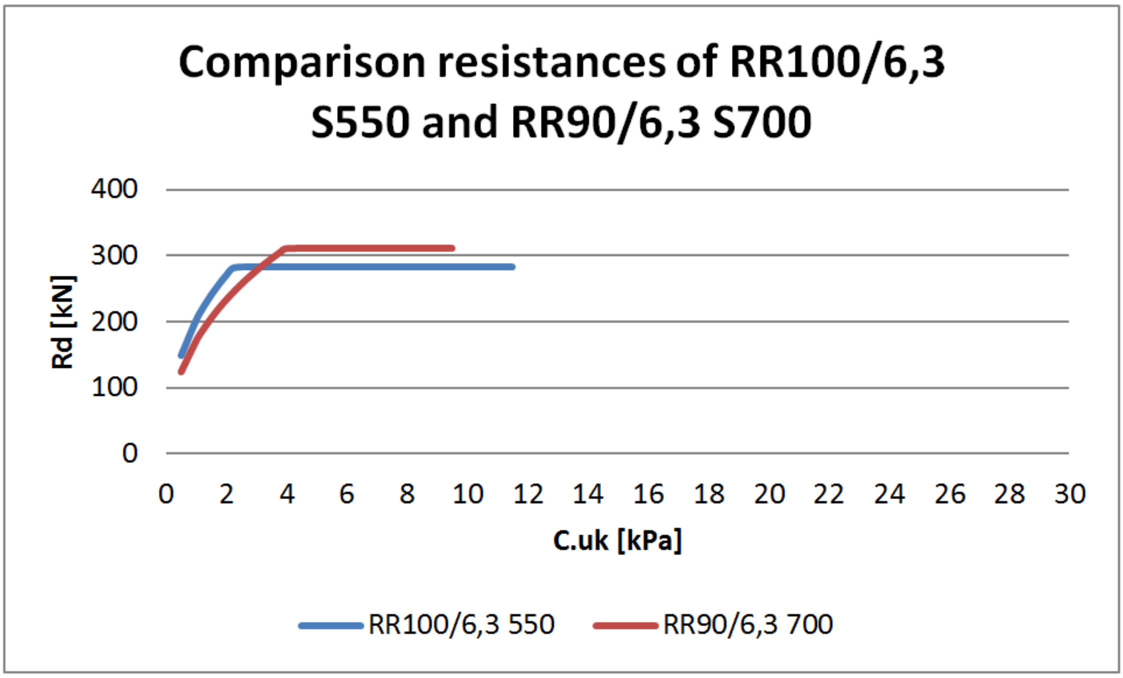

Figure 7. Comparison resistances of RR100/6,3 S550 and RR90/6,3 S700

Figure 8 represents that RR100/6.3 S650 benefits in geotechnical resistance for 4 %. Limit of undrained shear strength of RR100/6.3 is 3 kPa.

