Influence of vertical loading on lateral behaviour of pile in sand

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CONTENTS

ABSTRACT

Due to the depletion of global fossil fuel reserves, there has been a growing movement towards promoting low-carbon lifestyles and environmental conservation. Renewable energy has emerged as a prominent area of research, with offshore wind power and tidal turbines being the primary focus of investigation. The offshore wind power foundation is continuously impacted by wind load and wave load throughout the entire year. A large-diameter monopile is a conventional foundation construction that ensures the stability of offshore wind power generation structures.

This thesis uses numerical analysis with RS Pile software to examine the impact of vertical loads on the sideways behaviour of piles in sandy soils. The objective of the study is to improve the comprehension of the combined vertical and lateral forces acting on monopile foundations, which are vital for offshore wind turbines. The research consists of three main phases: firstly, a comparative analysis is conducted between laboratory tests performed by Li et al. (2021) and the RSPILE model to assess the accuracy and reliability of numerical predictions. Secondly, the relationship between load and displacement, as well as load and bending moment, is determined for monopiles of different diameters under lateral loading conditions using the RSPILE model. These findings are then compared with results obtained from the VERSET 3D model developed by Finn and Dowling (2016). Lastly, the displacement and bending moment of monopiles subjected to combined vertical and lateral loads are quantified using the RSPILE model, and these results are contrasted with those obtained from piles subjected to lateral loads only. The results demonstrate notable disparities in the behaviour of piles when subjected to combined loading conditions, emphasising the significance of including vertical stresses into the design of monopile foundations for offshore wind turbines.

DECLARATION

I certify that this thesis:

1. does not incorporate any material previously submitted for a degree or diploma in any university without acknowledgment.
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signature of student..............................Mayur....................

Print name of student.................Mayurkumar Modi.................................

Date.............23/05/2024..

I certify that I have read this thesis. In my opinion, it is/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering (civil). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

Signature of Principal Supervisor..

Print name of Principal Supervisor................Dr. Hongyu Qin..................................

Date..

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I would like to express my gratitude to my supervisor, Dr. Hongyu Qin, for providing valuable guidance on my study cases and for promptly addressing any questions that arose during my research process. Due to my lack of experience with RS Pile, I was unable to fully grasp many of the subtleties. With the assistance of Dr Hongyu Qin, I effectively achieved results by using the numerical analysis method. Furthermore, I would like to express my gratitude to Fei Huang. He made significant contributions to the analysis of the previous scholarly data and numerical simulation in my experiment.

I hold high regard for the other instructors, namely Professor Rocco Zito, Dr Nicholas Holyoak, Dr Aliakbar Gholampour, Professor Adrian Werner, and Dr Cristina Solórzano-Rivas. They have provided me with a substantial amount of valuable knowledge in several fields.

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CHAPTER 1: INTRODUCTION

1.1 Introduction and Background:

Offshore wind energy has the potential to significantly decrease greenhouse gas emissions, hence contributing to a cleaner future (Chen and Duffour, 2018). However, as we go towards offshore wind generation, it becomes increasingly crucial to provide sturdy and reliable foundations. To guarantee the structural stability of offshore wind turbine foundations, it is imperative to prioritise both environmental protection and energy security. This extends beyond mere economic issues. Li et al. (2021) argue that the stability of these foundations is crucial since even minor structural issues can result in significant maintenance expenses, reduced operational efficiency, and, in extreme cases, catastrophic failures. Offshore wind is becoming increasingly popular as a source of clean, renewable electricity. To successfully harvest this energy, offshore wind turbine foundations must be stable and reliable, particularly in sandy offshore settings (Li et al., 2021).

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Figure 1 Six different types of offshore wind turbine foundations.

The offshore wind market has experienced substantial growth in recent years, mostly due to developments and innovations in turbine capacity. The industry is widely recognised as one of the most effective approaches for society to transition from carbon-based energy sources to renewable energy sources. The Green of Europe Deal, established in Brussels, Belgium in 2019, aims to achieve carbon neutrality in Europe by 2050. Offshore wind farms have emerged as the primary technology to facilitate the realisation of this objective. Currently, offshore wind power accounts for over 11% of Europe's energy consumption [Wind Europe: Brussels, Belgium, 2018]. Experts predict that this percentage will rise to 30% or even higher by the year 2030. Monopiles remain the predominant choice for the foundation of offshore wind turbines (OWTs), representing 87% of all installations up until 2019 (Wind Europe 2018; Fan et al. 2021).

Prior research has yielded conflicting findings about the impact of vertical loading on piles on lateral displacements under equivalent lateral loads, with some studies suggesting enhancement while others suggesting reduction. Karthigeyan et al. (2006 and 2007) conducted a series of 3D finite element analyses on piles and found that vertical loads increase the lateral load capacity of piles in sandy soils but decrease it in clayey soils. Hussien et al. (2012, 2014a, and 2014b) observed a little rise in the sideways strength of free-head piles on sandy soil when subjected to vertical loads. They attributed this increase to higher pressures exerted by the sand surrounding the upper section of the pile. Several methodologies have been suggested in an effort to elucidate previous research discoveries. It is increasingly important to determine the impact of vertical loading on lateral displacements to properly design combined-loaded pile systems, including those used to support rising offshore wind turbines (OWTs).

1.2 Aim and Objectives:

Aim: This study contains the influence of vertical load on the lateral behaviour of piles in sand by using numerical analysis in RS pile software.

Objectives: The study material is divided into three sections. The initial phase of the study entails a comparison between the laboratory tests done by Li et al. (2021) and the RSPILE model. The primary objective of this research was to analyse the influence of vertical loading on the lateral soil reaction-displacement (p-y) curves at different depths of a pile.

The second part employs the numerical model RSPILE to determine the relationship between load and displacement, as well as load and bending moment, for monopiles of varying diameters subjected to lateral loading. These results are then compared to the findings of (Finn and J. Dowling 2016), who conducted their analysis using the VERSET 3D model.

In the third part, the RSPILE model is utilised to quantify the amount of displacement and bending moment that occurs upon the application of a vertical load on the pile and compare it with the only laterally loaded pile results.

1.3 Scope of the thesis:

Given the constraints of limited time and money for study. This study examined the impact of vertical loading on the lateral soil reaction-displacement (p-y) curves at various depths of a pile. It also analysed the relationship between load displacement for monopiles of different diameters under H (horizontal load) and VH (vertical-horizontal load) conditions using the RSPILE model. The project does not include full-scale field tests and experimental centrifuge tests.

1.4 The structure of the thesis:

This thesis comprises an introductory chapter, followed by four subsequent chapters, which are outlined as follows:

- Chapter 2 – Literature review: This chapter presents a thorough examination of the impact of vertical loading on the lateral behaviour of piles in sand. The presentation also includes key studies that examine the benefits and drawbacks of each strategy. Next, a comprehensive assessment is conducted of the existing studies.

- Chapter 3 – Methodology: This section elucidates the procedure of constructing the current model, including the employed theories and the derivation of all equations utilised in the model.

- Chapter 4 – Results and Discussion: This chapter presents the main discoveries. The results are contrasted with findings from prior research and RS Pile outcomes. An analysis of the acquired results is presented, highlighting its significance and its implications.

- Chapter 5 – Conclusion and Future Work: This chapter provides a concise overview of the main discoveries and their impact on the field of study. However, recommendations are put forward for further research considering the constraints of the current model.

CHAPTER 2: LITERATURE REVIEW

2.1 Background:

Offshore wind power is crucial for providing low-carbon energy. Over the past ten years, Europe has witnessed significant development of offshore wind generation on a vast magnitude. The structural design of most offshore wind power-producing equipment is uncomplicated and utilitarian. The marine environment surrounding offshore wind turbine foundations differs significantly from that of land pile foundations and experiences more intricate loads. These loads include horizontal forces such as offshore wind, waves, and tidal pressure (Li et al., 2013). To ensure that the upper layer of this equipment can support different types of loads, the foundation of the bottom layer structure commonly utilises piles (Abadie et al., 2018). The monopile has a short service life due to the presence of numerous intricate forces acting upon it. Ewea (2009) stated that the expected lifespan of an offshore wind structure is typically 20 to 25 years due to the constant exposure of the piling foundation to various loads throughout the year. However, it is important to note that this timeframe is simply a general reference, and the actual service life can vary depending on multiple factors. Hence, the investigation of the interaction between piles and soil holds great significance.

