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INVESTIGATING THE SOIL STRESS LEVELS FOR DIFFERENT PILE GEOMETRIES UNDER DIFFERENT LOADING CONFIGURATIONS

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Abstract

The high complexity of investigating the mechanical response of reinforced concrete pile foundations embedded in different soil domains is well known, thus not allowing a deep understanding of the overall structural and geotechnical response of the foundation system. This study investigates the Soil-Structure-Interactions (SSI) and the development of stress levels for different pile configurations under different imposed lateral displacements and superstructural loads.

SSI has a significant effect on the lateral resistance of pile groupings that assume two or more piles. The state-of-the-art 3D detailed numerical investigation performed in this research work foresaw an investigation of the effects that pile groupings under imposed lateral displacement have on soil stresses and the overall response of the soil and foundation system. An in-depth study of the resulting stress regions and levels in the soil medium was performed for different loading configurations.

The study concluded that the base reaction is proportional to the imposed displacement and the number of piles in the grouping, while the geometry of the foundation system significantly affects the soil stress development. Finally, when torsion is developed at the level of the foundation system, a significantly complicated deformation field derives that requires an advanced modelling approach to objectively and accurately investigate the overall mechanical response of the soil and foundation domains.

Keywords: Soil-structure-interactions, finite element method, numerical investigation, pile groupings, reinforced concrete.

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1 INTRODUCTION

In industry and the academic scene, engineers make use of software to model large and complex reinforced concrete (RC) structures. The majority of these software packages make use of the Finite Element Method (FEM) to compute how the structure and in some cases how the founding material would react to various loading scenarios. When analyzing the mechanical behavior between the structure and the founding soil it can be challenging to visualize or study what is occurring below the structure as the soil does not provide indicators of stresses or strains that other materials such as steel would. By attempting to model conditions that the built structure would be experiencing in-situ, the engineer can visually represent results and develop a better understanding of factors that are affecting the capacity of a structure.

Structures are typically built on top of foundations, which serve as anchors and support the structure while allowing reactions to be transferred and loads to be distributed into the soil. Pile foundations are one of the many different types of foundations that interface between the soil and the structure. Pile foundations are generally used where the soil conditions are poor, this could be expansive soils or weak, collapsible, and compressive soils that extend below the base of the structure. Occasionally single piles act as foundations for parts of a larger structure but most commonly piles are closely spaced, grouped, and tied together by a pile cap to support structural members.

When pile foundations are grouped the total capacity of the group is not equal to the sum of the capacity of the individual piles. When the spacing between piles is small the stress regions around each pile overlap according to the load applied at the pile cap. The overlapping stress regions reduce the load-bearing capacity of the individual pile and thus in turn the capacity of the pile grouping. Factors such as the soil type, the method of pile construction, pile geometry, and the load application and direction also affect the stress regions around the pile foundation.

The reaction of soil when loads or displacements are applied, and stresses are induced is relatively complex to model as the soil does not exhibit a definite elastic stress region. There are many non-linear material models of soil that each have their own unique relationships between the stress and strain of soils. The behavior of soils is sometimes simplified to a model with an elastic and plastic region defined by a "yield point" which is classified as the failure point of the soil. If the critical stresses were to be reached in the soil that surrounds the foundations, the structure would develop a large settlement or even collapse due to the loss of support. Therefore, engineers need to understand both structural and soil mechanics, this knowledge provides insight into the interaction between the structure and the soil, and how the stress regions form in the soil around foundations. The implementation of FEM in large-scale construction jobs could lead to a reduction in the occurrence of structural failures and in turn, provide engineers with safer designs.

2 SOIL REACTION AROUND LATERALLY LOADED PILES

Applied loads on piles can be axial, either having a tensile or compressive component, lateral or moment. Although horizontal loads are minor in comparison to vertical loads in the majority of foundations, there are some cases, such as retaining structures piles and harbor constructions that are subjected to large lateral loads. Furthermore, significant lateral loads occur in the event of an earthquake and other seismic actions.

Horizontal soil displacement in front of laterally loaded piles was researched and presented in [1]. It was concluded that horizontal displacements are often greater than vertical displacements and that both values reduce exponentially as the distance from the pile surface increases. Using a Strain Wedge (SW) model, [2] examined the strain induced in front of a laterally loaded pile. They concluded that using the SW model to solve the problem of a laterally loaded pile is a robust method. In several experimental tests using a pile model, [3] found that spacing greater than six times the pile diameter had no group impact. The group impact rises when the pile gap is reduced by 5.65 pile diameters, according to [4]. X-ray computed tomography was used to analyze 3D failure patterns in the sand caused by a laterally loaded pile [5]. The failure zones stretch, and the volume and angle of the failure zone rise as the pile loading level increases, although there is an ultimate value at some loading levels, according to the findings. In addition, as the depth along the pile increases, the area of the failure zone reduces. The 3D form of the failure zone is near conical as shown in Figure 1.

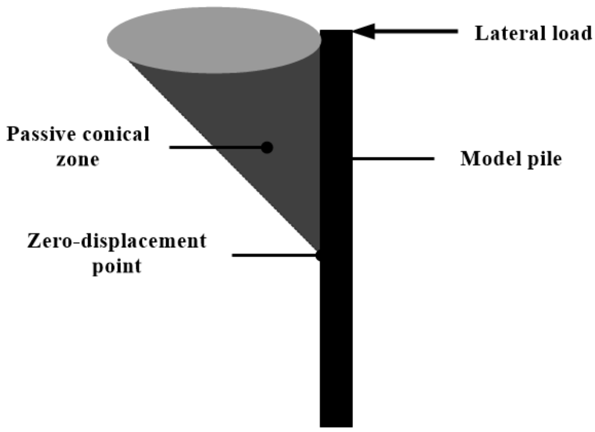

Figure 1: Conical passive zone of a laterally loaded pile.

3 NUMERICAL MODELLING OF PILE FOUNDATIONS

The pile foundations assessed herein are groupings commonly used in the construction of bridges, piers, and building foundations. The founding soil medium is assumed to be uniform in composition and stiffness. The soil modelled can be classified as a non-expansive, medium stiff to hard clay and there is no layer of soil or rock for the pile to be embedded into. For this reason, the pile foundations modelled are considered friction piles. Induced stresses and strains in the soil caused by pile driving or other installation methods were not considered in this investigation as this phenomenon was outside the scope of this research work. It is important to note at this point that the piles that will be modelled are vertical, thus battered piles will not be considered in this study [6].

The modelled piles have a diameter of 40 cm and an embedded depth of 7 m. The pile cap has a depth of 60 cm leaving a gap of 10 cm which allows the pile cap to decouple from the soil surface, thus allowing the piles to transfer all the imposed loading into the soil medium. Piles are spaced at 3.5 times the pile diameter (1.4 m spacing). The average hexahedral element size is 10 cm. The formulation of the isoparametric hexahedral finite elements that were used in this research work is based on the elements used in [7]. The pile cap system consists of modules (1.4 m by 1.4 m by 0.6 m deep) that are meshed together to form a single pile cap that tied the pile foundations together. The pile caps increased in size as the number of pile foundations increased.

All the pile foundations assumed the same reinforcing layout being 1% longitudinal reinforcing (12Y36) and (Y10) stirrups spaced at 100 mm intervals with 30 mm of concrete cover. The reinforcing in the pile cap varies from the traditional cage structures. To reduce the model's complexity a simplified layout was used. It is important to note at this point that the reinforcement was modeled as embedded rebar elements and the discretization and embedded rebar mesh generation were performed according to [8].

The soil geometry for each pile grouping was unique. As the number and rows of piles increased, the soil geometry needed to be increased accordingly. The edge distance for the perimeter piles remained constant for all pile groupings, 2.8 m in the direction of the imposed displacement (x-direction) and 2.1 m in the y-direction (see Figure 2).

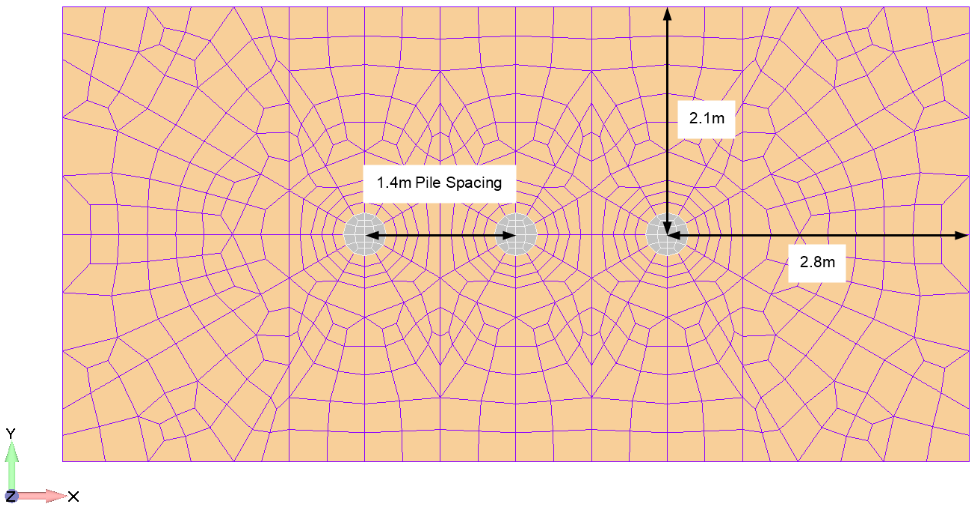

Figure 2: Hexahedral mesh and soil geometry of a 3-pile grouping (G3)

As illustrated below in Figure 3, all models had a constant soil domain depth of 9 meters with translational fixity in the x and y directions on the vertical perimeter planes and complete fixity in x, y, and z on the horizontal base plane.

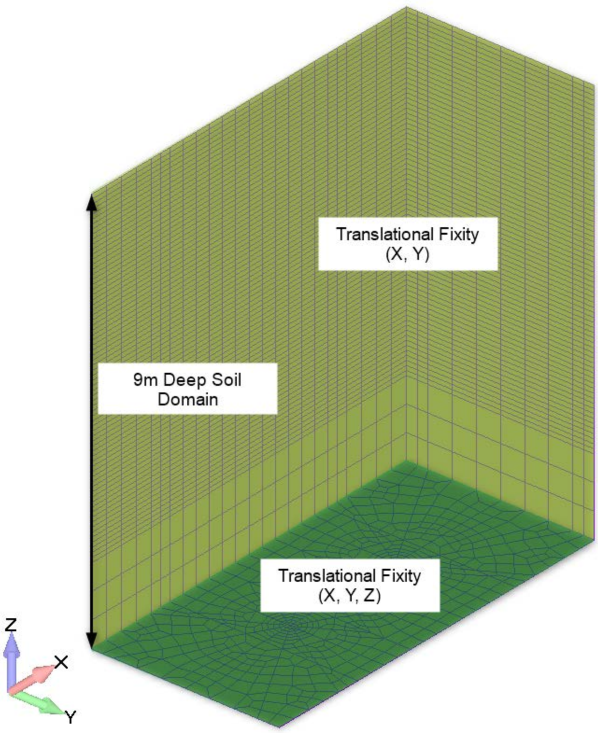

Figure 3: Boundary conditions of soil domain (Fixed DOFs)

For the needs of this research work, two different imposed displacements were assumed. The first foresaw a horizontal imposed displacement that was solved by using a displacement control problem [9], whereas the second assumed the imposition of displacements that would lead to the development of pure torsion at the level of the pile grouping.

For this experiment, uniform material properties were chosen for all models, based on engineering judgment (as shown in Table 1). The soil modeling employed a von Mises yielding criterion, in line with the approach adopted in [6]. For the needs of the nonlinear numerical modeling of the RC domain of the piles, the 3D detailed approach presented in [7] was adopted. This approach foresees the simulation of cracking through the use of the smeared crack approach, where the microcracking effect is also accounted for [7].

Material	Modulus of Elasticity (MPa)	Poisson's ratio	Compressive/Tensile Strength (MPa)
Clay Soil	100	0.3	0.25
Concrete	30,000	0.2	60
Steel	200,000	0.3	450

Table 1: Material properties of all models

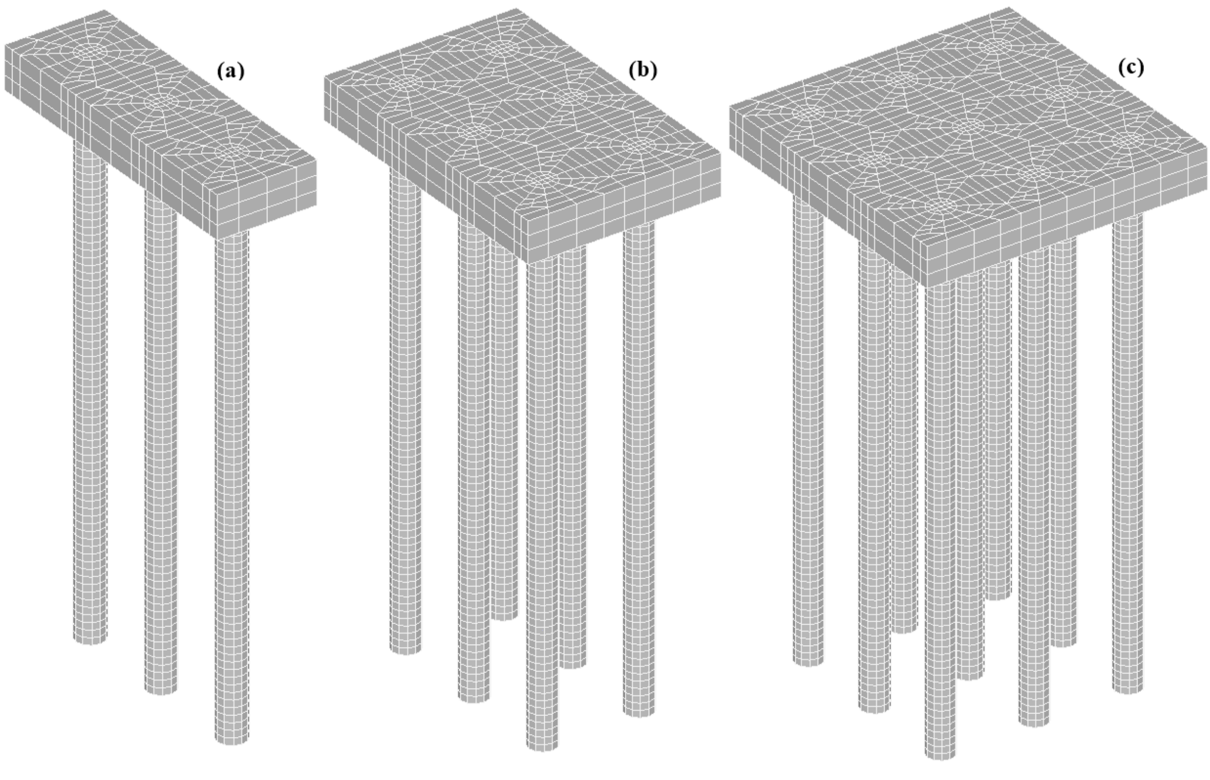

Figure 4: Pile and pile cap system. (a) G3 pile grouping, (b) G2x3 group and (c) G3x3 group

As this study investigates the grouping effects of pile foundations, multiple numerical models were created. The pile group models are denoted based on their arrangement, characterized by the group (G) and the number of rows (y-direction) by the number of piles in the x-direction. Three representative pile group models are depicted in Figure 4. Figure 4a portrays a single group of three piles (G3). Figure 4b showcases a group of piles comprising two rows, each containing three piles (G2x3). Figure 4c illustrates a group of piles consisting of three rows, each with three piles (G3x3). These models serve as a comprehensive representation of the pile group arrangements under investigation.