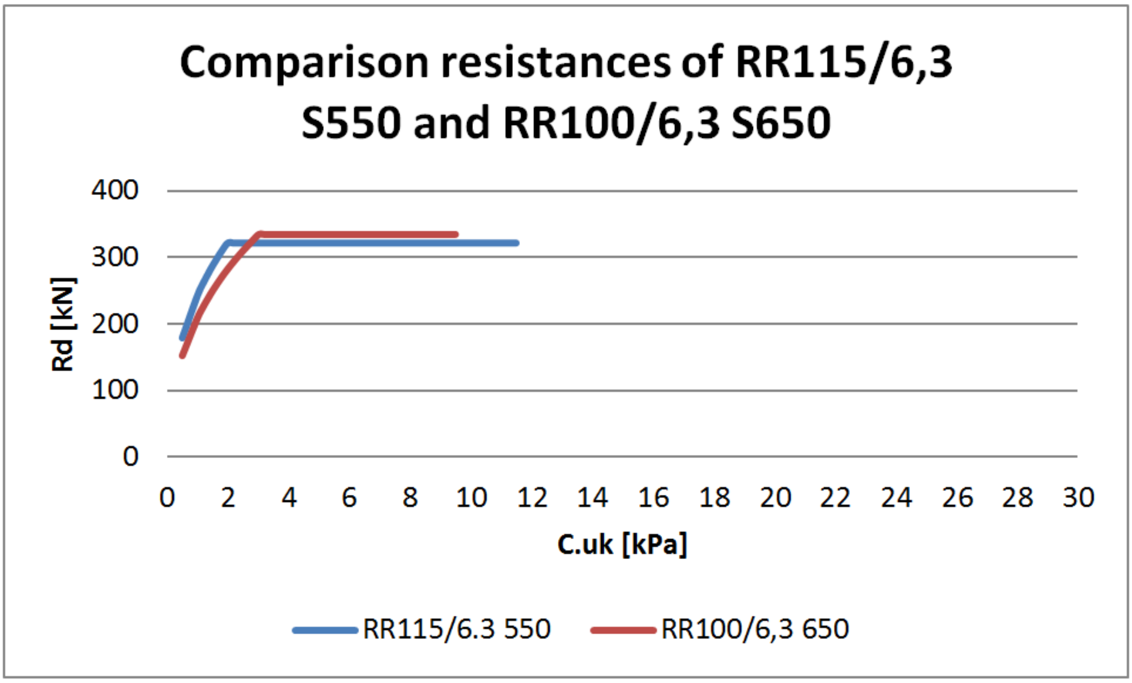

Figure 8. Comparison resistances of RR115/6,3 S550 and RR100/6,3 S650

Figure 9 represents that RR100/6.3 S700 benefits in geotechnical resistance for 12 %. Limit of undrained shear strength of RR100/6.3 is 3,4kPa.

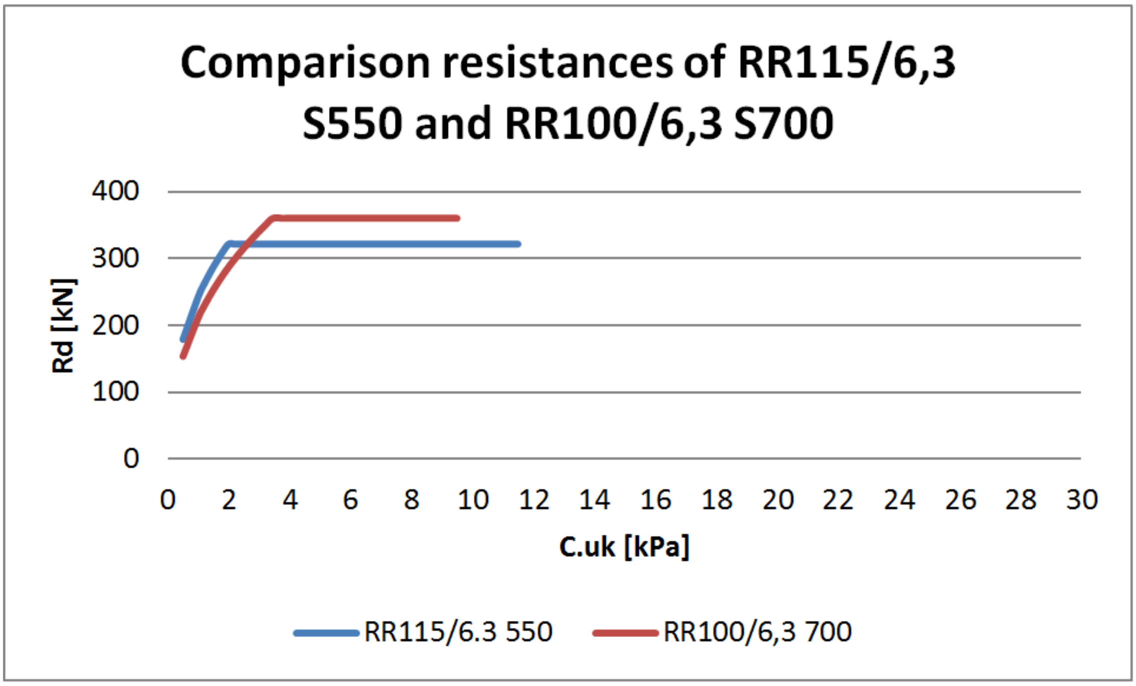

Figure 9. Comparison resistances of RR115/6,3 S550 and RR100/6,3 S700

Figure 10 represents that RR115/8 S700 benefits in geotechnical resistance for 2,3 %. Limit of undrained shear strength of RR115/8 is 4,3kPa