2.2 Mechanical Characteristics of sandy soils:

Sandy soils are well known for their distinct mechanical properties. The density, porosity, and grain size of sand significantly influence the soil's response to vertical loading. The research conducted by Gaaver (2013) and Karthigeyan, Ramakrishna, and Rajagopal (2007) has emphasised the importance of these characteristics in regulating the bearing capacity and behaviour of piles.

The study conducted by Karthigeyan, Ramakrishna, and Rajagopal (2007) involved the performance of several geotechnical tests to investigate the impact of compaction and grain size on the mechanical properties of sandy soils. The findings demonstrated that increased compaction and the presence of finer-grained sands resulted in enhanced shear resistance and load-bearing capacity.

The properties of the soil have a significant impact on the behaviour of piles in sandy offshore settings. The study emphasised the importance of conducting soil investigations to tailor the foundation design according to the soil condition.

Gaaver's (2013) research aimed to gain a deeper understanding of the impact of porosity and density on pile dynamics in sandy soils. This study incorporated both computational models and physical experiments. Based on their research, soils with higher sand content, lower porosity, and greater density had less settlement and consolidation when subjected to vertical stress. This discovery has substantial implications for foundation planning as it suggests that selecting the appropriate soil conditions might enhance pile stability and reduce the risk of settling in offshore wind turbine structures.

2.3 Monopile foundation:

Monopiles can be classified into various types. Materials can be classified into concrete piles, steel piles, wood piles, and composite piles. The classification of piles is based on their function. Piles can be categorised into four types: vertical compression piles, vertical uplift piles, horizontal load piles, and composite load piles. Based on the type of section, it can be categorised as either a square pile or a circular hollow pile. Nevertheless, the piling foundation of offshore wind power generation endures the demanding conditions of seawater and the soil layer beneath the seabed throughout the year, while also withstanding diverse weights. Thus, the primary method used for establishing offshore wind power generation is using large-diameter hollow steel round monopiles.

Monopiles consist of a single steel tube with one end open, which is forcefully inserted into the seabed. The typical dimensions of piles used to support early offshore wind turbines (OWTs) were diameters ranging from 4 to 6 metres and embedded lengths ranging from 20 to 30 metres. These piles had length-to-diameter (L/D) ratios of 5 to 6 (Doherty and Gavin 2012). The required pile diameter to limit pile mudline rotation is projected to increase to a range of 8 to 10 metres as turbines reach a capacity of 10 MW, according to Byrne et al. (2019). Due to the low weight of the turbine and the large diameter of the pile, the embedded lengths of Monopiles have not increased significantly, resulting in a fall in L/D ratios to values between 2 and 3.

2.4 Behaviour of pile in sandy soils:

Research has investigated how different soil types affect the ability of piles to sustain vertical loads, specifically focusing on pile performance in sandy soils. Prendergast, Reale, and Gavin (2018) discovered through thorough field testing that the performance of piles is significantly affected by compaction and the kind of soil. The research conducted by Konstantinidis and Botsaris (2016) highlighted that the degree of pile penetration emerged as a critical factor. Konstantinidis and Botsaris (2016) conducted comprehensive field experiments to investigate how the depth at which piles are inserted into the ground and the type of soil affects the efficiency of piling in sandy offshore areas. The research indicates that the load-bearing capacity of piles is significantly affected by the type of soil employed. Specifically, piles constructed in fine-grained, densely packed sands exhibited greater resistance to vertical pressures compared to those constructed in softer, coarser-grained sand. Furthermore, the analysis revealed that the extent of pile penetration played a significant role. Deeper penetration was shown to be correlated with a higher load-bearing capacity, emphasising the importance of proper pile arrangement in the building of foundations. Liu, Guo, and Han (2019) conducted a study on the impact of sandy soil compaction on the performance of offshore wind turbine foundations. As part of their research, they performed numerical simulations and conducted in-lab experiments. The results indicate that adequate soil compaction during the construction phase significantly influenced the performance of the pile. Well-compacted sandy bottoms enhance the overall stability of offshore power turbine substructures by increasing their bearing capacity and reducing the likelihood of pile settling. This realisation underscores the importance of precise construction techniques and stringent quality assurance protocols in the planning and building of foundations for offshore power facilities.

2.5 Horizontal and Vertical Loading:

According to Yegian (1973), the top layer of the pile is in touch with the turbine and is situated above the seabed beneath the water surface. Additionally, a significant portion of the pile is in contact with the surrounding sand and soil below the seabed. Therefore, it is necessary to examine many load situations. This encompasses the forces exerted by wind and waves in the horizontal direction. A range of vertical loads act on the pile, including self-weight and drag loads. Due to intricate crustal movements in offshore regions, the seafloor will undergo fluctuations because of deep-sea earthquakes and tsunamis. Hence, the force exerted on the pile may encompass the internal force of the earth as well (Hetenyi, 1946). Furthermore, the predicted loading is contingent upon the structure's geometry and the stiffness of the foundation. Hence, a specific quantity of load geometry iterations is necessary during the calculation process. Due to the simultaneous presence of numerous forces, the characteristics of the pile are intricate. This study focuses on both horizontally loaded piles and a combination of Axially and Laterally loaded piles.

2.6 Why Vertical and Lateral Loads are essential to study interaction effect:

Pile foundations are commonly employed to provide support for structures constructed on loose or soft soils when shallow foundations would experience significant settlements or have limited bearing capability. These piles serve the purpose of bearing both vertical and lateral loads, as well as a combination of the two. In modern practice, piles are initially assessed separately for their ability to withstand vertical loads and their potential settlement. Additionally, their ability to resist lateral loads and their flexural behaviour are also evaluated. This approach is applicable only for small lateral loads. However, in coastal and offshore applications, the lateral loads are considerably high, typically ranging from 10-20% of the vertical loads. In such cases, it is crucial to study the interaction effects caused by the combined vertical and lateral loads. Therefore, a systematic analysis is necessary (Karthigeyan et al, 2006 and 2007).

2.7 Numerical Analysis Method:

The finite element method is a highly effective numerical technique. The method employed is numerical analysis, which involves discretising intricate things and utilising mechanics and computer technology to solve intricate issues. The utilisation of finite element analysis for pile foundation analysis commenced in the 1970s. Over the course of several decades, numerous algorithms have been created, and their theoretical foundations have become increasingly comprehensive and refined. Numerous intractable problems have been effectively resolved using other approaches. The numerical simulation of pile-soil interaction has garnered increasing attention from civil workers, and its study is currently experiencing a highly dynamic landscape. Currently, pile foundation analysis has become the prevailing trend. Ultimately, the numerical analysis of pile-soil interaction requires addressing two fundamental issues: firstly, investigating the linear and nonlinear constitutive model of soil; secondly, accurately describing the constitutive relationship on the pile-soil contact surface and selecting appropriate contact elements.

The wide range of advanced finite element analysis software allows for favourable conditions and convenient methods for numerically simulating pile-soil interaction. When using the ABAQUS software for large-scale finite element analysis of pile-soil interaction, the conventional calculation method involves simplifying the interaction into a spring element that accounts for horizontal, vertical, and torsional characteristics based on the p-y curve method.

Most of the existing research on the simultaneous loading of piles relies on numerical modelling techniques, such as finite element analysis. Poulos and Davis, as well as Anagnostopoulos and Georgiadis, were pioneers in analysing the impact of vertical stress on the lateral reactions of piles by two-dimensional finite-element analysis. Due to the inherent three-dimensional nature of pile-soil interaction, there are certain limits to using two-dimensional finite-element analysis. Considering this observation, several scholars have employed three-dimensional finite-element analysis to investigate the lateral response of piles when subjected to lateral loading.