4 IMPOSED DISPLACEMENTS AND LOADING PROCEDURE

4.1 Push over analysis

Push-over analysis (POA) was conducted by imposing 10 mm (2.5% of the pile diameter) of uniform horizontal displacement (see Figure 5) to the pile caps using 10 or 20 displacement increments depending on the size of the mesh as can be seen in Figure 6. Furthermore, a vertical static load equal to 10% of the ultimate capacity of the RC pile or pile grouping was applied to each of the pile caps to simulate the superstructural loads.

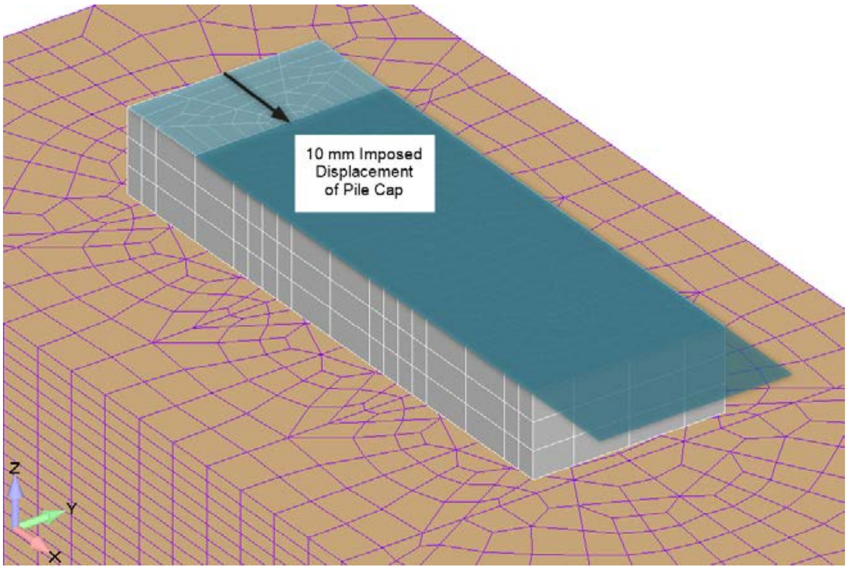

Figure 5: Graphical representation of the imposed displacement at the pile cap.

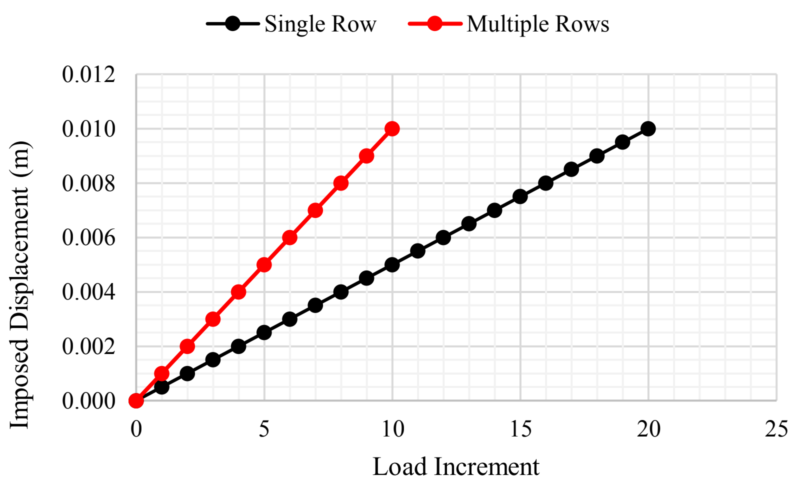

Figure 6: Loading of Pushover Analysis for smaller (Single Row) and larger models (Multiple Rows).

Pile groupings that consisted of a single row of piles (G1, G3, and G4) were not as computationally demanding as the larger groupings with two (G2x3, G2x4, G2x6) or three rows (G3x3, G3x4, G3x6) of piles. For this reason, it was decided to load the simpler models to the maximum imposed displacement in 20 load increments (see Figure 6 Single Row) and the larger models in 10 load increments (see Figure 6 Multiple Rows). The effect of changing the number of load increments does not affect the structure and how the model reacts to loading, it does however influence the refined representation of the numerically obtained P-δ curve [6].

4.2 Torsional Imposed Deformation

The Torsional Imposed Deformation (TID) was conducted by imposing a total 10 mm uniform displacement to two opposing faces of the pile caps using the same loading increments. The 10% vertical static load was also applied to these tests during analysis. Figure 7 shows the imposed rotation applied to the pile cap during the TID of the models.

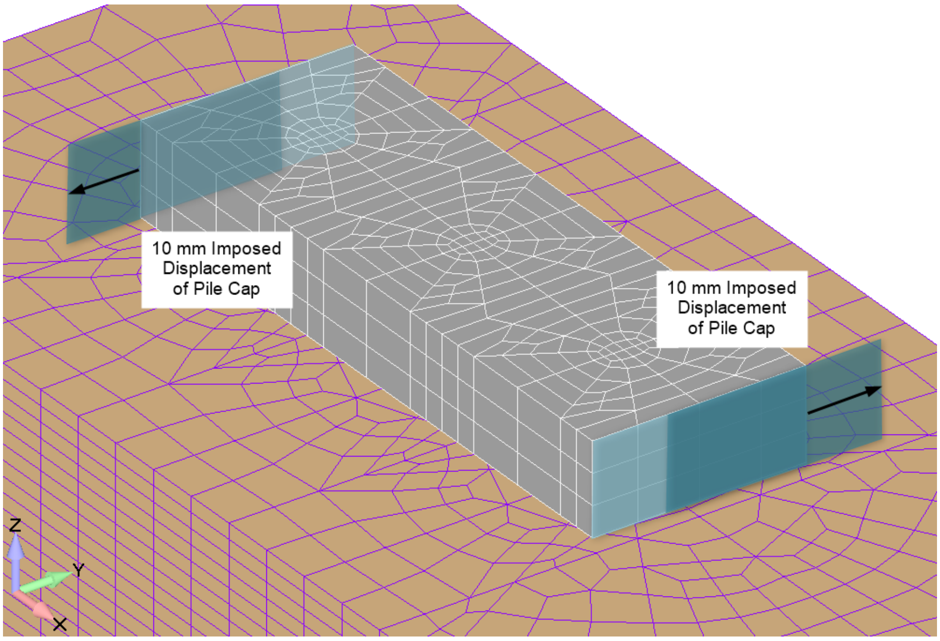

Figure 7: Imposed Rotation of the pile cap.

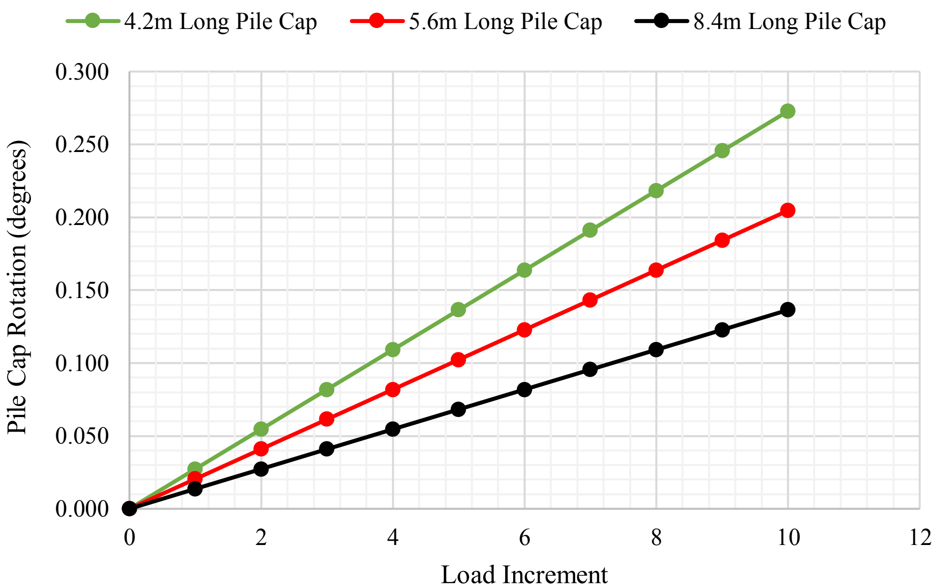

Figure 8: Loading of Torsional Imposed Deformation.

All the pile groupings underwent the same level of imposed displacement on each opposing pile cap edge, however as the length of the pile cap increased the rotation of the system decreased. Pile groupings with three piles in a row (4.2 m long pile cap) had a smaller rotational lever arm than the pile groupings with four (5.6 m long pile cap) or six (8.4 m long pile cap) piles in a row (see Figure 8).

5 PUSH-OVER ANALYSIS RESULTS

Failure in pile foundations can occur in multiple ways, most commonly being the failure of the surrounding soil (bearing failure, excessive lateral deformation, etc.) or the pile foundation itself could fail (pile plastic hinge, reinforcement rupture due to excessive bending, etc.). During the investigation conducted herein, it was discovered that the embedded rebar elements would fail when higher displacements were imposed upon the pile groupings due to excessive tension.

For the needs of this research work, the investigation of stress development in the soil domain was conducted by selecting three critical points along the pile length. These critical points can be seen in Figure 9, where the solid von Mises (SVM) stress development was plotted against the base shear reaction for every pile in the groupings studied. For pile groupings that consisted of two or three rows of piles (i.e., G2x3 and G3x3, etc.) the average of the stresses in each row was plotted against the base shear reaction as the percentage difference between the curves was low (less than 10%).

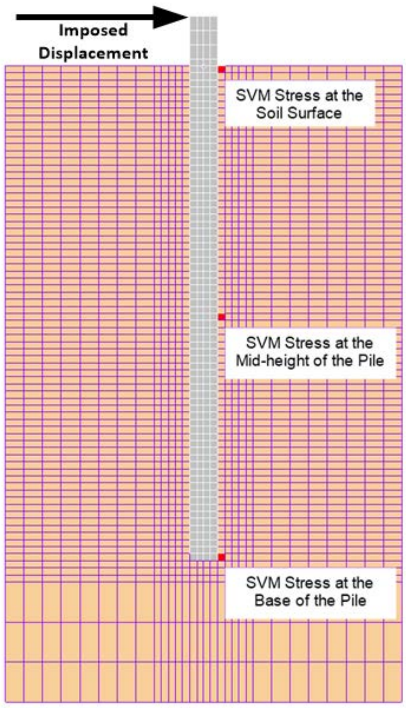

Figure 9: Points monitored for the development of the stress curves.

5.1 Single pile

When investigating the result from loading a single pile (see Figure 10), the soil elements at the surface layer reach the set maximum ultimate compressive stress (250 kPa) quite rapidly after a few load increments. The stress level at the base of the pile is usually higher than the stresses at the mid-height of the pile. This phenomenon is predominantly caused by the distribution of bearing stress at the base of the pile. When studying Figure 11 it is evident that there are relatively large increases in the SVM stresses in early load increments until a point where the stress growth rate stabilizes. At the mid-height of the pile, there is little to no growth in the SVM stress levels (this changes based on the grouping configuration). Near the base of the individual pile, it can be seen that there are effects of bearing stress that increase the SVM stresses surrounding the pile base, which is possibly caused by the applied vertical static load. This phenomenon becomes more complex when pile groupings are analyzed and will be discussed. These trends can be seen in pile groupings with some degree of variation.

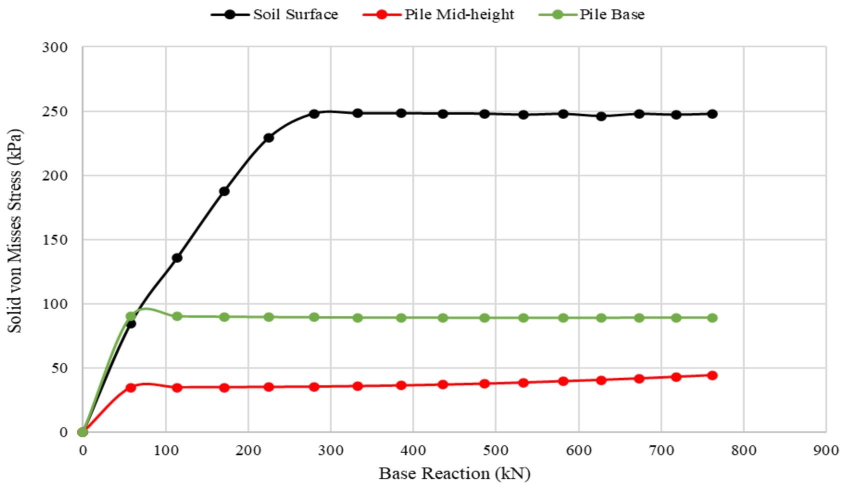

Figure 10: SVM stress development for a single pile G1.