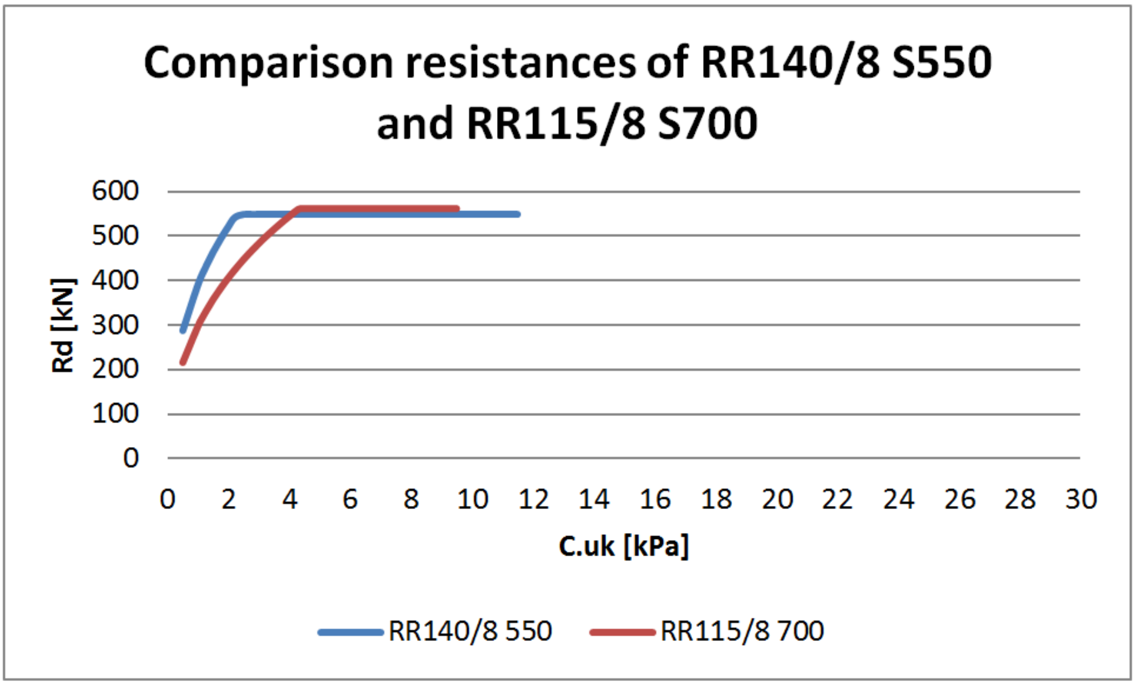

Figure 10. Comparison resistances of RR140/8 S550 and RR115/8 S700

Figure 11 represents that RR140/8 S700 benefits in geotechnical resistance for 4 %. Limit of undrained shear strength of RR140/8 is 4,7kPa

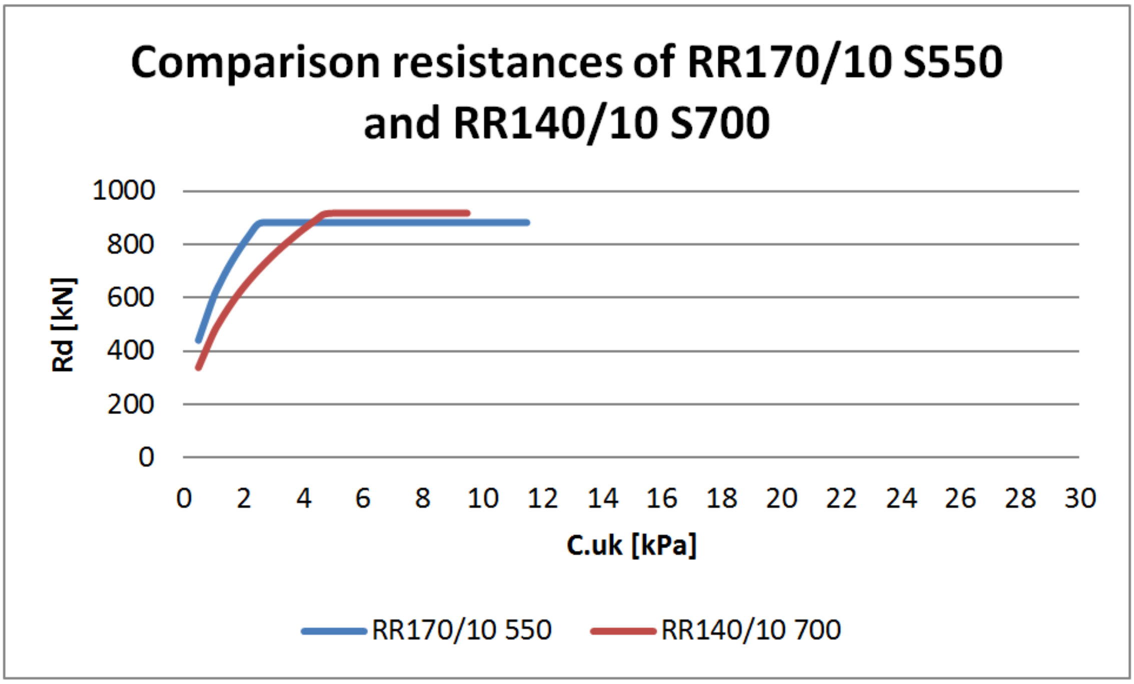

Figure 11. Comparison resistances of RR170/10 S550 and RR140/10 S700

Figure 12 represents that RR170/12,5 S650 benefits in geotechnical resistance for 15%.Limit of undrained shear strength of RR170/12,5is 4,5kPa