Madhav and Sarma conducted a study on the behaviour of long piles in clay when subjected to both vertical and lateral loads. They employed the finite-difference approach to analyse the reaction of the piles. The investigation examined the behaviour of a pile under mixed loading and compared it to the scenario where just lateral loads are applied. The findings indicate that the implementation of vertical loading leads to an elevation in the lateral displacement and bending moment at the top of the pile, spanning its whole embedded length. In the given scenario, these response characteristics increased twofold when subjected to vertical loading.

2.8 Limitations of research:

Finite elements are useful because they can be used in a lot of different situations and are very accurate. They can also be used to make strong models, and they can also find the stress-strain relationship in the earth around the pile. It works well to model the nonlinear properties of soil, like how it hardens, creeps, seeps, and compacts. It fixes the problem that the old way of analysing soil turns it into a stretchy state, which makes it hard to accurately model how the pile contacts the soil. Additionally, numerical analysis can be managed in some ways to make it more or less accurate, and the forms and methods are mostly the same. It is a way to do numerical analysis that is easy to program. So, the finite element method is a good way to investigate the properties of a single pile or a group of piles under both vertical and horizontal loads, as well as how the piles interact with the ground. The problem with the finite element method is that it makes the answer more complicated, especially when analysing things in three dimensions. It's especially hard to get convergence and the machine takes a long time. The choice of modelling methods and parameters has a big impact on the logic and accuracy of the answer.

CHAPTER 3: METHODOLOGY

The most important part of this study is a numerical analysis and comparison with previous researchers' experimental results.

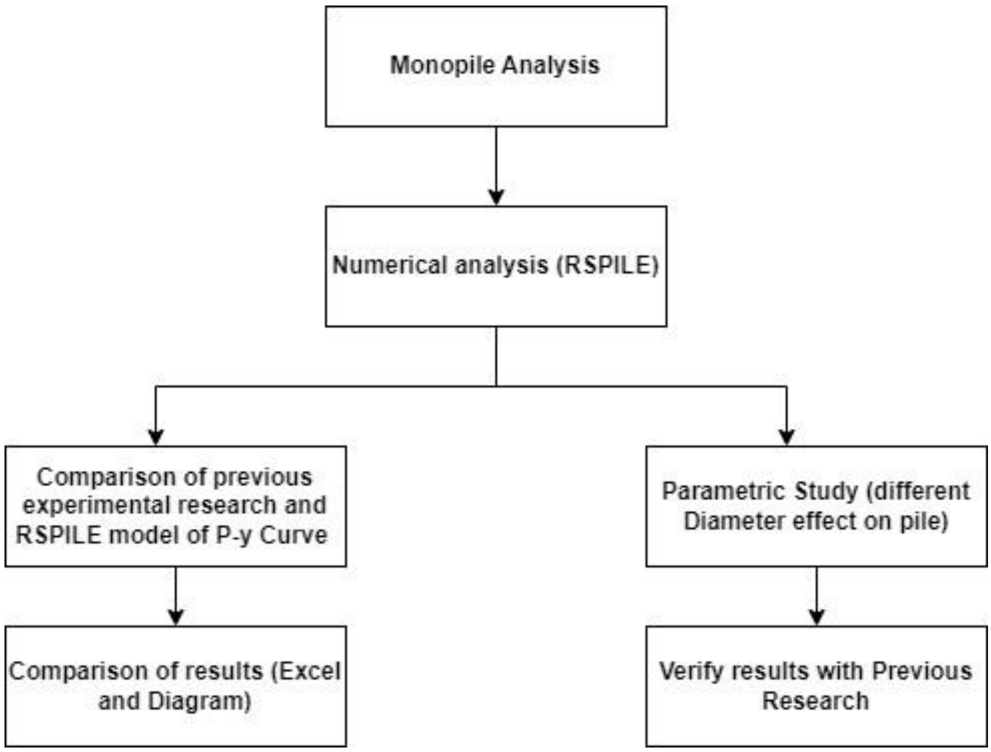

Figure 2 Flow chart of monopile analysis methodology.

3.1 Numerical Analysis Method:

Due to advancements in numerical analysis technology, it has become increasingly popular to use numerical simulation for calculating and analysing structural properties. This thesis utilises the RS Pile software to test the experimental data obtained during the model experiment. It then summarises the function law based on the data and conducts a numerical simulation of the actual size pile diameter using the derived function. This approach helps solve the challenge of conducting field experiments in real engineering problems.

This thesis is broken into three parts of numerical analysis. The initial phase of the study involves employing the model to analyse the impact of vertical loading on the lateral soil response-displacement (p-y) curve for various pile depths, utilising eleven distinct lateral load scenarios. Afterwards, the outcomes derived from the model are contrasted with the discoveries of prior investigations and the RS Pile software. The second part employs the numerical model RSPILE to determine the relationship between load and displacement, as well as load and bending moment, for monopiles of varying diameters subjected to lateral loading. These results are then compared to the findings of (Finn and J. Dowling 2016), who conducted their analysis using the VERSET 3D model. In the third part, the RSPILE model is utilised to quantify the amount of displacement that occurs upon the application of a vertical load on the pile and compare it with the only laterally loaded pile results.

3.2 Introduction of RS Pile:

The software can analyse the installation of driven piles, as well as piles subjected to axial and lateral loads. The software can calculate the axial capacity of driven piles, as well as determine the internal forces and displacements of the pile under different loads and soil movements.

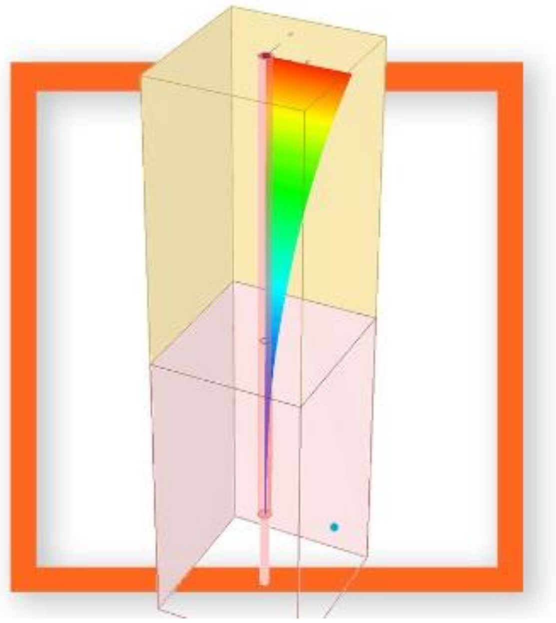

Figure 4 Screenshot of RS pile software.

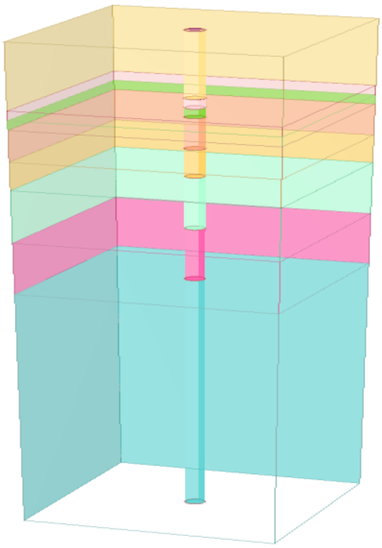

Figure 3 3D view of the monopile installation.

3.3 Soil response modelled by p-y curve:

To accurately analyse a laterally loaded pile foundation in soil/rock, it is necessary to employ a nonlinear relationship that expresses the soil resistance as a function of pile deflection. Figure 5a depicts a cylindrical pile subjected to lateral loading. When not under load, the stresses exerted on the wall of the pile are evenly distributed and have a magnitude of one unit, as depicted in Figure 5b. When the pile undergoes a deflection of y1 at a depth of z1, the stress distribution resembles Figure 5c, with a resisting force of p1. The stresses decrease on the backside of the pile and increase on the front side. In this situation, certain unit stresses consist of both normal and shearing components as the displaced soil attempts to move around the pile.