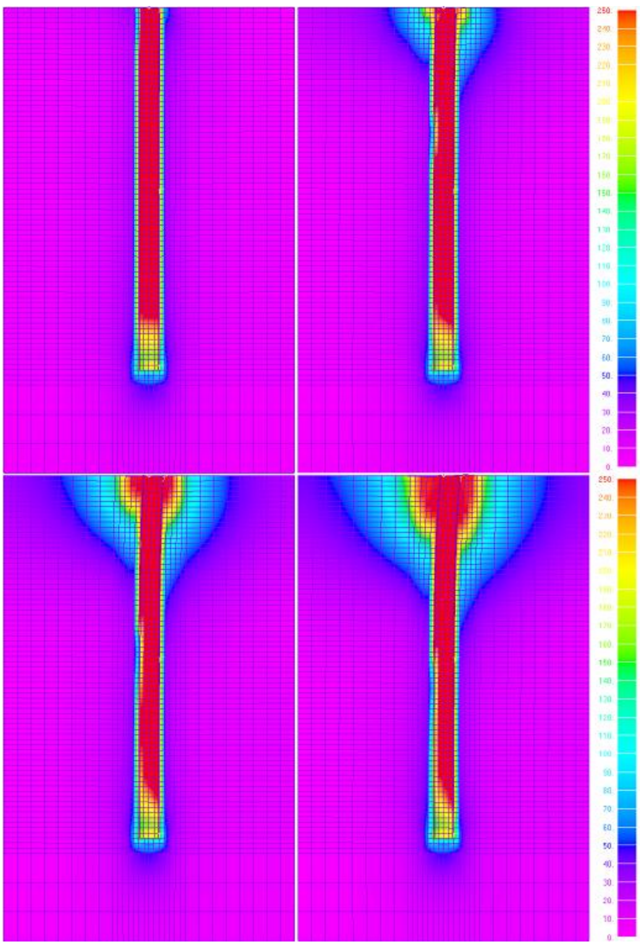

Figure 11: SVM stress distribution around a single pile (kPa) with increasing imposed displacements.

5.2 Pile groupings

As an imposed displacement is applied to the pile groupings a shear reaction develops in the soil medium. The shear reaction is directly proportional to the imposed displacement and the size of the pile grouping. As the number of piles in the pile grouping increase so does the base rection (shear reaction) of the foundation. In Figure 12 it can be seen that increasing the group size results in a higher base reaction and subsequently a higher lateral resistance. The orientation of the pile grouping with respect to the applied load or displacement also influences the lateral resistance of the pile foundations. The development of the shear resistance for pile groupings G2x6 and G3x4 are similar. Both groupings have the same number of piles (12) and the only factor contributing to the difference in lateral resistance is the orientation of the group. Pile groups with a longer group length in the direction of the applied force or displacement will have higher lateral resistances.

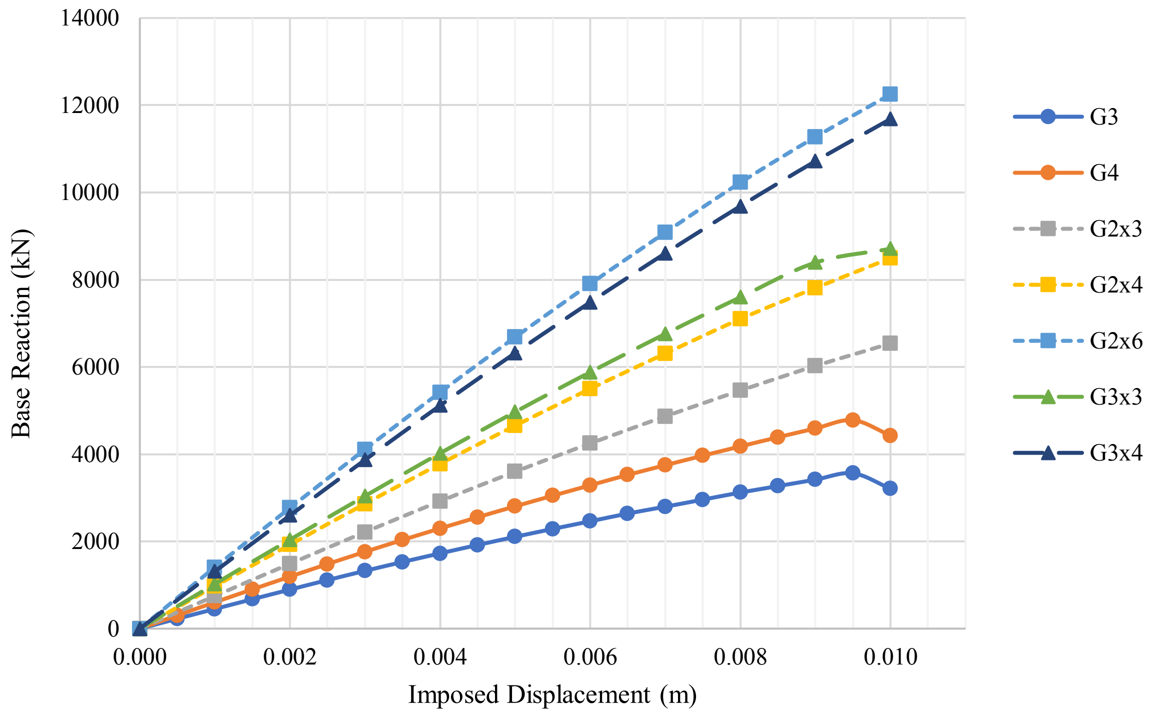

Figure 12: Combined P-δ curves for various pile groupings.

It should be noted that for pile groupings G3, G4, and G3x3 there is a slight decrease in the shear reaction near the end of the loading procedure. This is caused by cracks developing and propagating in the concrete at the base of the pile cap combined with reinforcement yielding. This failure first occurs in the last pile (due to high soil compression) and spreads to the rest of the piles eventually reaching the leading pile (first pile).

When considering soil elements that surround the piles at the soil surface level, it can be seen that the stress around the individual piles in the group reaches the ultimate compressive resistance of the soil (250 kPa). The soil around the leading pile in the group reaches the maximum stress and plateau quite fast when compared to the subsequent piles. The trailing piles in the group have soil-stress development curves that are almost parallel with a small degree of difference. These relationships can be seen in Figure 13.

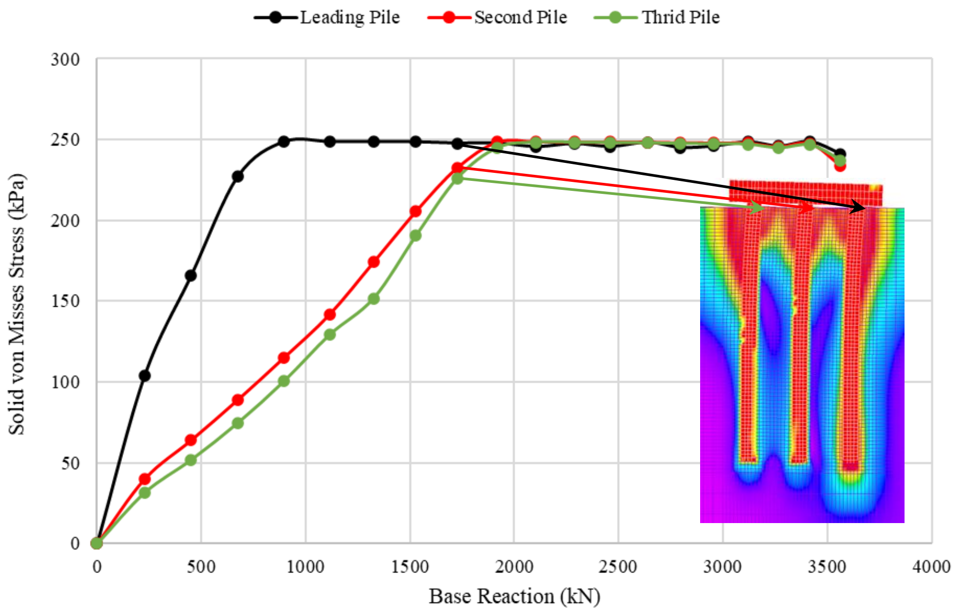

Figure 13: Stress development curve of pile grouping G3 at the soil surface.

When assessing the soil elements that surround the piles at the mid-height of the pile foundation, the stress around the individual piles in the group gradually increases but does not reach the ultimate compressive resistance of the soil. The leading pile in the group is found to develop a higher soil-stress increase rate than the subsequent piles. On the other hand, the trailing piles in the group have soil-stress development curves that are relatively similar to the third (last pile) deriving a slight decrease and then a higher increase rate in stress levels. This mechanical response is depicted in Figure 14.

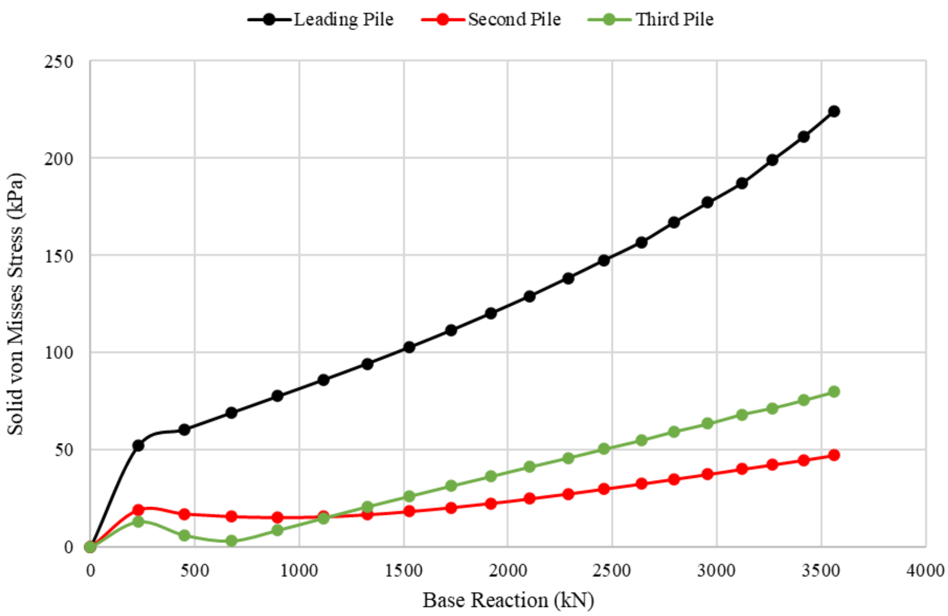

Figure 14: Stress development curve of pile grouping G3 at the mid-height of the pile.

The soil elements that surround the piles at the base have more complex reactions to lateral loading. Stress in the soil elements around the pile base of the leading pile increase until the ultimate compressive force is reached, where this happens near the midpoint of the loading stage as seen in Figure 15. The middle pile or piles in the group have a steady decrease in soil-stress levels in the front of the pile and an increase in stress at the rear of the pile. This effect is attributed to the movement of the pile in the opposite direction to the applied displacement (see Figure 16). The movement of the pile grouping in the negative x-direction occurs when the system experiences out-of-plane clockwise rotation.

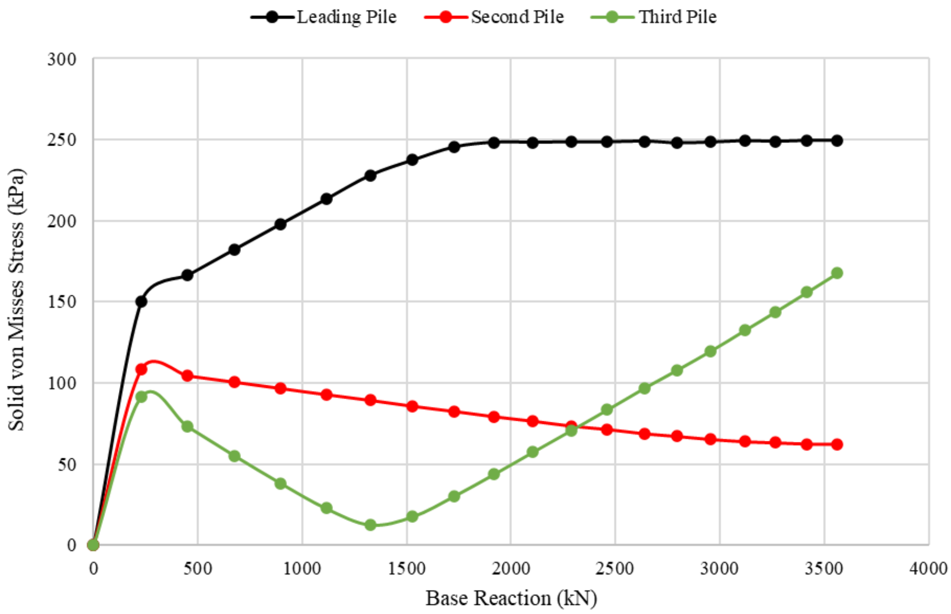

Figure 15: Stress development curve of pile grouping G3 at the pile base.

The deformation shape of the soil elements with increasing displacement steps (DS) can be seen in Figure 16, where the deformation has been scaled by 50 times. It is easy to observe that the high initial vertical displacement of elements under the leading pile is evident. The soil elements surrounding the leading and second pile deform downwards (settlement), while there seems to be some degree of heave of elements surrounding the third pile foundation. These effects cause the pile group to rotate about the out-of-plane axis in a clockwise manner and if the rotation were to become excessive it would result in the cracking or failure of the pile cap, buckling failure of the pile, or reinforcement failure.

In Figure 15 it can be seen that the last pile in the group experiences a rapid decrease in soil stress until a turning point on the curve is reached. Following this, there is a rapid increase in stress levels, whereas the total rotation of the system eventually causes a decrease in stress. The stress increase at the base of the pile occurs when the rotation of the pile grouping is resisted by an increasing bearing stress in the soil surrounding the last pile. These phenomena can be seen in Figure 17. The SVM stress development in the soil domain and the discussed phenomena can be seen in Figure 18.