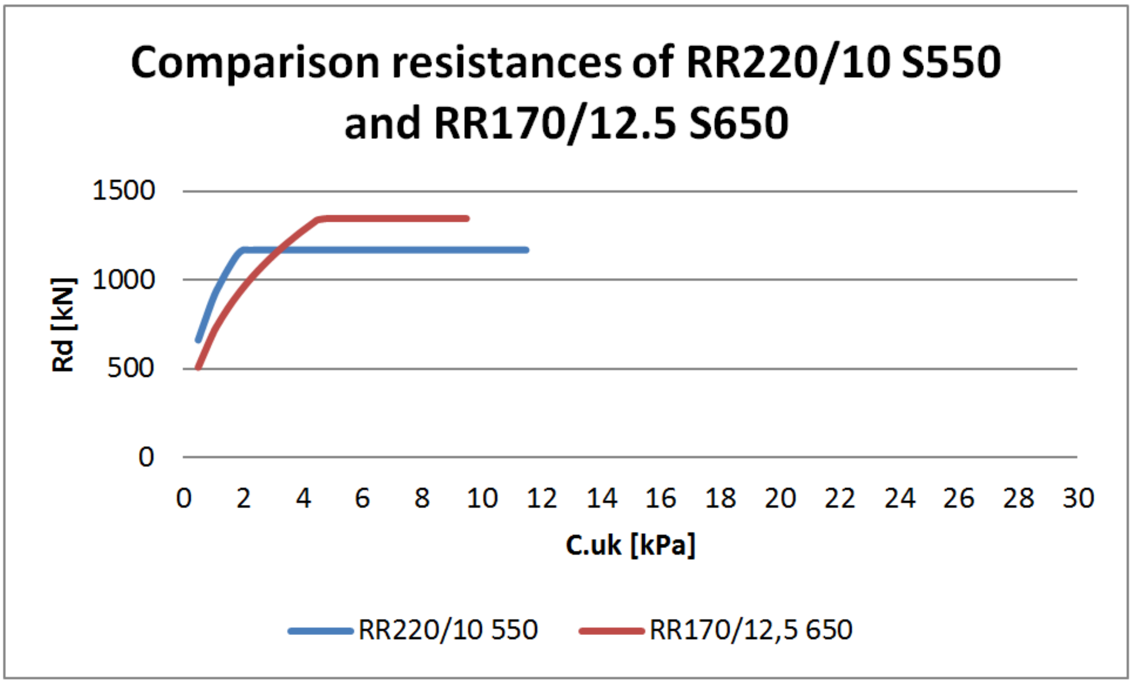

Figure 12. Comparison resistances of RR220/10 S550 and RR170/12.5 S650

Figure 13 represents that RR170/12,5 S700 benefits in geotechnical resistance for 24%. Limit of undrained shear strength of RR170/12,5 is 5,2 kPa