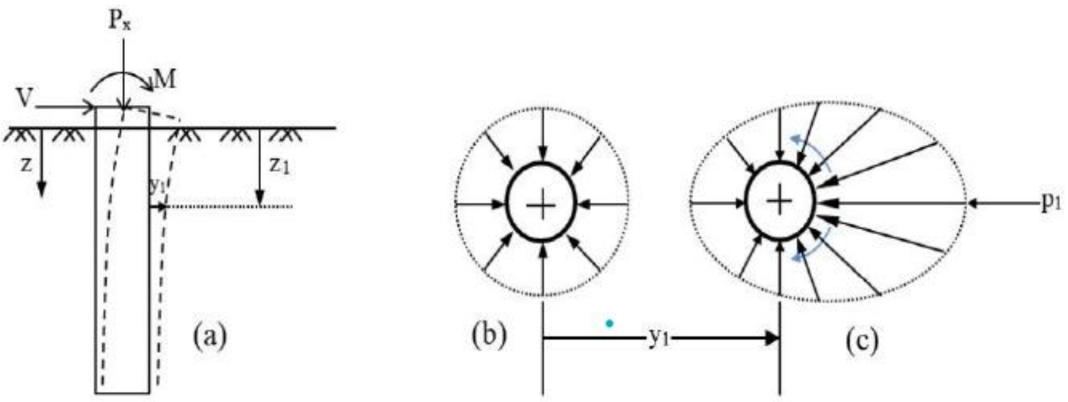

Figure 5 Unit stress distribution of pile under lateral load.

When conducting this type of investigation, the primary characteristic to consider from the soil is the reaction modulus. The soil resistance at a specific depth of the pile is divided by the horizontal deflection of the pile at that same depth, resulting in a value known as pile stiffness. RS Pile defines the reaction modulus (Epy) by utilising the secant of the p-y curve, as depicted in Figure 6. P-y curves are generated at specific depths to demonstrate that the soil reaction modulus depends on both the deflection of the pile (y) and the depth below the ground surface (z).

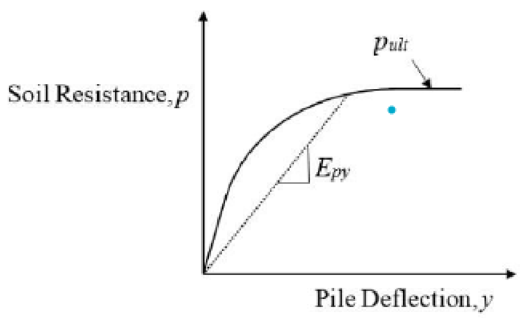

Figure 6 Generic p-y curve defining soil reaction modulus.

3.4 Modelling of soil reaction – displacement curve (p-y):

The investigation utilised input parameters in a test done by Li et al. (2021) on dense dry Geba sand. The pile is considered to have linear elasticity, with an elastic modulus of E = 210 GPa and a Poisson's ratio of 0.3. The soil and pile parameters are presented in Table 1 and Table 2, respectively.

Table 1 Soil properties p-y curve model

Soil type	**Dense dry Geba sand**
Effective Unit Weight	18 KN/m3
Relative Density (Dr)	80%
Angle of Internal Friction	38
Coefficient of Curvature (Cc)	1.24
Uniformity Coefficient (CU)	1.55
Specific Gravity (Gs)	2.67

Table 2 Pile properties of the p-y curve model

Pile Material	**Steel Pipe**
Pile Diameter (D)	1.8 m
Embedded length/diameter ratio (L/D)	5
Embedded length (L)	9 m
Eccentricity of loading (e)	8D = 8*1.8 = 14.4 m
Total Length of pile	23.4 m

As per Li et al. (2021), consecutively, eleven distinct horizontal loads are applied to a pile. These loads are H = 0KN, 38KN, 79KN, 119KN, 158KN, 198KN, 238KN, 278KN, 316KN, 355KN, and 393KN. The purpose is to examine how vertical loading affects the lateral soil reaction-displacement (p-y) curves at various depths of the pile. Maintain a constant vertical load of zero for all scenarios.

Modelling Step:

- Specify the boundary conditions and implement the model features.
- Establish a soil model and enter the necessary soil properties.

- Establish the pile model and input the pile's specifications.
- Modify the data to ensure that the results align with the experimental findings.
- Apply laterally load.
- Export data.

3.5 Parametric Study:

In this thesis parametric study is divided into two cases.
Case 1: consider pile is only horizontally loaded.
Case 2: The pile is considered both horizontally loaded and vertically loaded.

For both cases, the investigation utilised input parameters in a test done by (Finn and J. Dowling 2016). The pile is considered to have linear elasticity, with an elastic modulus of E = 200 GPa and a Poisson's ratio of 0.3. The soil and pile parameters are presented in Table 3 and Table 4, respectively.

Table 3 Soil model of parametric study

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Table 4 Pile properties of parametric study

Pile Material	**Steel pipe**
Embedded length of pile (L)	16.1 m
Pile Diameter	0.324 m
The eccentricity of loading (e)	0.483 m
Wall thickness (t)	0.0095 m
The total length of the pile	16.583 m

Case 1: RS Pile utilises the complete model for doing three-dimensional numerical analysis. The diameter of the pile foundation is categorised into seven sizes: D = 0.5m, 0.75m, 1.0m, 1.25m, 1.5m, 1.75m, and 2.0m. By using WEBPLOTDIGITIZER, find out the lateral load from (Finn and J. Dowling 2016) load-displacement curve. This study focuses on the behaviour of a monopile when subjected to horizontally loaded. The behaviour change primarily involves two aspects: the alteration of lateral load and the modification of bending moment. Hence, to guarantee the precision of the experiment, it is imperative to authenticate the experimental results using RS Pile.

Case 2 The diameter of the pile and the lateral load remain unchanged from instance 1. We assume a vertical load of 500 KN. Assess the impact of vertical load on the lateral movement of the pile.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 The pile displacement is measured at different depths along the pile:

As mentioned above, the investigation utilised input parameters in a test done by Li et al. (2021) on dense dry Geba sand. In the first part, check how much displacement occurred at different depths along the pile. The results of displacement-depth from the pile head are shown in Figure 7, Figure 8 and Table 5 below,

a

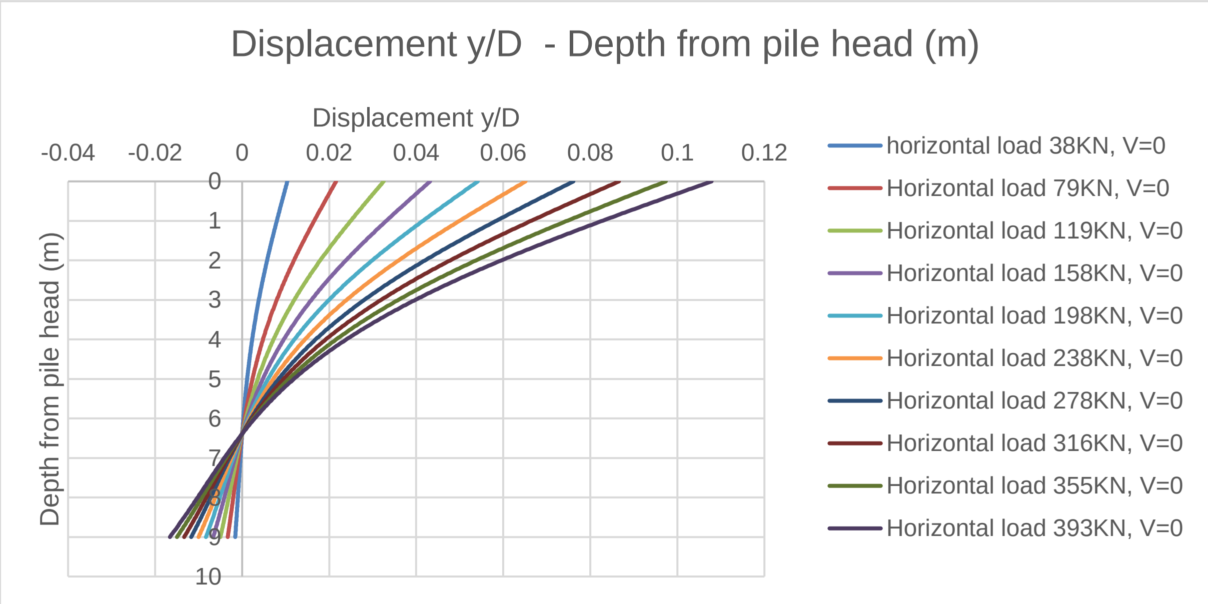

Figure 7 Displacement - Depth from pile head curve of RS pile model.