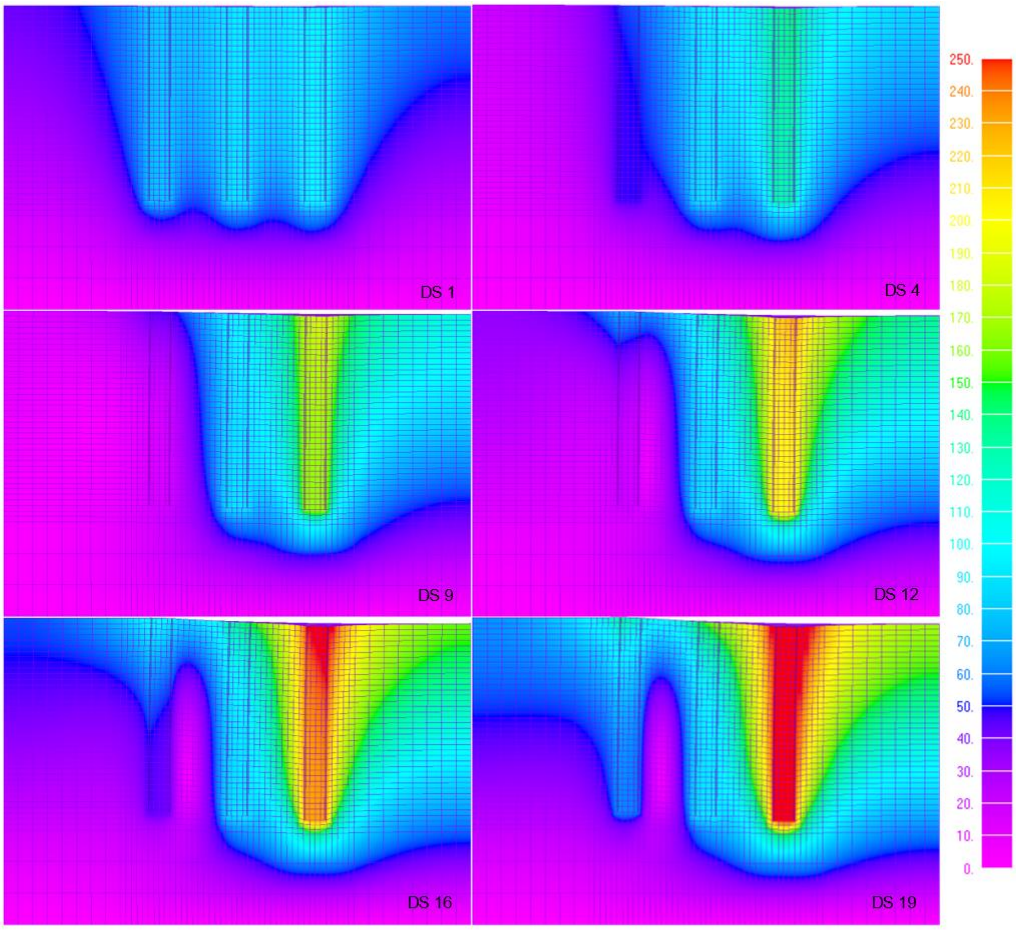

Figure 16: 50x scaled total translation in the bottom half of the soil domain (G3).

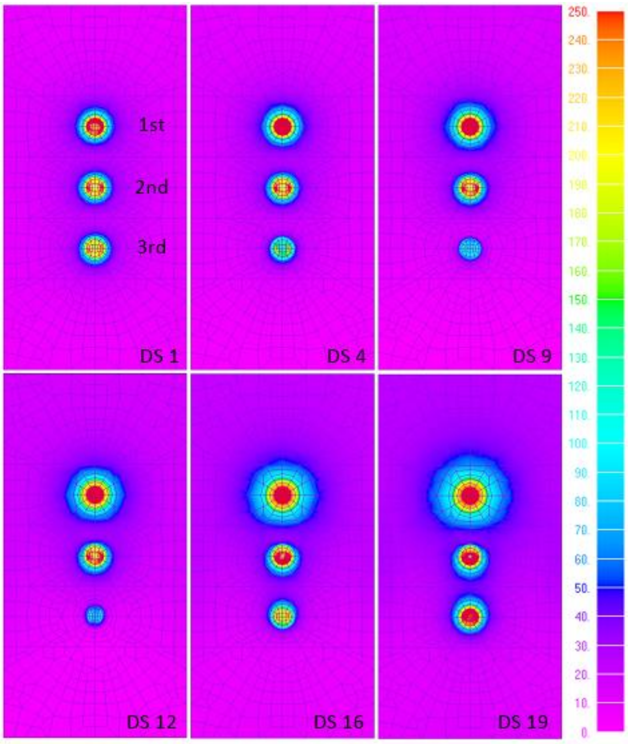

Figure 17: Bearing stress under the leading (top), second (middle), and third (bottom) pile foundation (G3).

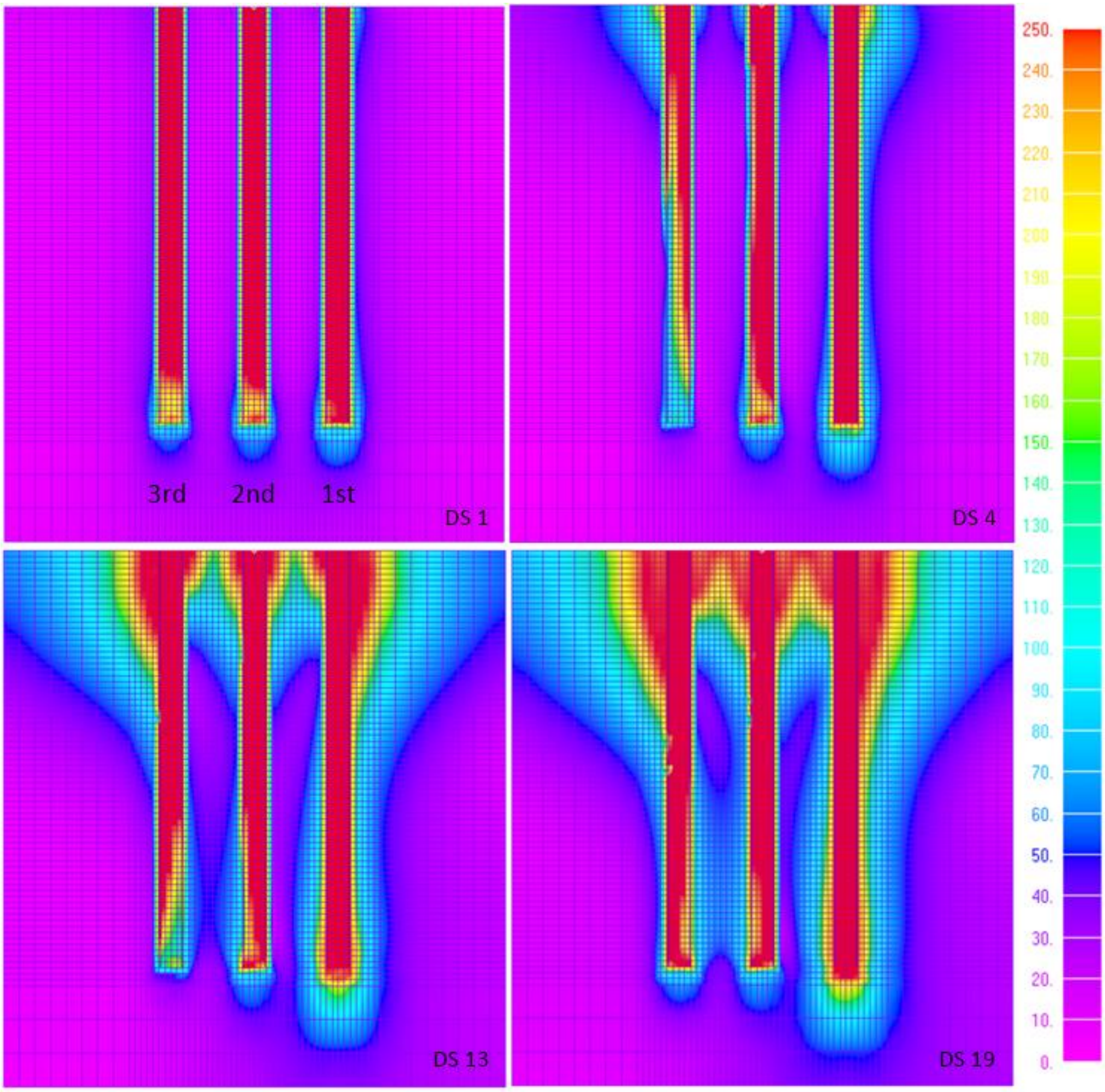

Figure 18: SVM stress contours for pile group G3 at different displacement levels.

The overlapping of stress regions in the soil surrounding the pile foundation can result in the plastification of the soil and consequently the failure of the pile system. The stress within the elements at the soil surface can be seen in Figure 19a. High stresses surround the pile and accumulate where the stress bulbs overlap, an effect that results in a block of elements with the same stress magnitude. In Figure 19b and Figure 20, the stress isosurfaces can be seen (predominantly the leading and the second pile) in a region of equal stresses. These high stresses surrounding the leading pile were explained previously by the rotation of the pile cap and the overall deformation of the foundation system when pushed horizontally. It is also important to note that the vertically applied superstructure load also contributes to the development of the field within the soil domain. It is noteworthy to state here that the vertical load also decreases the overall horizontal rotation of the piling foundation system, as it was found from the parametric investigation, thus acts as a stabilizing mechanism.

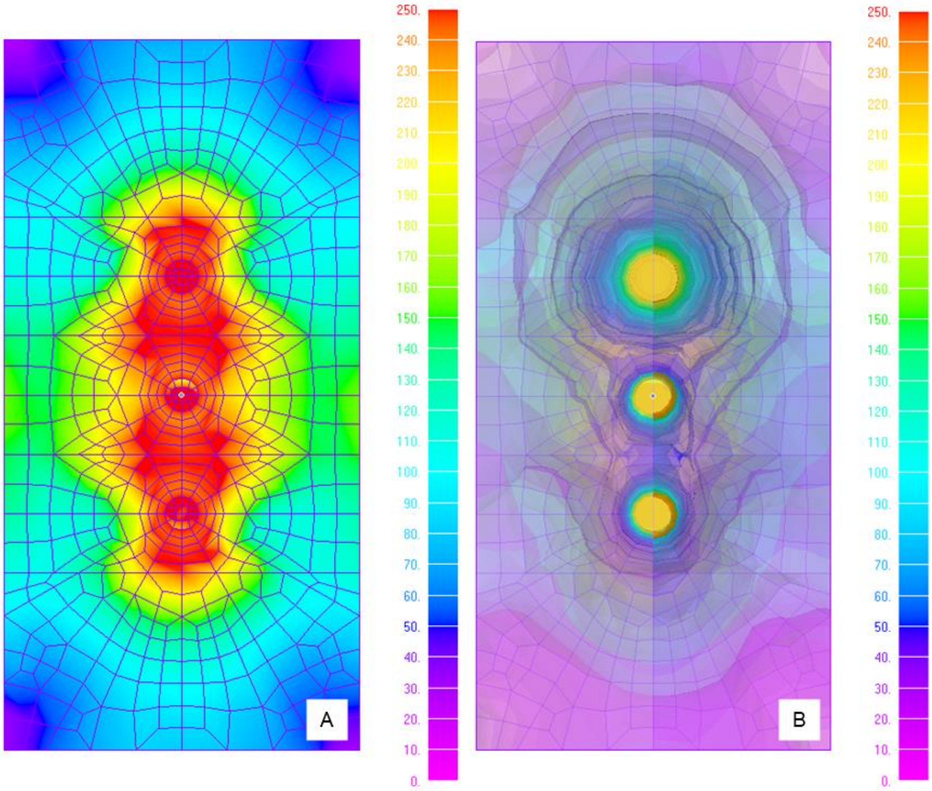

Figure 19: Top view of soil domain (G3) illustrating (a) soil stress distribution and (b) overlapping stress isosurfaces in kPa.

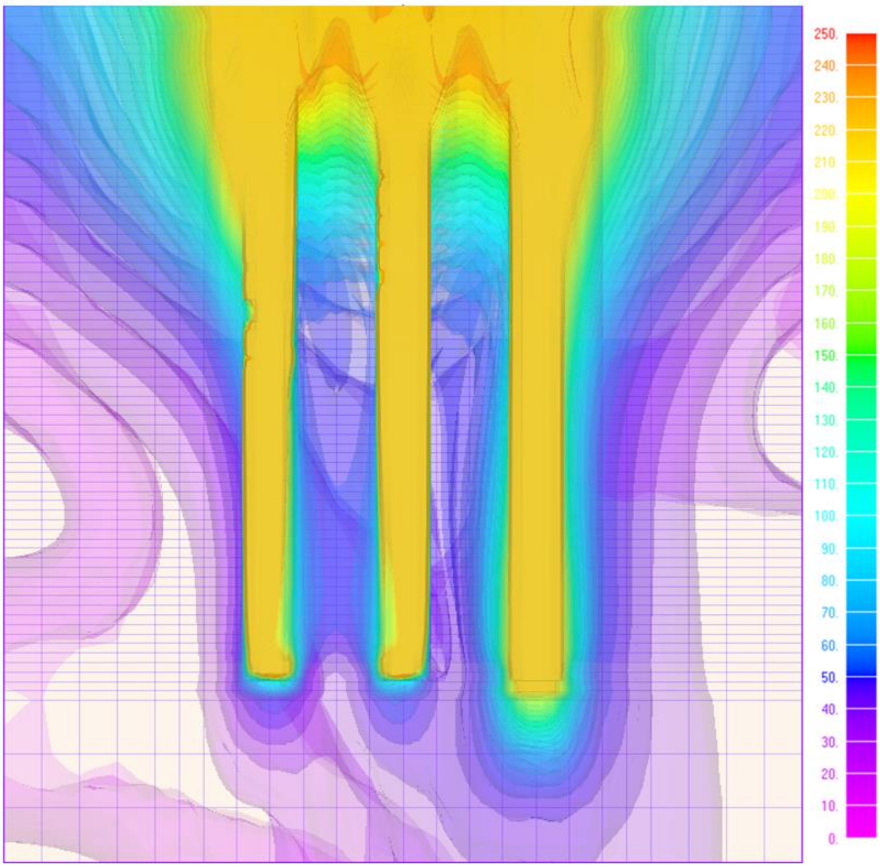

Figure 20: Section view illustrating stress isosurfaces in the soil around model G3 in kPa (DS 19).

The relationships discussed for the pile grouping G3 can be applied to the larger pile groupings analyzed for the needs of this research work. The SSI and phenomena were observed in all the subsequent pile groupings. The figures below serve to validate the previously discussed behaviors. Larger pile groupings show the intermediate curves in the stress development of the pile groupings under imposed horizontal displacements and vertical superstructural loads. The validation of the above statement can be seen below using the pile groupings G4 (see Figure 21 through Figure 24) and G2x6 (Figure 25 through Figure 28).