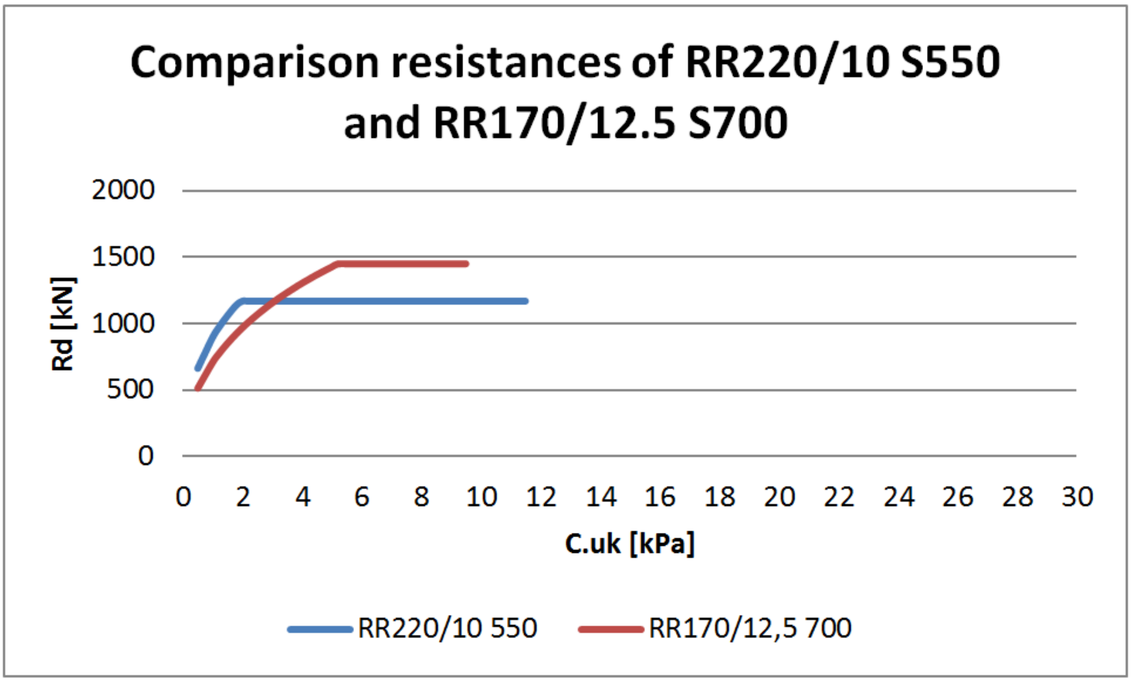

Figure 13. Comparison resistances of RR220/10 S550 and RR170/12.5 S700

Figure 14 represents that RR220/12,5 S650 benefits in geotechnical resistance for 21,6%. Limit of undrained shear strength of RR220/12,5 is 3,4 kPa

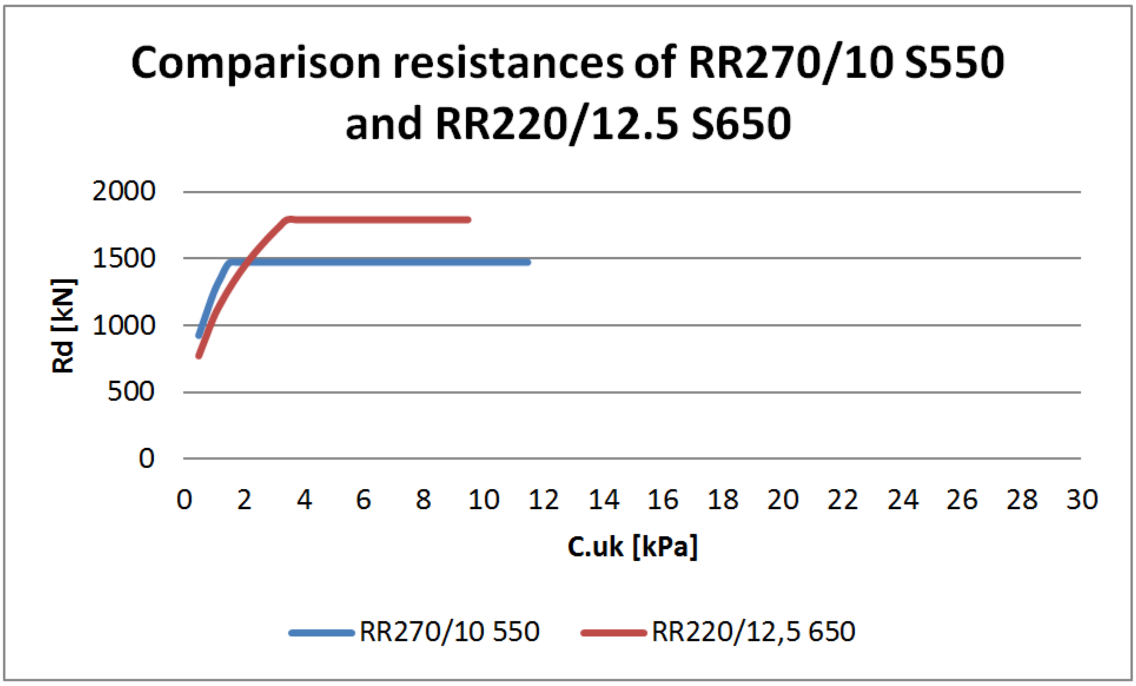

Figure 14. Comparison resistances of RR270/10 S550 and RR220/12.5 S650

Figure 15 represents that RR220/12,5 S700 benefits in geotechnical resistance for 31%. Limit of undrained shear strength of RR220/12,5 is 3,9 kPa