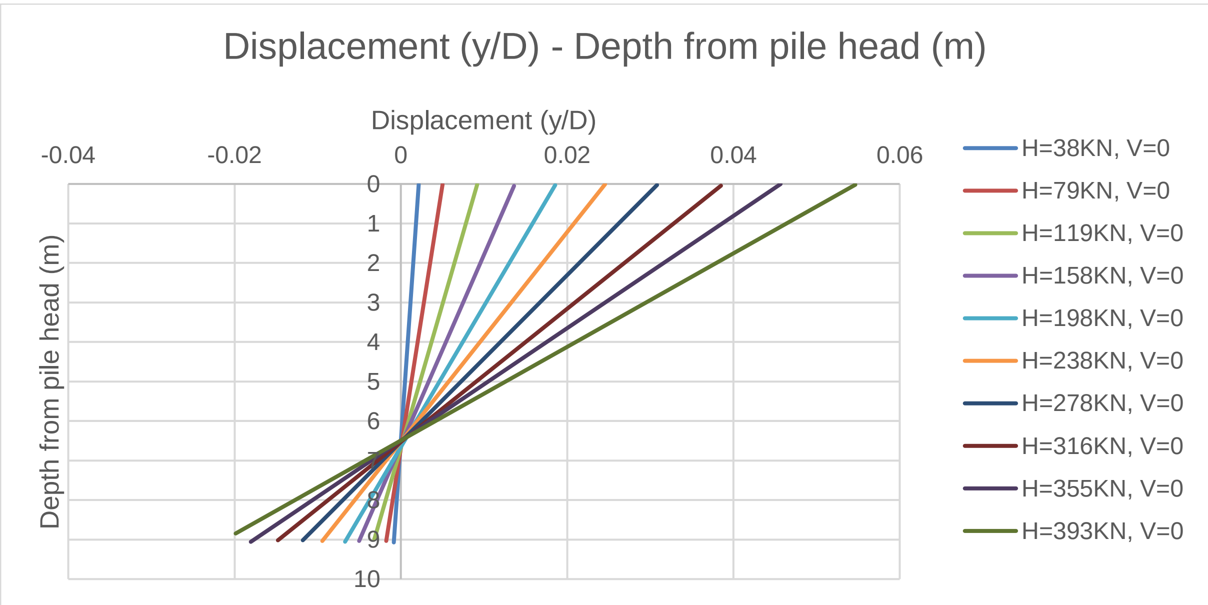

Figure 8 Displacement - Depth from pile head curve of laboratory experiment of the previous scholar.

Table 5 The results comparison of RS pile model and lab experiment of displacement-depth from pile head

Load (KN)	Maximum displacement of Li et al. (2021) Laboratory experiment (cm)	Maximum Displacement of RS pile model (cm)
H = 0, V = 0	0	0
H = 38, V = 0	0.002	0.010
H = 79, V = 0	0.005	0.021
H = 119, V = 0	0.091	0.032
H = 158, V = 0	0.013	0.043
H = 198, V = 0	0.018	0.054
H = 238, V = 0	0.026	0.065
H = 278, V = 0	0.032	0.076
H = 316, V = 0	0.038	0.086
H = 355, V = 0	0.047	0.097
H = 393, V = 0	0.058	0.010

Both models indicate that an increase in the horizontal force applied results in an increase in the settlement of the pile head. As the applied force increases from 0KN to 355KN, the displacement of the pile head increases to 0.097cm for the RS pile and 0.047cm for the lab experiment. The discrepancy between the RS pile model and the laboratory result is about threefold in this instance.

As the applied force increases to 393KN, the settlement of the pile head reaches around 0.010 cm for the RS pile and 0.058 cm for the lab experiment. In this instance, the discrepancy between the RS pile model and the laboratory result is about twofold.

When we talk about the reason behind this high variation in results of the RS pile model and Lab experiment is that rigid piles are used in lab experiments while elastic piles are used in the RS pile model.

4.2 The soil reaction is measured at different depths along the pile:

Check how much soil reaction occurred at different depths along the pile in this part. The results of soil reaction depth from pile head are shown in Figure 9, Figure 10 and Table 6 below,

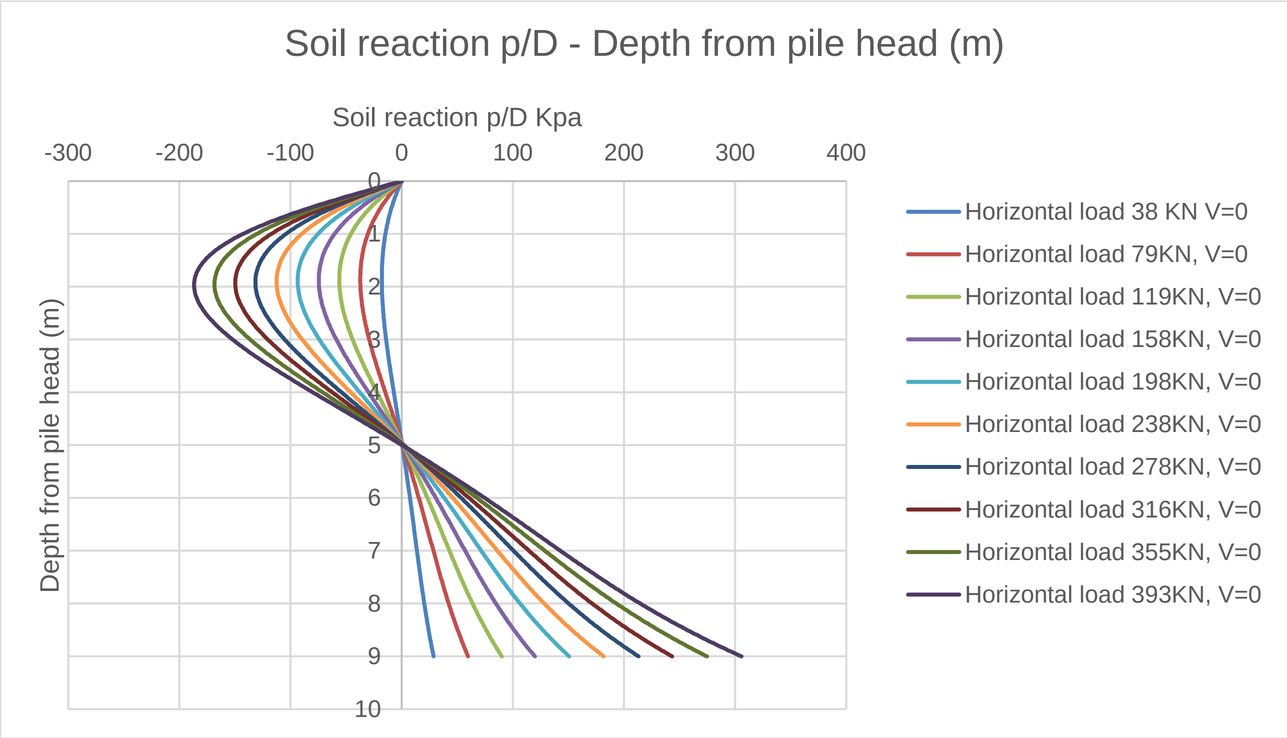

Figure 9 soil reaction - depth from pile head curve of Rs pile model.