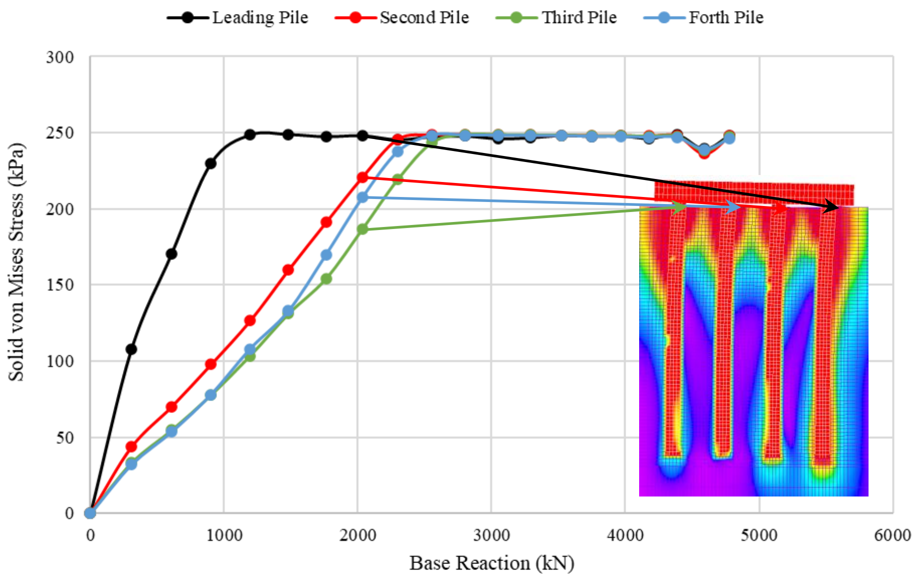

Figure 21: Stress development curve of pile grouping G4 at the soil surface.

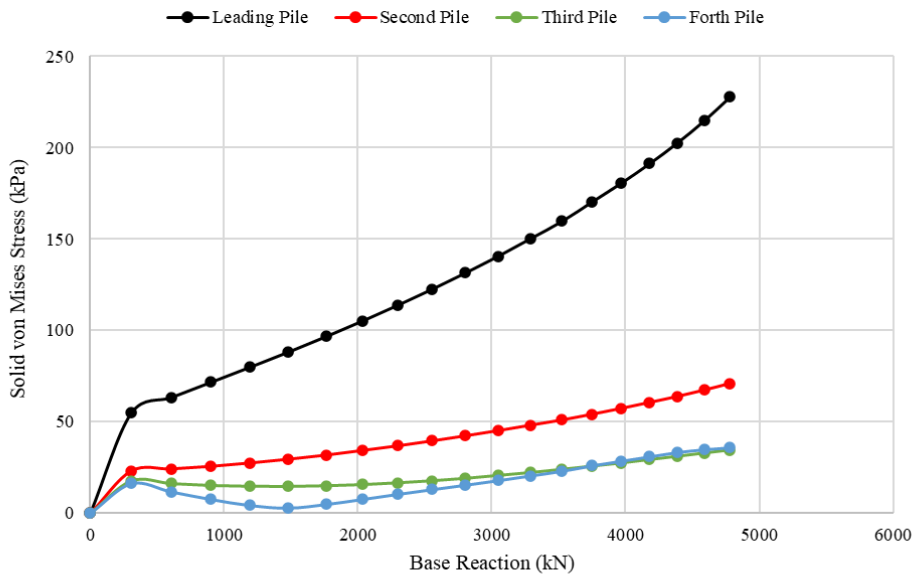

Figure 22: Stress development curve of pile grouping G4 at the mid-height of the pile.

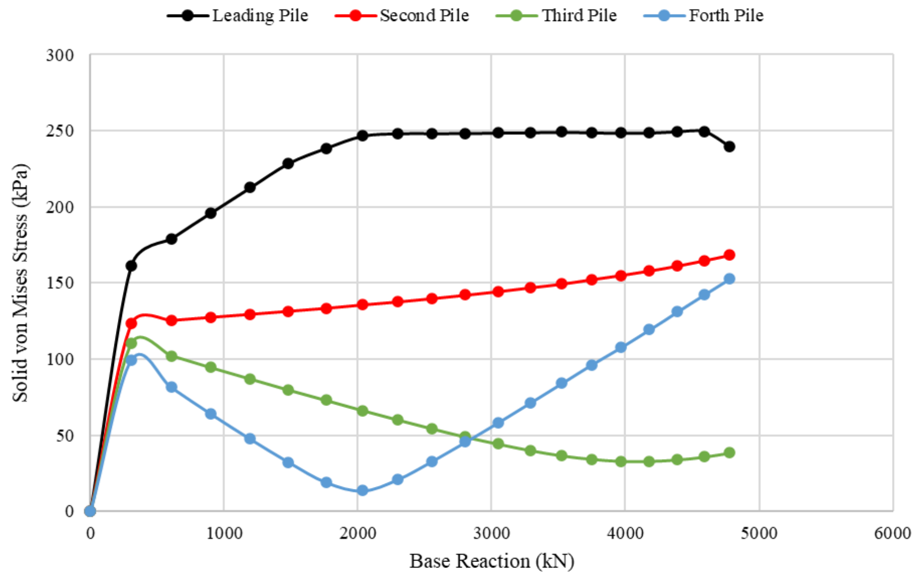

Figure 23: Stress development curve of pile grouping G4 at the pile base.

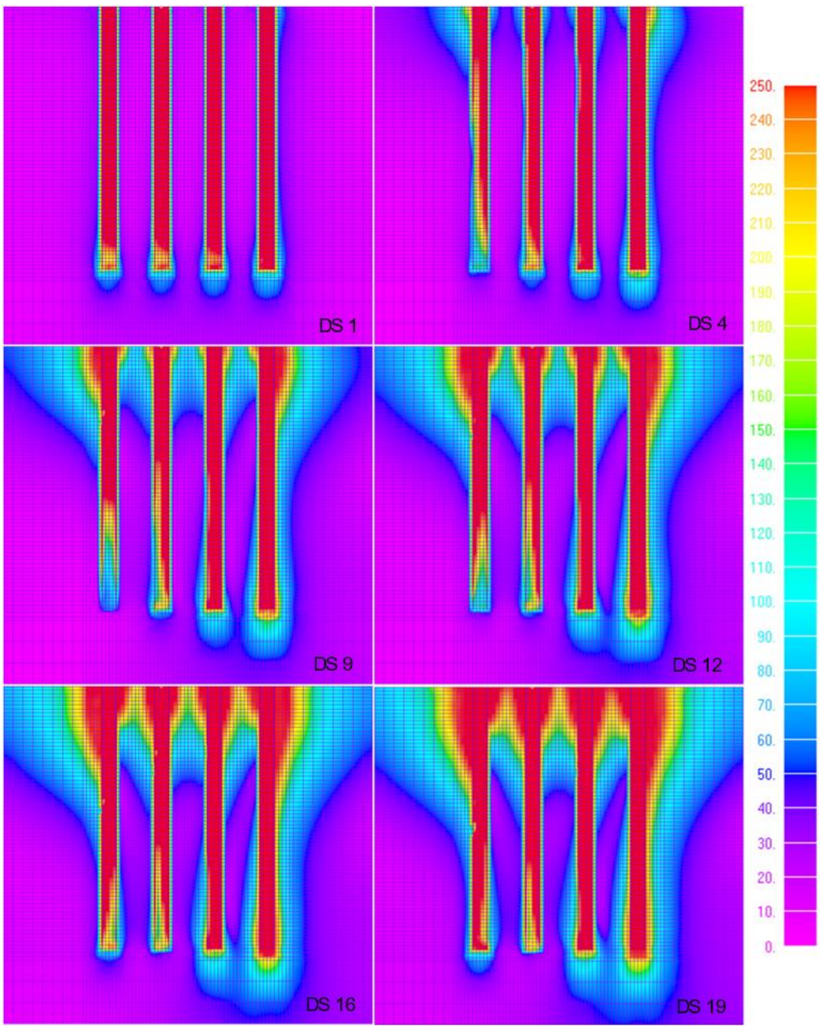

Figure 24: Stress development (kPa) in pile grouping G4 at increasing imposed displacements. Number of displacement increments imposed: max DS = 20.

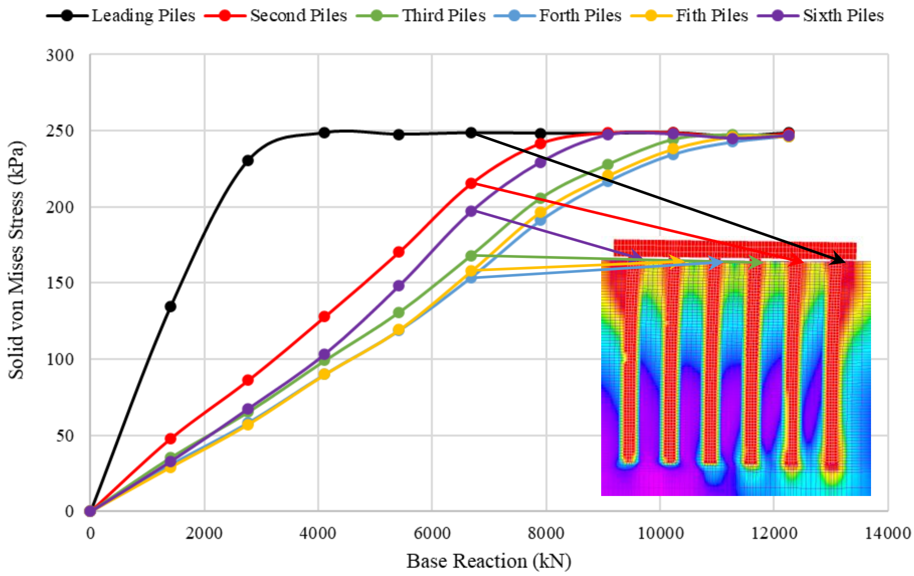

Figure 25: Stress development curve of pile grouping G2x6 at the soil surface.

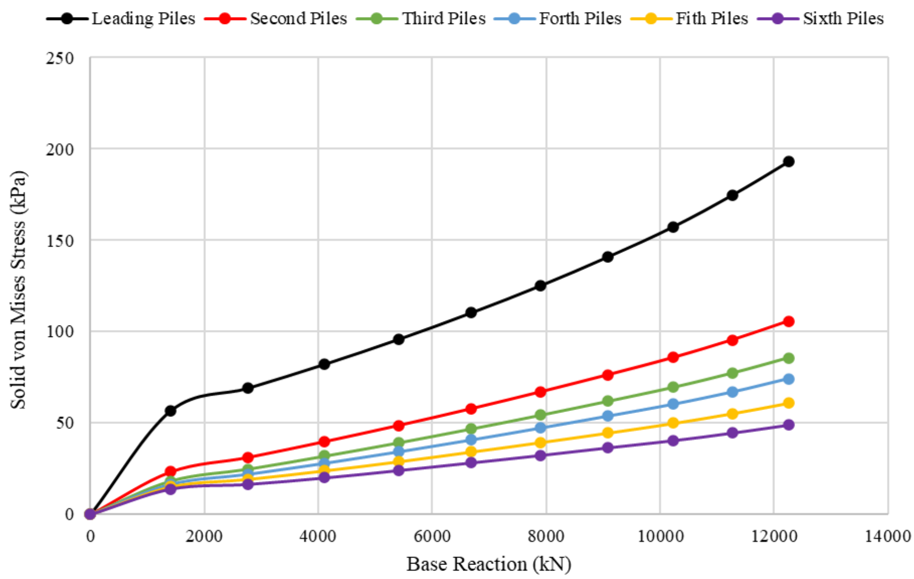

Figure 26: Stress development curve of pile grouping G2x6 at the mid-height of the pile.

Figure 27 shows that the effect of soil stress decreases at the last pile's base which is more visible since the geometry of the pile foundation system G2x6 is larger and more complicated (see Figure 28) compared to the G3 group series. The overall rotation of the foundation requires a larger horizontal displacement to fully develop, significantly affecting this way the soil stress development as noted from the graphs in Figure 27. This finding also highlights the complexity of the SSI problem that in this study only accounts for a monotonic loading condition, neglecting the more complicated phenomena that will derive when a cyclic load is applied.

Furthermore, it is also easy to observe that the stresses within the soil domain increase significantly under the base of the leading piles (see Figure 28). This is attributed to the overall rotation of the pile cap as it is being pushed along the x-axis. This mechanical response was found to develop for all groupings investigated in this research work.

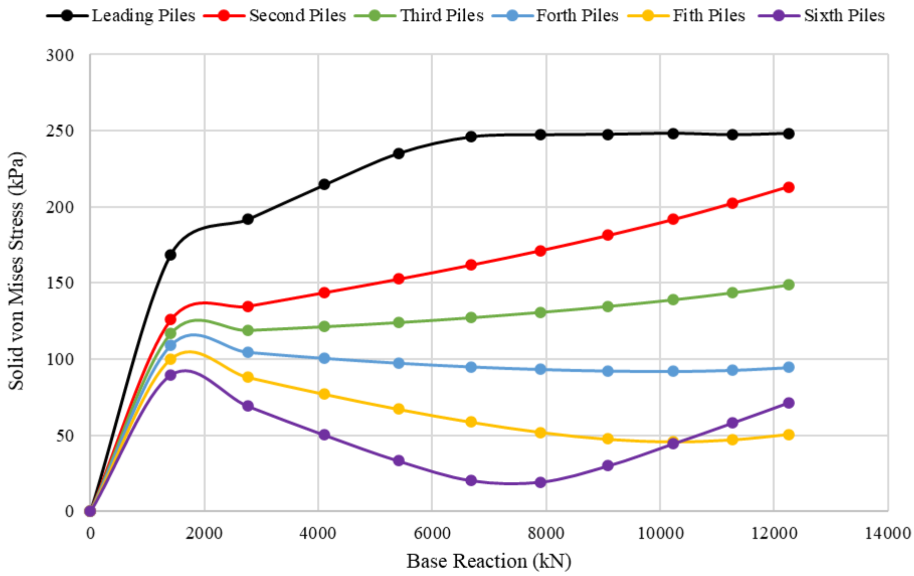

Figure 27: Stress development curve of pile grouping G2x6 at the pile base.