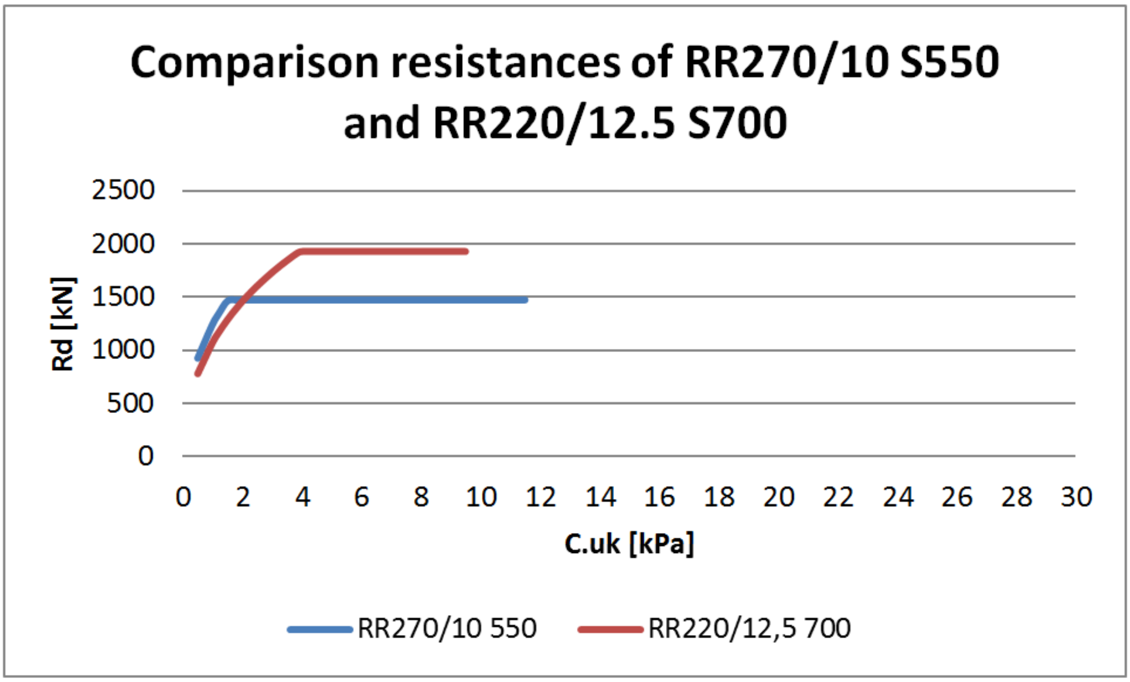

Figure 15. Comparison resistances of RR270/10 S550 and RR220/12.5 S700

Figure 16 represents that RR270/10 S700 benefits in geotechnical resistance for 6,5%. Limit of undrained shear strength of RR270/10 is 2,3kPa

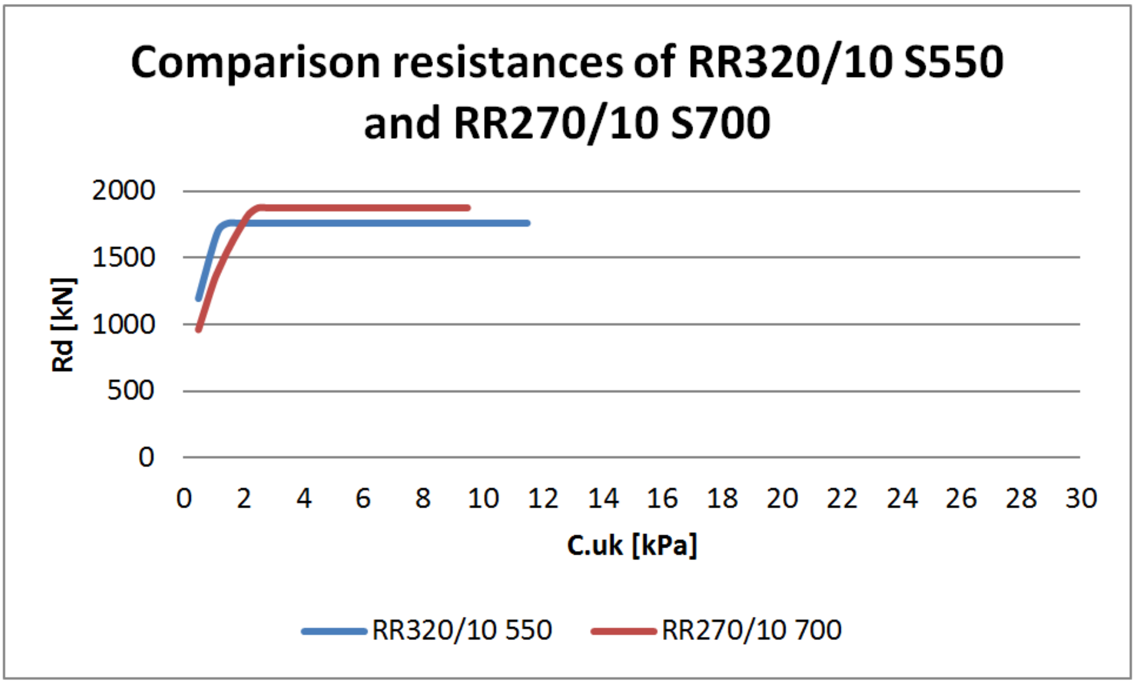

Figure 16. Comparison resistances of RR320/10 S550 and RR270/10 S700

Appendix 3
1 (2)

DESIGN VALUES OF STRUCTURAL COMPRESSION RESISTANCE ACCORDING TO UNDRAINED SHEAR STRENGTH, BUCKLING LENGTH AND PILING CLASSES.