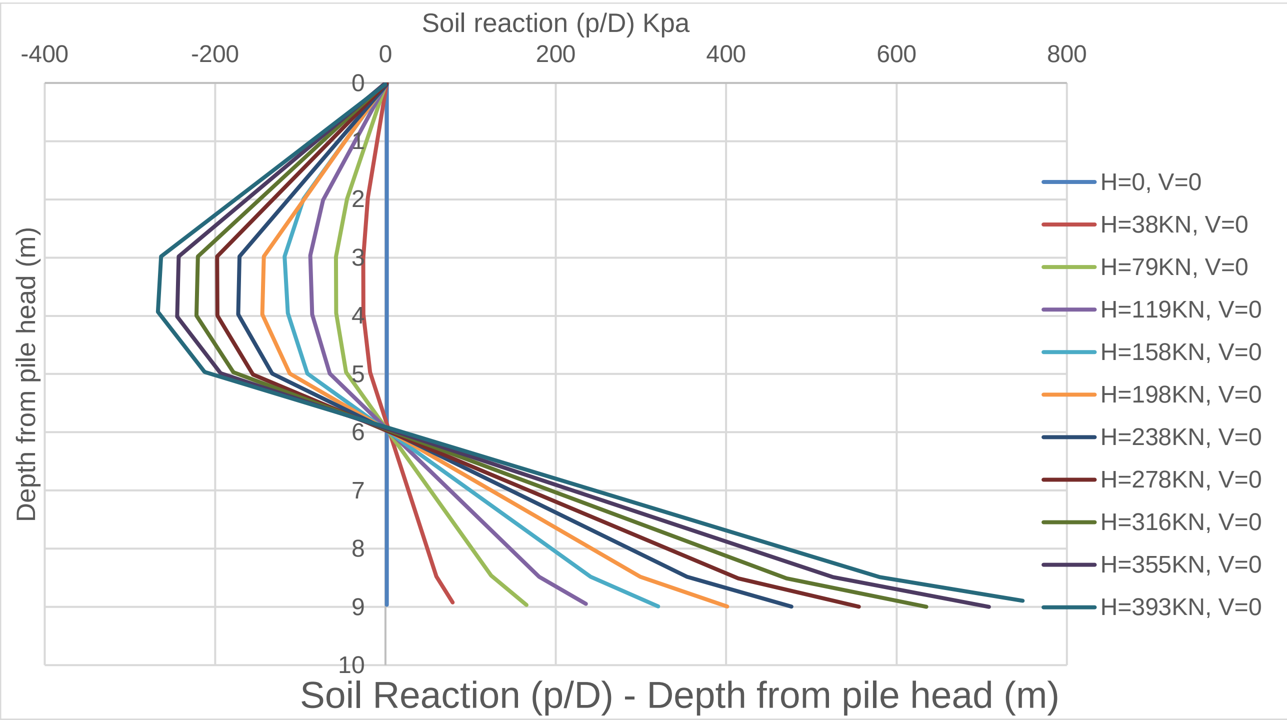

Figure 10 soil reaction - Depth from pile head curve of laboratory experiment of the previous scholar.

Table 6 The results comparison of RS pile model and lab experiment of soil reaction-depth from pile head

Load (KN)	Maximum soil reaction of Li et al. (2021) Laboratory experiment (Kpa)	Maximum soil reaction of RS pile model (Kpa)
H = 0, V = 0	0	0
H = 38, V = 0	28.68	68.80
H = 79, V = 0	59.71	126.87
H = 119, V = 0	90.09	210.42
H = 158, V = 0	119.88	278.90
H = 198, V = 0	150.66	401.25
H = 238, V = 0	181.72	476.65
H = 278, V = 0	213.12	555.82
H = 316, V = 0	243.29	635.00
H = 355, V = 0	274.67	708.59
H = 393, V = 0	310.66	748.65

Both models indicate that an increase in the horizontal force applied results in an increase in the soil reaction. As the applied force increases from 0KN to 355KN, the soil reaction increases to 274.67kpa for the RS pile and 708.59kpa for the lab experiment. The discrepancy between the laboratory result and the RS pile is about threefold in this instance.

As the applied force increases to 393KN, the soil reaction reaches around 310.66 for the RS pile and 748.65kpa for the lab experiment. In this instance, the discrepancy between the RS pile model and the laboratory result is about twofold.

4.3 Effect of pile diameter on lateral displacement for only horizontally loaded pile:

As mentioned above, the investigation utilised input parameters in a test done by (Finn and J. Dowling 2016). Eight different diameters of the pile are analysed: 0.324m, 0.5m, 0.75m, 1.0m,1.25m, 1.5m, 1.75m, and 2.0m. The results comparison of load-displacement are shown in Figure 11 and Table 7 below,

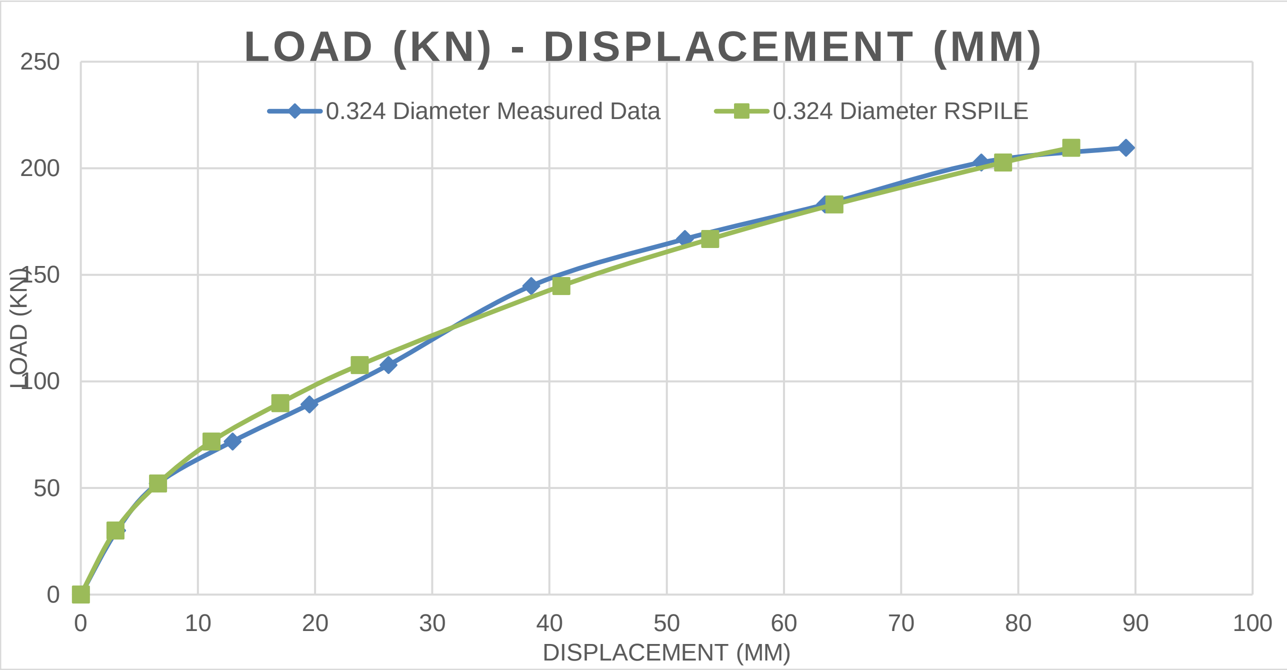

Figure 11 Results of Load - Displacement curve of 0.324m diameter.

Table 7 The results comparison of Rs pile and Verset 3D model of load-displacement curve

0.324m Diameter of pile		
Load (KN)	Measured Displacement (Verset 3D) (mm)	RS pile displacement (mm)
0	0	0
30.11	3.088	2.95
52.12	6.56	6.59
71.81	12.93	11.14
89.81	19.49	17
107.72	26.25	23.8
144.78	38.41	41
166.79	51.54	53.7
183.011	63.51	64.3
202.7	76.83	78.7
209.65	89.19	84.5

Both models indicate that an increase in the horizontal force applied results in an increase in the displacement. As the applied force increases from 0KN to 209.65KN, the displacement increases to

84.5mm for the RS pile and 89.19mm for the Verset 3D. The discrepancy between the Verset 3D and the RS pile is about 2% in this instance.

The calibrated software is used to construct load-deflection curves for various pile diameters ranging from 0.5 to 2.0 m.