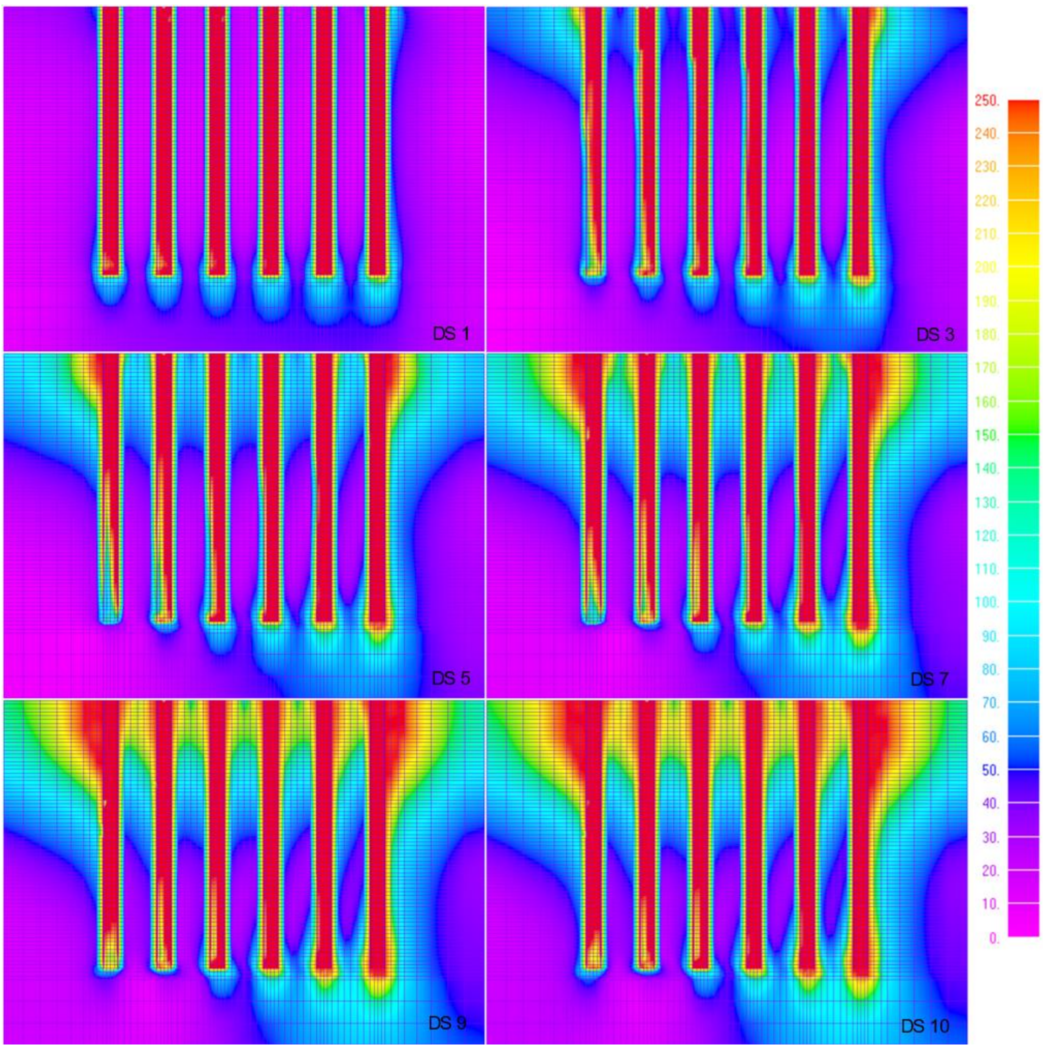

Figure 28: Stress development (kPa) in pile grouping G2x6 at increasing imposed displacements. Number of displacement increments imposed: max DS = 10.

6 TORSIONAL IMPOSED DEFORMATION

Similarly, to the POA, larger pile groupings were more susceptible to developing soil failure due to the overlapping 3D stress regions. Larger pile group systems exhibited stiffer behavior than the smaller groupings and this caused the embedded rebar elements in pile groupings G2x6, G3x3, and G3x4 to fail at the maximum imposed torsion.

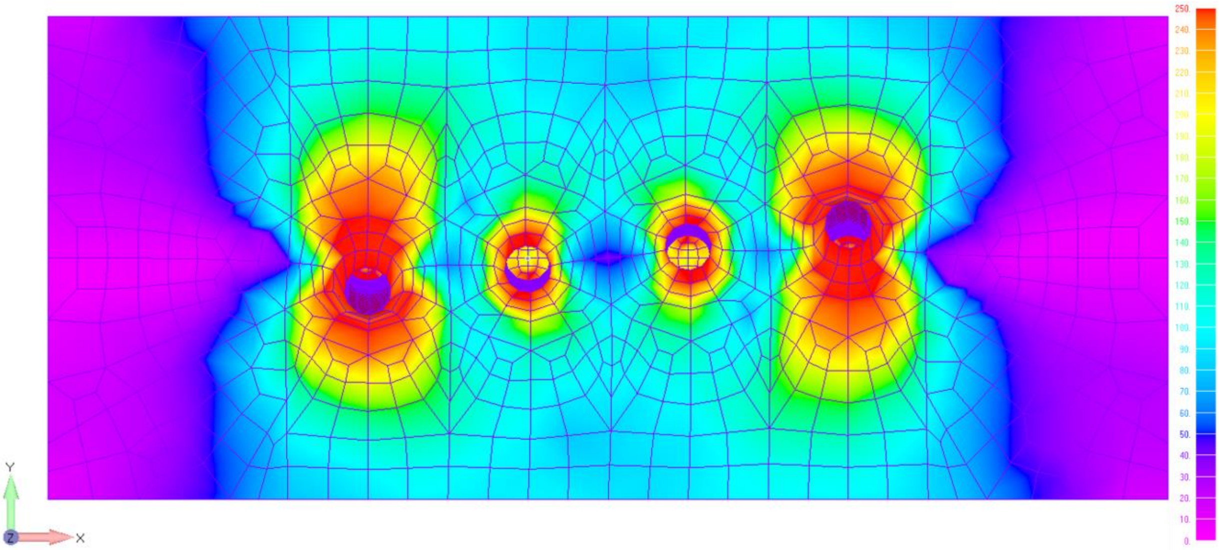

Figure 29: Scaled deformed top view showing the SVM stress distribution around group G4 (kPa) under imposed torsion (DS 20).

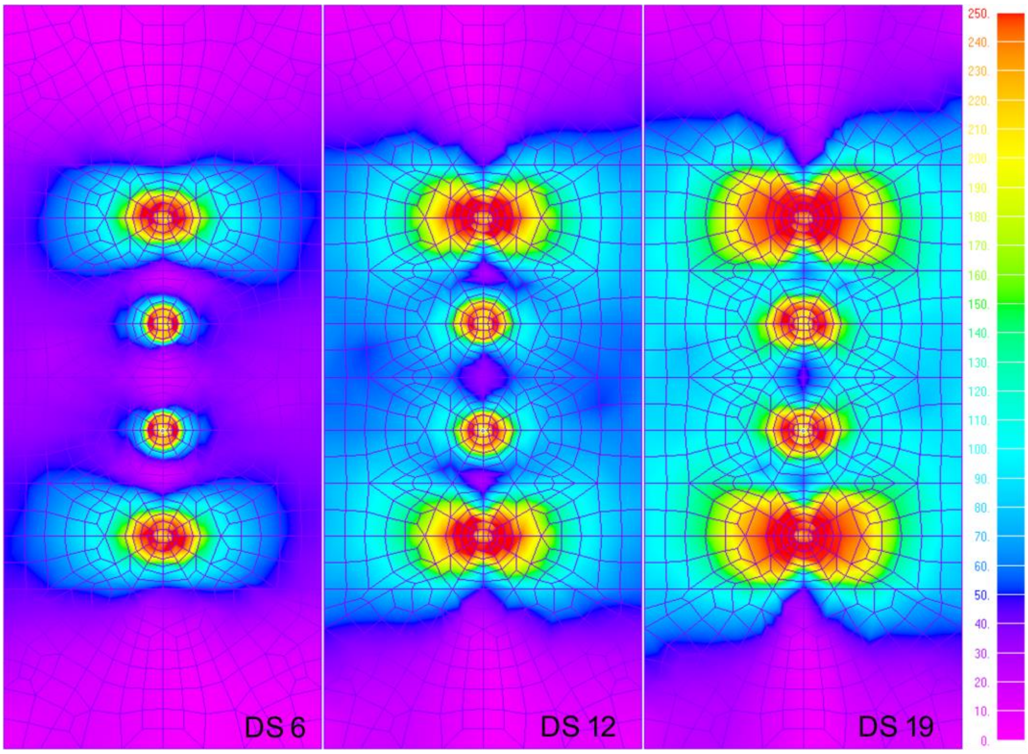

Figure 30: Top view of SVM stress development (kPa) for displacement steps 6, 12, and 19 for group G4. Number of displacement increments imposed: max DS = 20.

As an imposed rotation is applied to the pile groupings, stress develops in the soil medium. Accordingly, the developed stress is proportional to the imposed angle of twist on each pile group. The stress development of pile systems experiencing torsion is symmetrical, the soil elements around the first and last pile had equal stresses both in front and behind the pile and the stress development of the soil elements around the central piles was also mirrored. This mechanical phenomenon can be seen in Figure 29. It is also worth noting that the soil surrounding the central piles, experiences lower stresses than around the piles positioned at the ends, a phenomenon attributed to the lower relative deformation (see Figure 30).

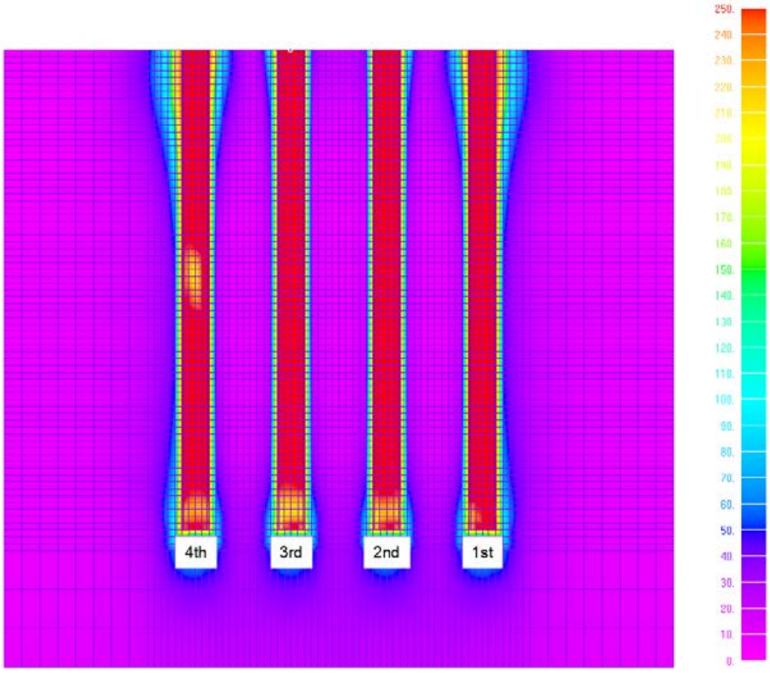

Figure 31: SVM stress contours (kPa) for group G4 at DS 6. Number of displacement increments imposed: max DS = 20.

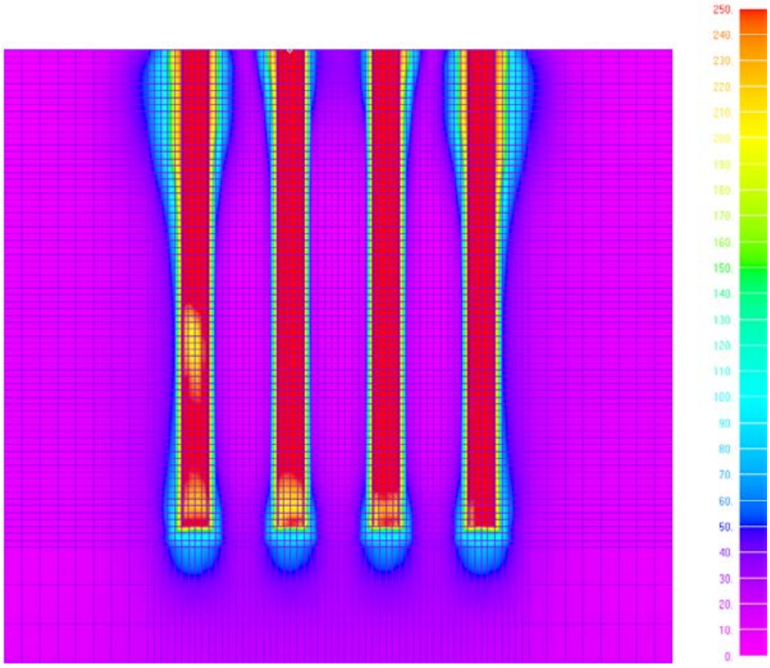

Figure 32: SVM stress contours (kPa) for group G4 at DS 12. Number of displacement increments imposed: max DS = 20.

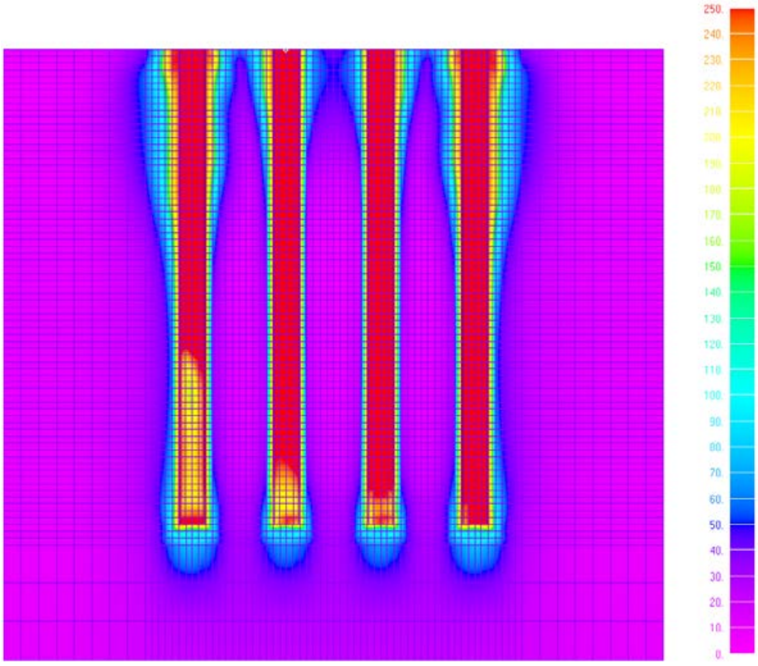

Figure 33: SVM stress contours (kPa) for group G4 at DS 19. Number of displacement increments imposed: max DS = 20.