Pile	Steel garde	Initial deflection	Design value of structural compression resistance Rd [kN] undrained shear strength Cuk [kPa]						Design values of geotechnical resistance Rd [kN]		
		σ.g [m]	5	7	10	15	20	30	PTL1	PTL2	PTL3
RR75	S550	Lcr/400	247	276	306	337	357	380	154	206	257
		Lcr/600	259	290	322	355	375	399			
RR75	S600	Lcr/400	255	287	321	357	380	408	168	224	280
		Lcr/600	267	301	338	376	400	428			
RR75	6S50	Lcr/400	262	297	334	375	402	435	182	243	304
		Lcr/600	273	311	351	395	423	456			
RR75	S700	Lcr/400	268	305	346	391	421	459	196	262	327
		Lcr/600	279	319	362	411	443	482			
RR90	S550	Lcr/400	310	344	379	414	436	462	183	244	306
		Lcr/600	326	363	400	436	458	483			
RR90	S600	Lcr/400	322	360	399	440	466	497	200	267	333
		Lcr/600	337	378	421	464	490	520			
RR90	S650	Lcr/400	332	373	417	464	494	530	217	289	361
		Lcr/600	347	392	439	489	519	555			
RR90	S700	Lcr/400	340	385	433	486	520	562	233	311	389
		Lcr/600	355	403	455	511	547	589			
RR100	S550	Lcr/400	376	415	453	492	515	543	212	283	354
		Lcr/600	396	437	478	517	541	567			
RR100	S600	Lcr/400	391	435	479	524	552	585	231	309	386
		Lcr/600	411	458	505	552	580	611			
RR100	S650	Lcr/400	404	452	502	554	587	626	251	334	418
		Lcr/600	423	475	529	583	616	654			
RR100	S700	Lcr/400	416	468	523	582	619	664	270	360	450
		Lcr/600	434	490	550	612	651	695			
RR155/6,3	S550	Lcr/400	443	486	529	570	595	325	241	321	402
		Lcr/600	467	513	557	599	624	651			
RR155/6,3	S600	Lcr/400	463	519	560	603	639	674	263	351	438
		Lcr/600	486	539	591	641	670	704			
RR155/6,3	S650	Lcr/400	479	534	589	646	681	722	285	380	475
		Lcr/600	503	562	621	679	714	754			
RR155/6,3	S700	Lcr/400	494	554	615	650	720	768	307	409	511
		Lcr/600	517	581	647	715	756	803			
RR115/8	S550	Lcr/400	543	605	667	732	773	821	331	441	552
		Lcr/600	571	637	705	772	813	860			
RR115/8	S600	Lcr/400	563	631	702	777	825	883	361	481	602
		Lcr/600	590	664	740	819	868	925			
RR115/8	S650	Lcr/400	580	654	733	818	873	941	391	522	652
		Lcr/600	606	686	771	862	919	987			
RR115/8	S700	Lcr/400	564	674	760	856	918	996	421	562	702
		Lcr/600	619	705	798	900	966	1045			
RR140/8	S550	Lcr/400	724	799	873	948	994	1048	412	549	686
		Lcr/600	763	843	922	998	1043	1095			
RR140/8	S600	Lcr/400	754	838	923	1011	1065	1129	449	599	748
		Lcr/600	792	883	974	1065	1119	1181			
RR140/8	S650	Lcr/400	779	872	968	7069	1132	1207	486	649	811
		Lcr/600	916	917	1020	1125	1189	1263			
RR140/8	S700	Lcr/400	801	902	1008	1122	1194	1282	524	699	873
		Lcr/600	837	946	1061	1181	1256	1342			
RR140/10	S550	Lcr/400	858	958	1061	1170	1238	1321	540	720	901
		Lcr/600	902	1010	1121	1235	1304	1385			
RR140/10	S600	Lcr/400	888	998	1114	1239	1319	1417	589	786	982
		Lcr/600	930	1049	1175	1307	1390	1488			
RR140/10	S650	Lcr/400	914	1033	1161	1302	1395	1509	639	851	1064
		Lcr/600	954	1083	1222	1373	1469	1585			
RR140/10	S700	Lcr/400	936	1063	1203	1359	1464	1595	688	917	1146
		Lcr/600	974	1111	1262	1431	1541	1676			
RR170/10	S550	Lcr/400	1123	1244	1366	1490	1567	1659	661	882	1102
		Lcr/600	1182	1313	1443	1571	1648	1736			