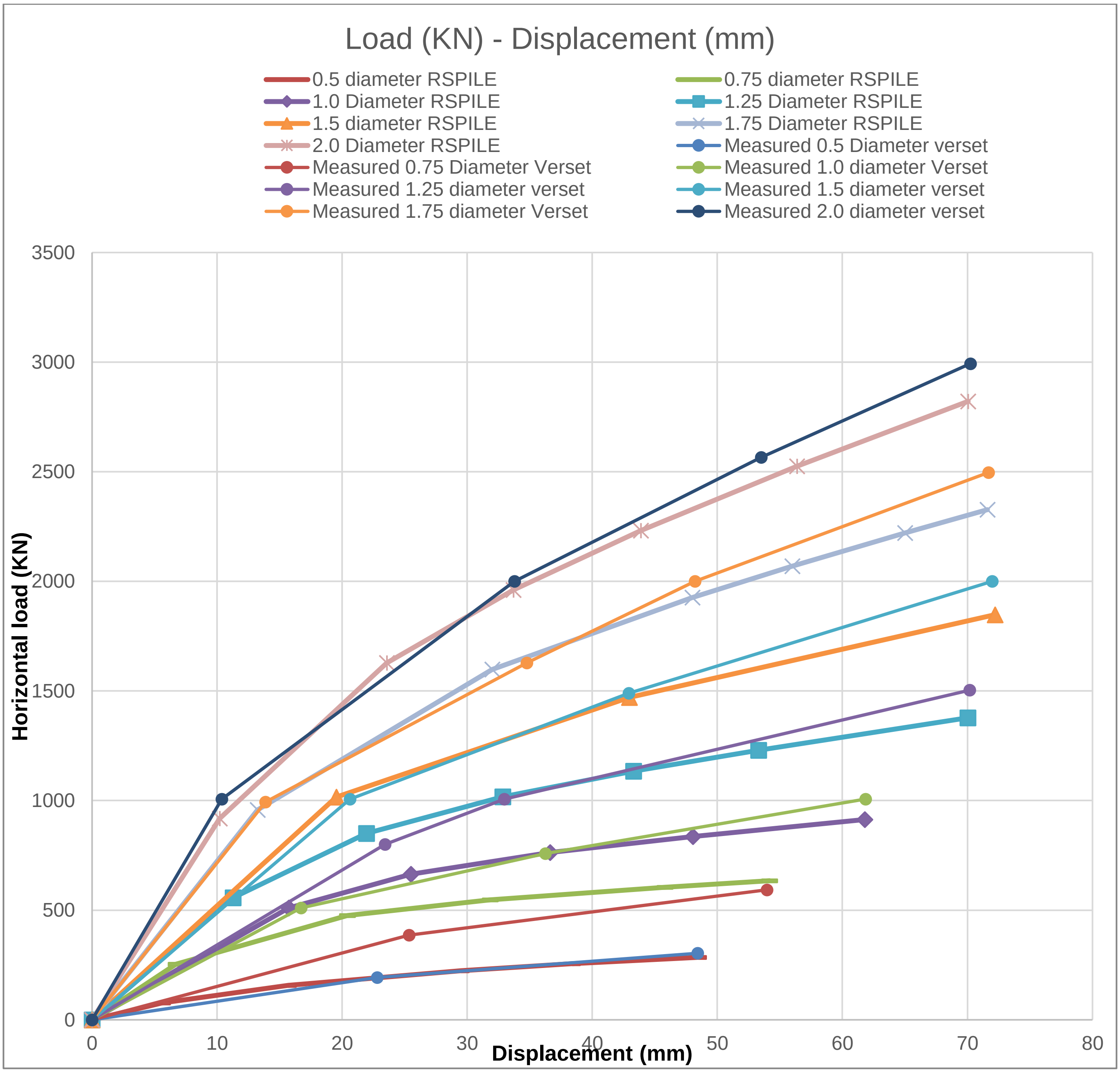

Figure 12 Results comparison of Verset 3D and Rs pile model of load-displacement curve.

Upon comparing the outputs of the Verset 3D and RS pile models, it is evident that both programmes yield identical outcomes. The maximum displacements for different pile diameters were as follows: 48.41mm for a 0.5m diameter, 53.97mm for a 0.75m diameter, 61.98mm for a 1.0m diameter, 70.028mm for a 1.25m diameter, 72.2mm for a 1.5m diameter, 71.6mm for a 1.75m diameter, and 70.06mm for a 2.0m diameter. Based on a comprehensive examination of all the results, it can be concluded that the displacement is slightly reduced when the pile diameter increases from 1.5m to 2.0m.

(Finn and J. Dowling 2016) derived a linear connection by summarising the numerical analysis results of the displacement of piles with varying diameters in different soil layers. It converts the load-displacement curve and moment-depth curve into logarithmic equations and plots all the data on a rectangular coordinate system. Figures 13 and 14 illustrate the linear relationship between load-diameter and moment-diameter.

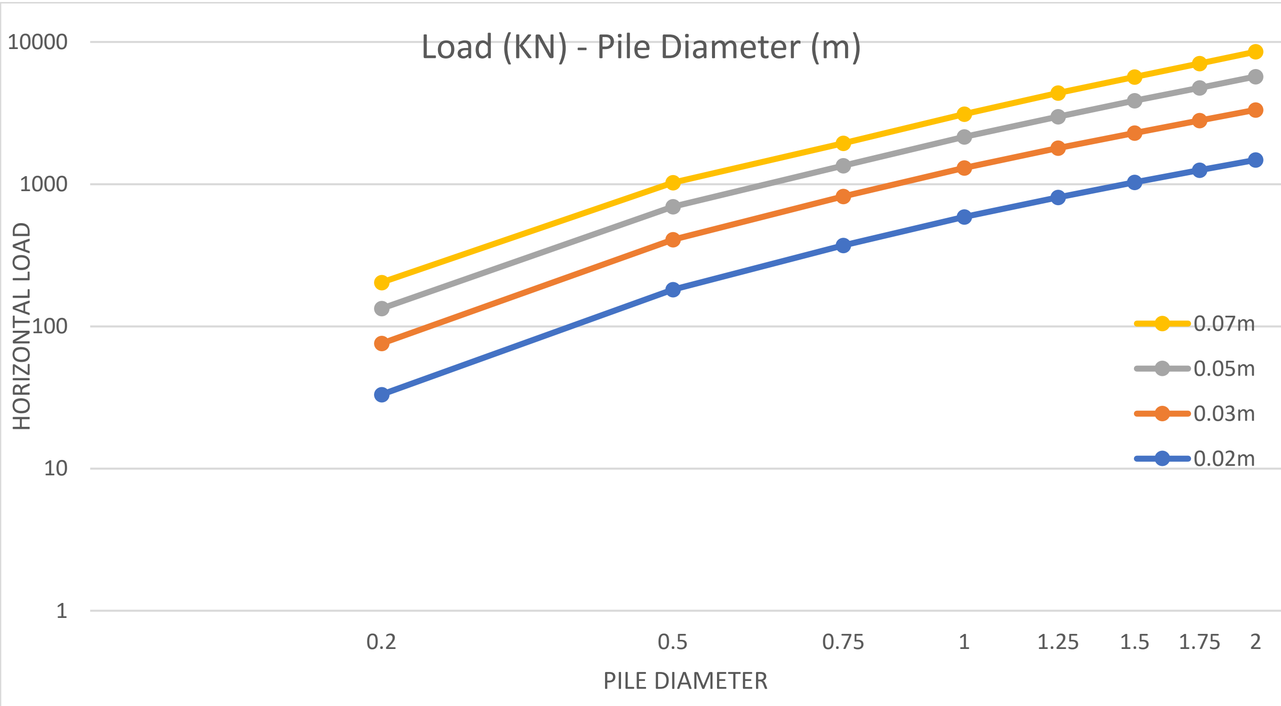

Figure 13 The logarithmic curve of Horizontal load-pile diameter.