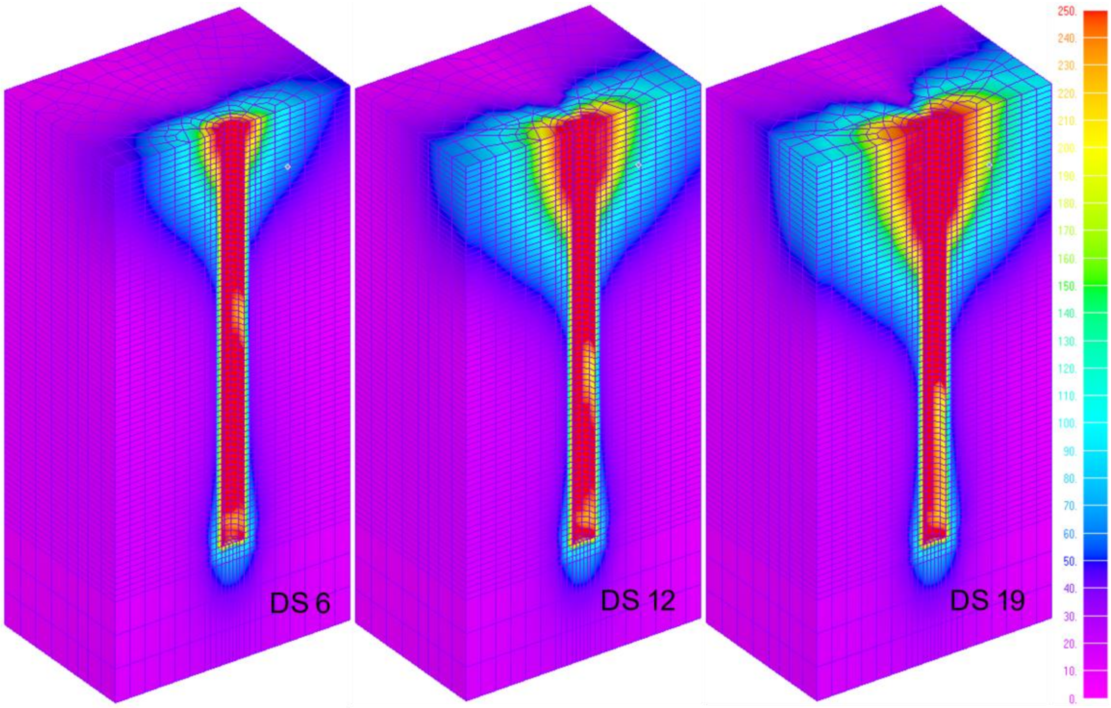

Figure 34: Dimetric view of SVM stress development (kPa) for displacement steps 6, 12, and 19 for group G4. Number of displacement increments imposed: max DS = 20.

Figure 31 through Figure **33** show how the first and fourth piles have identical stress development in the soil medium under increasing torsion for the case of model G4. The same applies to the second and the third pile. As torsion increases, the soil elements near the soil surface develop higher stresses, thus, the corresponding stress bulb increases in size and the pile foundation experiences bending at the pile level. The bending of the pile foundation results in compressive stresses in front of each pile and lower stresses behind the pile foundation. This can be seen when studying the stress development of the soil elements around the middle of the fourth pile that have lower stresses than the surrounding elements. This region of reduced stress increases in size as the applied torsion and in turn the bending of the pile increases (see Figure 34), a phenomenon that was found to be mirrored behind the first pile. It is worth noting that this behavior also occurs in the soil elements around the central piles but with significantly reduced effects, attributed to their position that is close to the center of rotation.

In Figure 35 the rapid increase in the soil stress of the first and fourth piles can be seen. For the case of the G4 model the central, second, and third piles, were found to have a lower rate of increase in soil stress. The soil elements around all the piles at the soil surface level reach the maximum compressive stress and plateau. This trend is visible for all pile groupings with some small degree of variation.

Figure 36 shows the stress development at the mid-height of the pile and indicates the rapid increase of the soil stress for the outer piles. There is a gradual increase in the soil stress at the soil elements that surround the central piles. At the base of the piles (see Figure 37) the soil elements of the outer first and fourth piles experience a gradual increase in the soil stress and the central pile elements experience a gradual reduction in the soil stress. Both above-mentioned trends are visible for all of the pile groupings studied in this experiment given that for all cases the outer piles are found to be the critical ones.

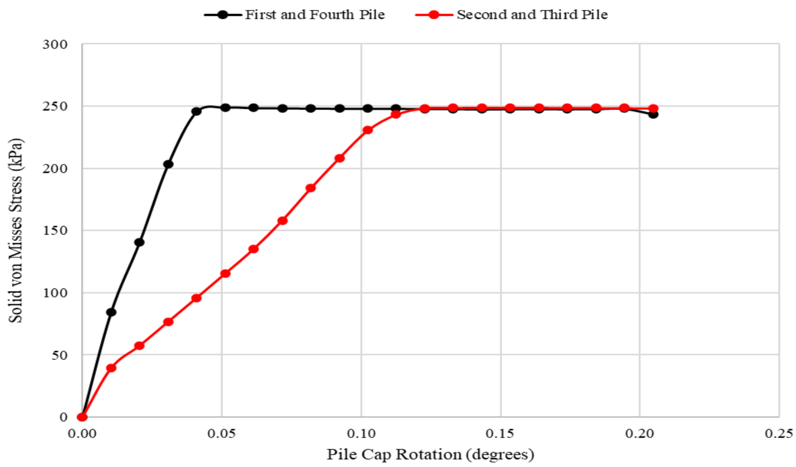

Figure 35: Stress development at the soil surface of pile group G4 under torsion.

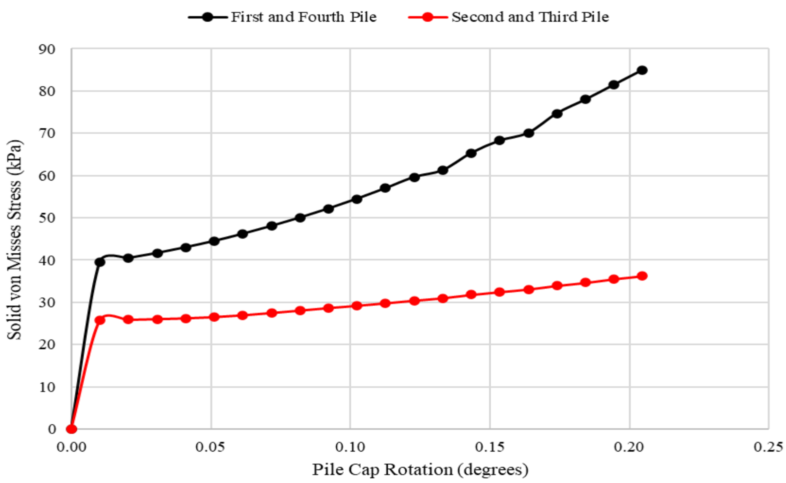

Figure 36: Stress development at the mid-height of the pile of group G4 under torsion.

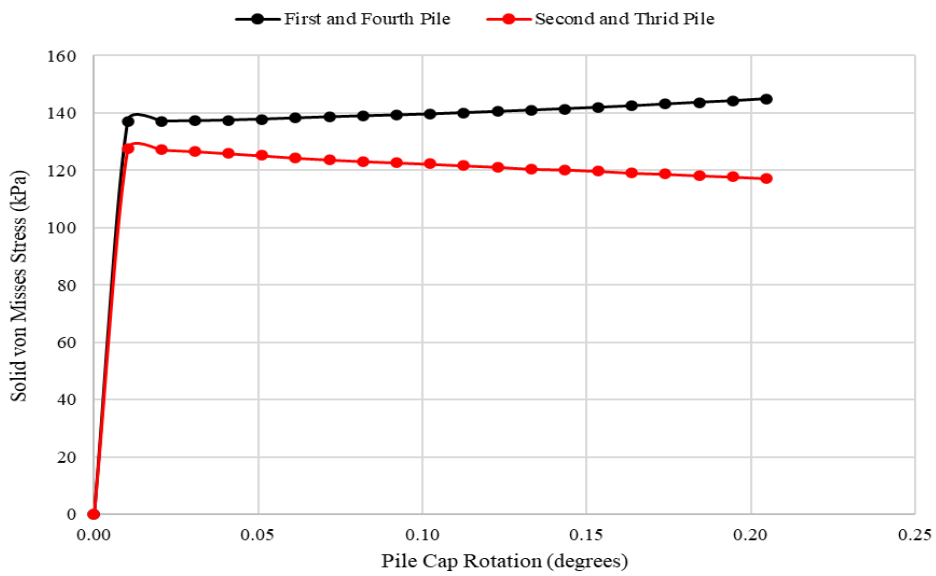

Figure 37: Stress development at the pile base of group G4 under torsion.

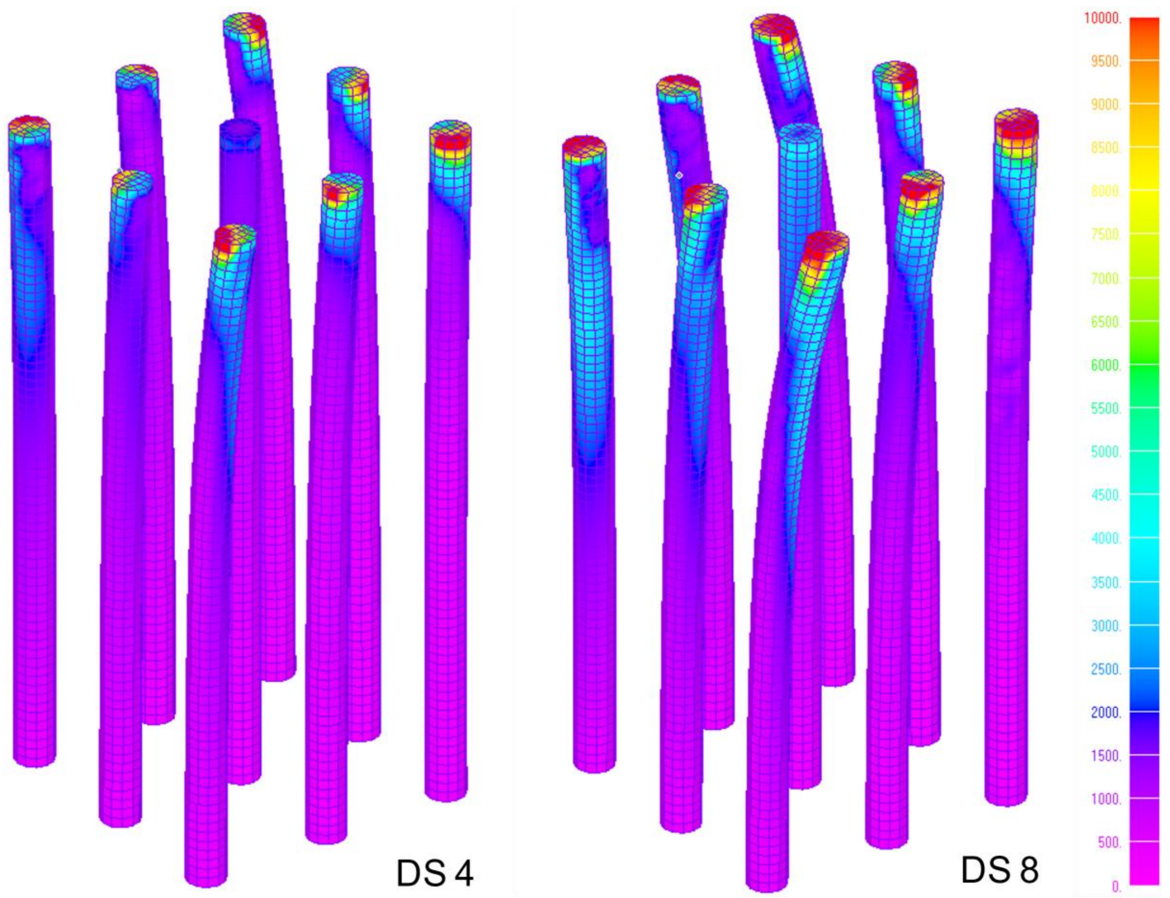

Figure 38: Bending development and SVM contours of pile foundations in pile group G3x3 with increasing torsion (kPa). Number of displacement increments imposed: max DS = 10.

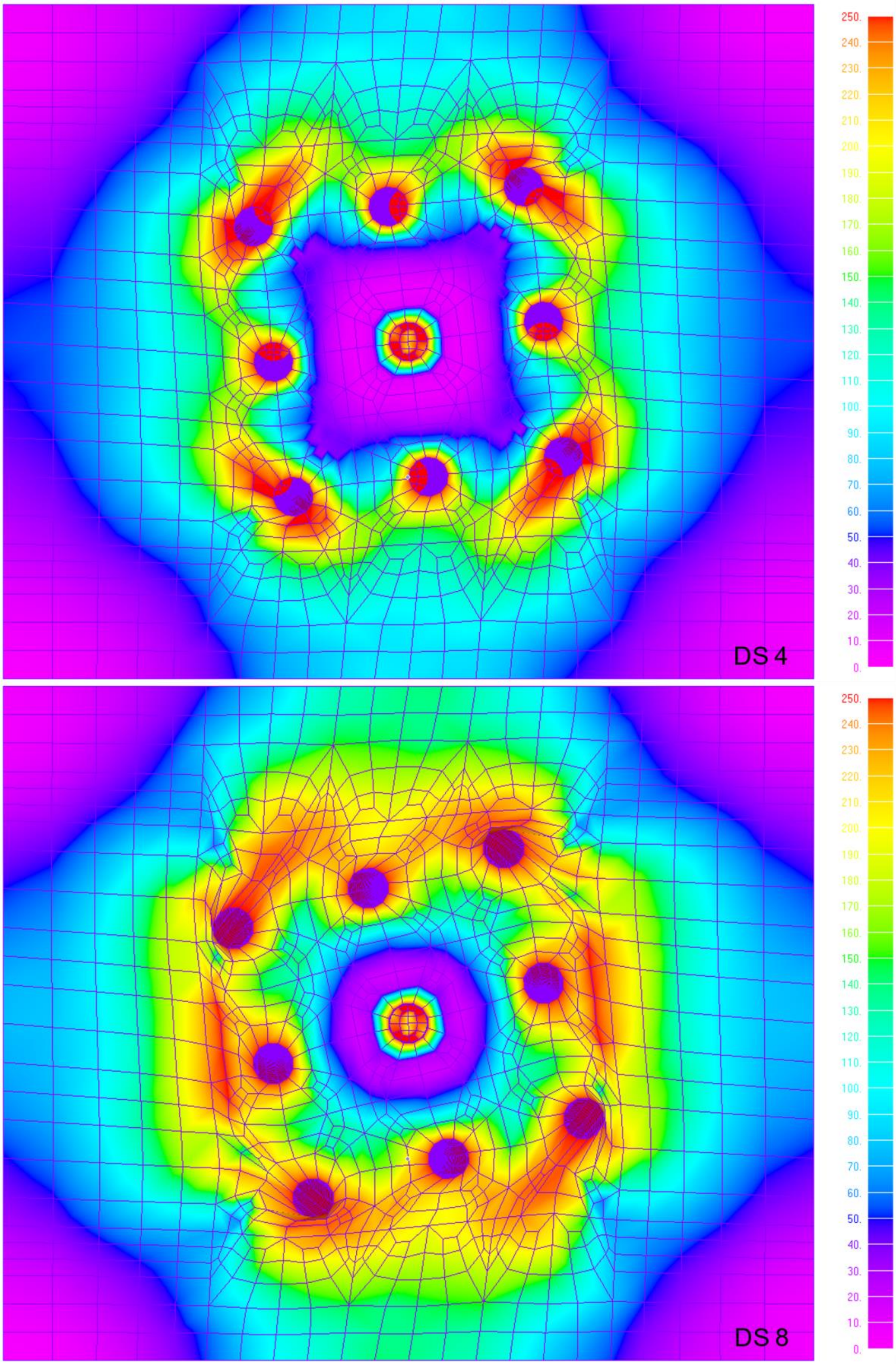

Figure 39: Scaled deformed view of the soil domain around pile group G3x3 with increasing torsion (kPa). Number of displacement increments imposed: max DS = 10.