RR170/10	**S600**	Lcr/400	1167	1302	1441	1586	1676	1785	722	962	1203
		Lcr/600	1225	1371	1520	1672	1764	1870			
RR170/10	**S650**	Lcr/400	1204	1352	1508	1673	1779	1906	782	1042	1303
		Lcr/600	1261	1421	1588	1764	1872	1998			
RR170/10	**S700**	Lcr/400	1237	1396	1568	1754	1874	2021	842	1122	1403
		Lcr/600	1291	1464	1648	1847	1972	2120			
RR170/12,5	**S550**	Lcr/400	1312	1469	1633	1808	1919	2056	854	1139	1424
		Lcr/600	1378	1548	1725	1910	2024	2159			
RR170/12,5	**S600**	Lcr/400	1356	1528	1712	1912	2042	2203	932	1242	1553
		Lcr/600	1420	1606	1805	2018	2154	2316			
RR170/12,5	**S650**	Lcr/400	1394	1579	1781	2006	2155	2342	1009	1346	1682
		Lcr/600	1455	1655	1874	2115	2272	2463			
RR170/12,5	**S700**	Lcr/400	1426	1623	1842	2091	2259	2472	1087	1450	1812
		Lcr/600	1484	1697	1933	2201	2379	2601			
RR220/10	**S550**	Lcr/400	1621	1776	1926	2074	2163	2268	876	1168	1461
		Lcr/600	1711	1870	2032	2181	2267	2366			
RR220/10	**S600**	Lcr/400	1695	1870	2044	2218	2323	2448	956	1275	1593
		Lcr/600	1784	1973	2156	2333	2437	2556			
RR220/10	**S650**	Lcr/400	1759	1954	2152	2353	2476	2623	1036	1381	1726
		Lcr/600	1847	2058	2268	2476	2599	2740			
RR220/10	**S700**	Lcr/400	1814	2028	2249	2478	2621	2791	1115	1487	1859
		Lcr/600	1900	2132	2368	2608	2752	2918			
RR220/12,5	**S550**	Lcr/400	1922	2130	2339	2552	2685	2843	1136	1515	1894
		Lcr/600	2025	2249	2471	2692	2824	2976			
RR220/12,5	**S600**	Lcr/400	1997	2229	2467	2715	2871	3059	1240	1653	2066
		Lcr/600	2098	2348	2604	2864	3022	3205			
RR220/12,5	**S650**	Lcr/400	2062	2315	2582	2866	3046	3265	1343	1791	2238
		Lcr/600	2160	2434	2721	3021	3206	3424			
RR220/12,5	**S700**	Lcr/400	2118	2391	2684	3003	3209	3462	1446	1928	2410
		Lcr/600	2212	2507	2823	3163	3378	3633			
RR270/10	**S550**	Lcr/400	2178	2363	2537	2705	2805	2922	1104	1473	1841
		Lcr/600	2300	2495	2672	2837	2931	3039			
RR270/10	**S600**	Lcr/400	2288	2501	2705	2903	3022	3161	1205	1606	2008
		Lcr/600	2413	2639	2850	3047	3161	3290			
RR270/10	**S650**	Lcr/400	2385	2625	2860	3091	3230	3393	1305	1740	2175
		Lcr/600	2510	2767	3013	3247	3382	3535			
RR270/10	**S700**	Lcr/400	2471	2738	3003	3269	3430	3619	1406	1874	2343
		Lcr/600	2595	2881	3162	3435	3594	3774			
RR320/10	**S550**	Lcr/400	2722	2931	124	3308	3417	3545	1320	1760	2200
		Lcr/600	2875	3091	3285	3462	3563	3679			
RR320/10	**S600**	Lcr/400	2871	3113	3341	3559	3688	3839	1440	1920	2400
		Lcr/600	3023	3284	3515	3728	3850	3988			
RR320/10	**S650**	Lcr/400	3004	3281	3545	3799	3951	4127	1560	2080	2600
		Lcr/600	3165	3458	3730	3983	4127	4290			
RR320/10	**S700**	Lcr/400	3123	3433	3734	4029	4204	4409	1680	2240	2800
		Lcr/600	3284	3615	3930	4226	4396	4587			
RR320/12,5	**S550**	Lcr/400	3291	3585	3867	4140	4305	4498	1718	2291	2864
		Lcr/600	3476	3788	4077	4349	4506	4685			
RR320/12,5	**S600**	Lcr/400	3450	3787	4114	4437	4632	4861	1875	2499	3124
		Lcr/600	3637	3996	4339	4664	4853	5067			
RR320/12,5	**S650**	Lcr/400	3590	3967	4342	4717	4945	5214	2031	2708	3385
		Lcr/600	3775	4181	4577	4960	5185	5439			
RR320/12,5	**S700**	Lcr/400	3712	4129	4551	4980	5244	5555	2187	2916	3645
		Lcr/600	3895	4344	4794	5238	5501	5801			