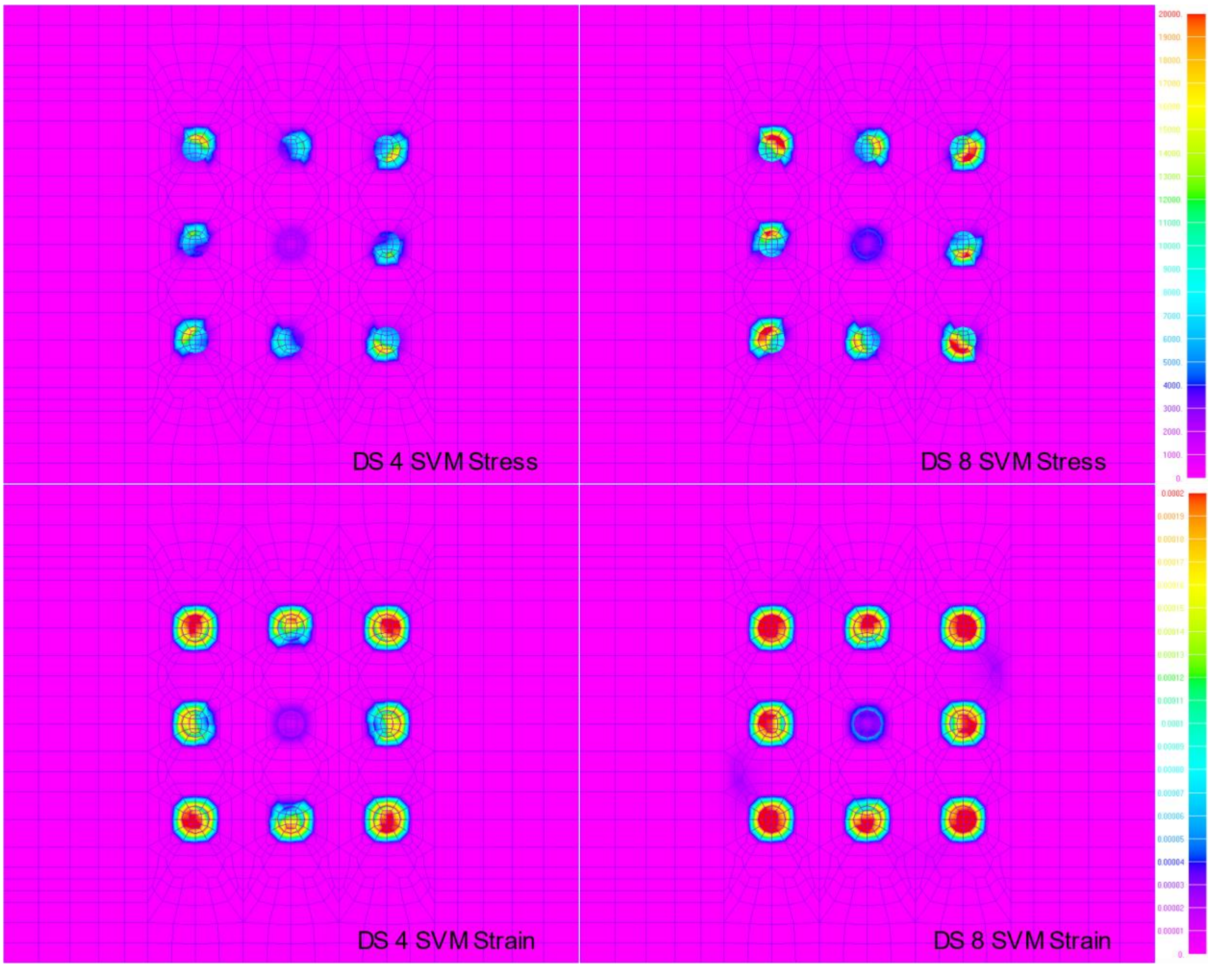

Figure 40: Crack propagation in pile foundation with increasing torsion (G3x3). Number of displacement increments imposed: max DS = 10.

Square pile groupings with odd numbers of piles in the group (3x3, 5x5, 7x7, etc.) have a central pile that lies on the rotational axis. As the central pile has no lever arm to experience bending, the pile undergoes pure torsion (see Figure 38). Because the central pile experiences no bending there is low-stress development in the soil medium around this pile as illustrated in Figure 39. The base of this central pile experiences some stress development which is caused by the vertical nominal load as opposed to imposed torsion. An interesting occurrence that was also observed during this experiment was the crack development and propagation in the pile foundations at the base of the pile cap. Cracks started forming on the tension side of the piles experiencing bending and these cracks developed along the circumference of the pile foundation. This behavior can be seen in Figure 38 through Figure 40.

The large variation in the stress of the soil elements around the central pile is visible in Figure 41 through Figure 43. The SVM stress curves represent the stress development of the soil elements around the second pile (central pile in three rows of model G3x3). At the soil surface and mid-height of the pile, the soil elements around the second pile in the first and second rows have identical stress development curves (<1% difference), while the central pile develops much lower soil stress levels.

Near the base of the pile, the behavior of the soil differs slightly, where is a gradual decrease in the stress of the soil elements around the base of the central pile. The relatively higher stresses around the base of the central pile are a result of bearing pressures under the pile foundation.

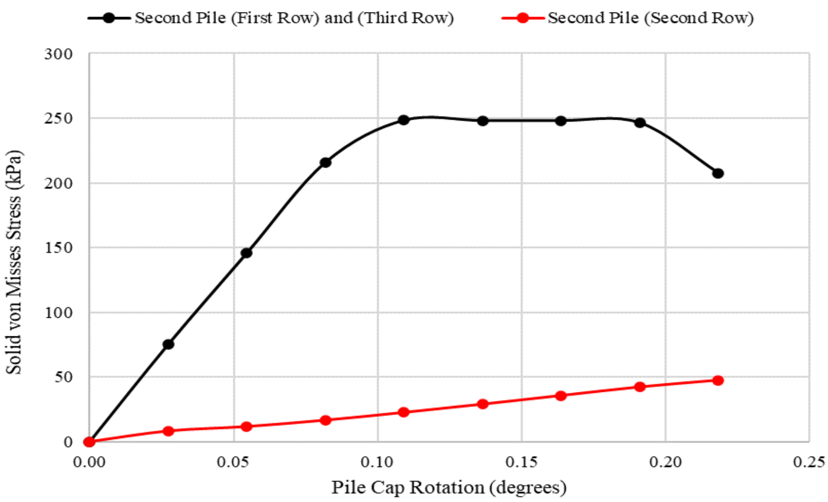

Figure 41: Stress development at the soil surface of pile group G3x3 under torsion.

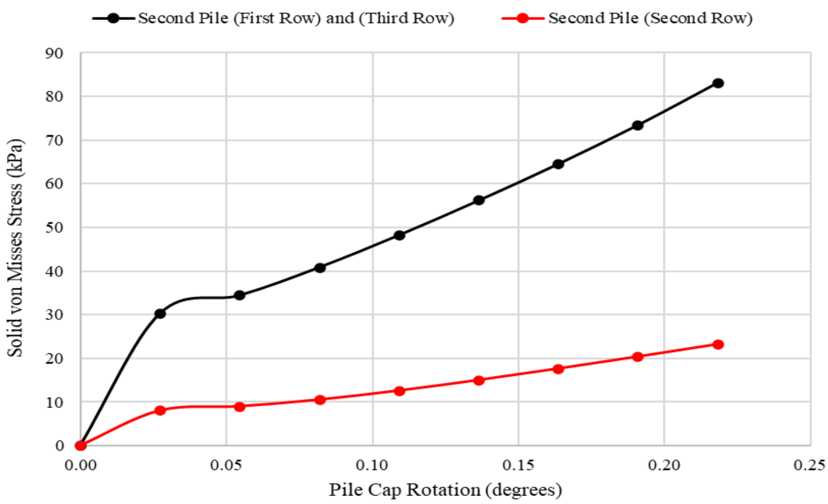

Figure 42: Stress development at the mid-height of the pile of group G3x3 under torsion.

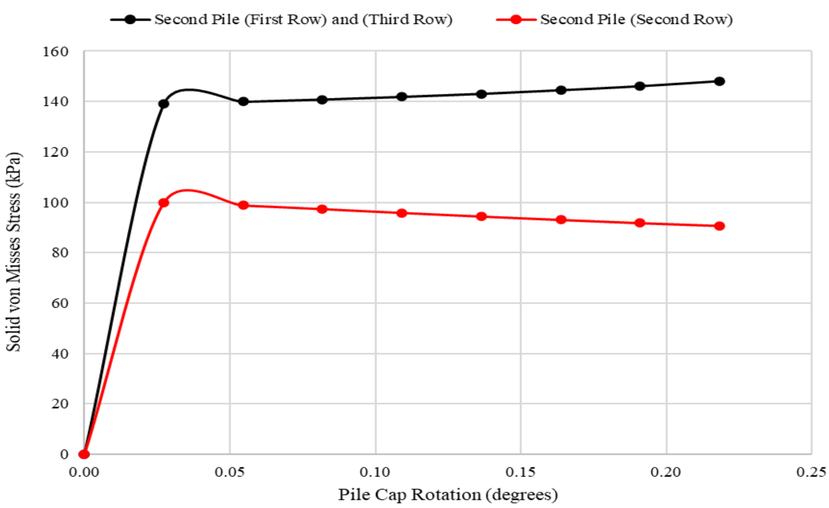

Figure 43: Stress development at the pile base of group G3x3 under torsion.

7 CONCLUSIONS

A numerical parametric investigation was presented in this manuscript, where the investigation of the stress level development of different pile foundations was performed. According to the numerical findings, the following conclusions can derive:

- As an imposed displacement is applied to a pile grouping, a base reaction develops in the soil medium that is proportional to the imposed horizontal displacement at the pile cap. The base reaction is not only directly proportional to the imposed displacement, but also to the number of piles in the grouping. Increasing the pile group size results in higher lateral resistance. The orientation of the pile grouping with respect to the applied load or displacement also influences the lateral resistance of the pile foundations. According to the parametric investigation, it was found that the pile groups with a longer group length in the direction of the applied force or displacement will have higher lateral resistances.
- Stress levels at the base of a single pile foundation are usually higher than the stresses surrounding the mid-height of the pile. This is predominantly caused by the distribution of bearing stress at the base of the pile which is a result of the applied load. There are high increases in the SVM stresses at the soil surface during the early loading stages of imposed displacements followed by a point where the stress magnitude remains constant. At the mid-height of the pile, there is little to no increase in the SVM stress levels, however, this effect changes when piles are grouped.
- For grouped pile foundations the soil that surrounds the leading pile reaches maximum stress and plateaus quite rapidly when compared to subsequent piles in the group. The trailing piles in the group have soil-stress development curves that are almost parallel to each other. This is attributed to the deformation that develops during the displacement control analysis that is controlled by the geometry of the foundation system.
- When investigating the soil that surrounds the piles at the mid-height of the pile foundation, the stress around the individual piles in the group gradually increases but does not reach the ultimate compressive resistance of the soil. It was found that the leading pile in the group has a higher soil-stress increase rate than the subsequent piles. The trailing piles in the group have soil-stress development curves that are relatively similar with the last pile having a slight initial decrease followed by an increase in stress levels. This phenomenon is attributed to the overall rotation of the foundation system due to the horizontal displacement of the pile-cap.
- Stresses in the soil around the base of the leading pile increase until the ultimate compressive force is reached. The middle pile(s) derive a steady decrease in soil-stress levels in the front soil domain of the pile. The last pile within the group experiences a rapid decrease in soil stress immediately followed by a rapid increase in the stress levels. Movement of the pile in the positive z-direction (uplift) and total rotation of the system causes a decrease in soil stress. Whereas the increase in stress at the pile base occurs when the rotation of the pile system is resisted by an increasing bearing stress in the soil surrounding the last pile
- The leading pile in a foundation system experiences relatively large vertical displacements due to the vertically imposed static load (superstructure loads) and the clockwise rotation of the foundation system. The soil surrounding the leading and second piles forces a rotation that pushes the piles downwards, whereas the soil around the trailing pile experiences heave. If this rotation were to become excessive, it would cause the pile system to fail either by a failure of the pile cap, bending and shear of the pile which occurs due to

reinforcement rupture, or concrete crushing due to excessive compression and shear deformation.

- Stress regions in the soil surrounding pile foundations were found to overlap, which may result in the failure of the soil if these levels reach a critical point. Therefore, the minimum spacing between piles should always be implemented during design.
- Soil-foundation interaction has a significant effect on the lateral resistance of the pile groupings. Numerical investigations are crucial as the knowledge obtained from these investigations gives insight into the interaction between the structure and the soil, and how the stress regions form around foundations. The implementation of 3D detailed modeling could lead to a reduction in the occurrence of structural failures and thus safer and more sustainable designs.

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