Table 8 The results of load-pile diameter for displacement

	Displacement (m)			
Diameter (m)	0.02m	0.03m	0.05m	0.07m
0.2	33.141	42.567	57.757	70.191
0.5	181.264	225.877	288.75	328.784
0.75	371.612	447.114	530.304	590.551
1	588.92	709.775	847.448	958.662
1.25	809.17	980.893	1199.131	1377.37
1.5	1029.39	1260.63	1570.061	1821.771
1.75	1252.654	1550.279	1962.697	2301.544
2	1479.047	1849.982	2378.93	2820.174

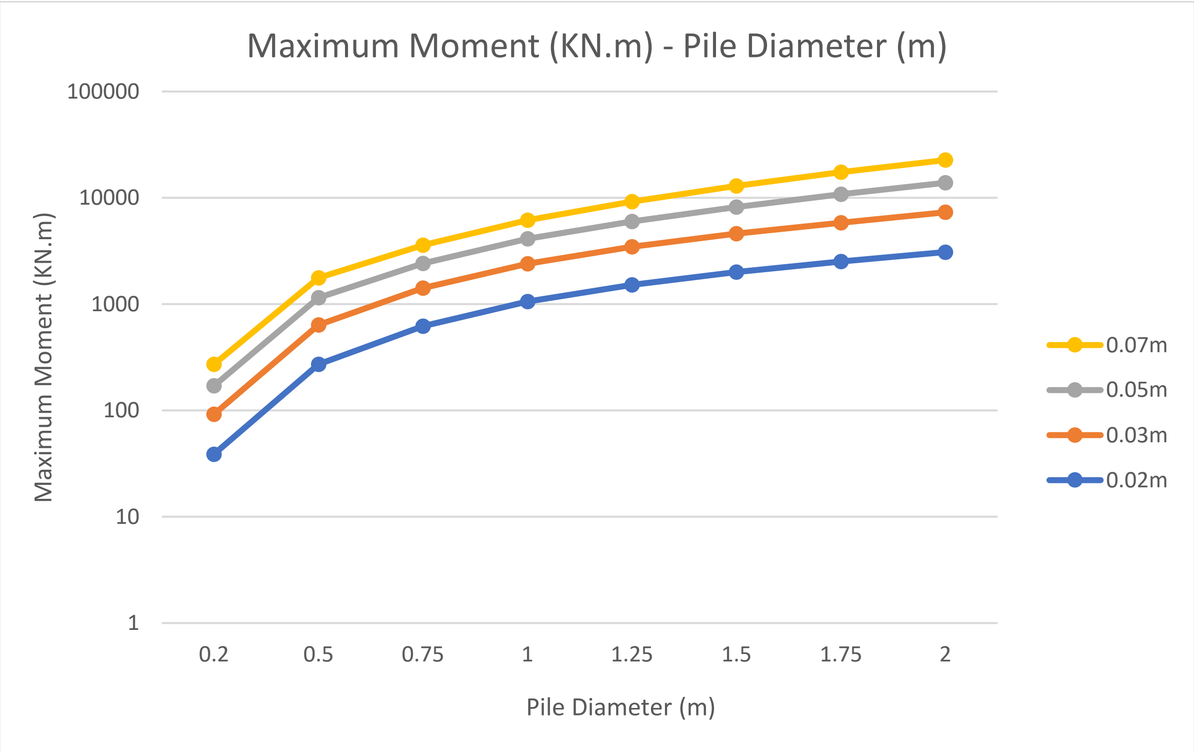

Figure 14 The Logarithmic curve of maximum moment-pile diameter.

Table 9 The Results of maximum moment-pile diameter

Maximum Moment (KN.m)				
Diameter (m)	0.02m	0.03m	0.05m	0.07m
0.2	38.826	53.305	78.512	101
0.5	272	367	514	614
0.75	620	793	1003	1170
1	1060	1340	1710	2040
1.25	1520	1940	2550	3220
1.5	2000	2590	3600	4780
1.75	2520	3320	4960	6640
2	3090	4220	6540	8800

4.4 Effect of pile diameter on displacement for both horizontally and vertically loaded piles:

In this case study, the investigation utilised input parameters in a test done by (Finn and J. Dowling 2016). There are eight different diameters of the pile analysed: 0.324m, 0.5m, 0.75m, 1.0m,1.25m, 1.5m, 1.75m, and 2.0m. We assumed a vertical load of 100KN for the pile with a diameter of 0.324m, and a vertical load of 500KN for the remaining seven piles. The results of load-displacement are shown in Figure 15, Figure 16 and Table 10 below,

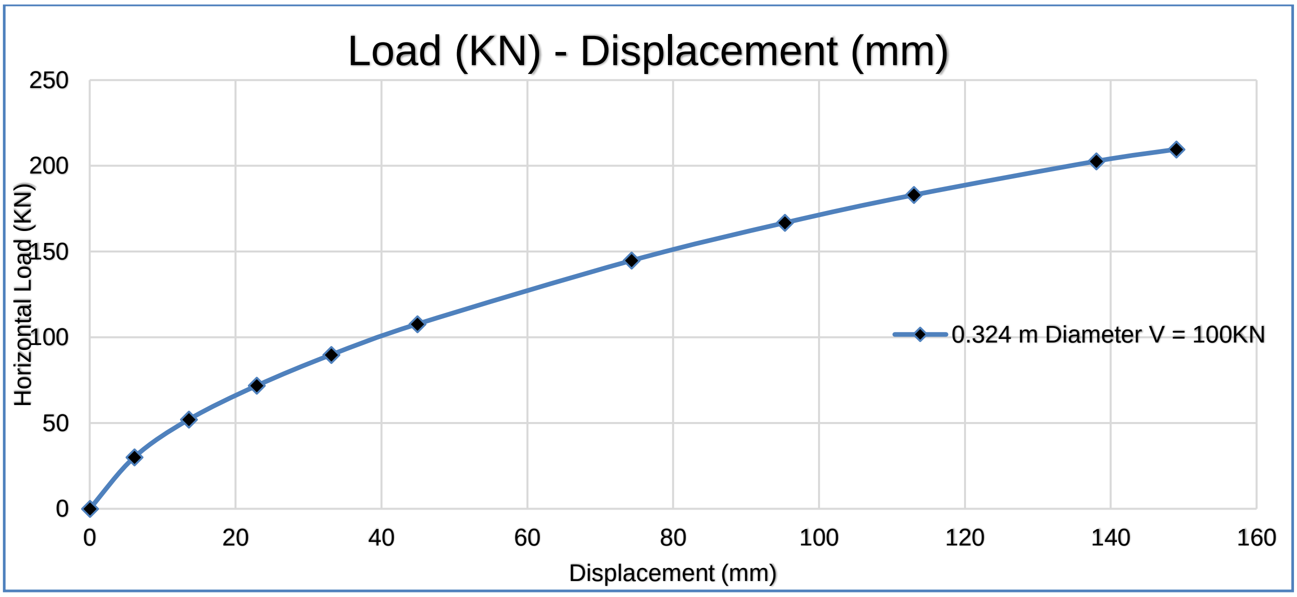

Figure 15 Load-displacement curve of 0.324m diameter of pile, V=100KN.

Table 10 The results of load-displacement for 0.324m diameter, V=100KN

0.324m diameter of pile, V=100KN	
horizontal load (KN)	**Displacement (mm)**
0	0
30.11	6.12
52.12	13.6
71.81	22.9
89.81	33.1
107.722	44.9
144.78	74.3
166.79	95.3
183.011	113
202.7	138
209.65	149

This case study displays the load-displacement characteristics of a pile with a diameter of 0.324m when subjected to a vertical force of 100 KN. At first, the pile exhibits a high level of rigidity and experiences a substantial rise in load for tiny displacements, such as 30.11 kilonewtons at 6.12 mm. As the displacement grows, the rate at which the load increments slows down, suggesting a decrease in stiffness (e.g., the load is 144.78 KN at a displacement of 74.3 mm). The stack demonstrates non-linear elastic characteristics that shift to yielding at greater displacements. The pile exhibited a significant load-bearing capacity and deformation tolerance under horizontal loading, with a maximum recorded load of 209.65 KN at a displacement of 149 mm.

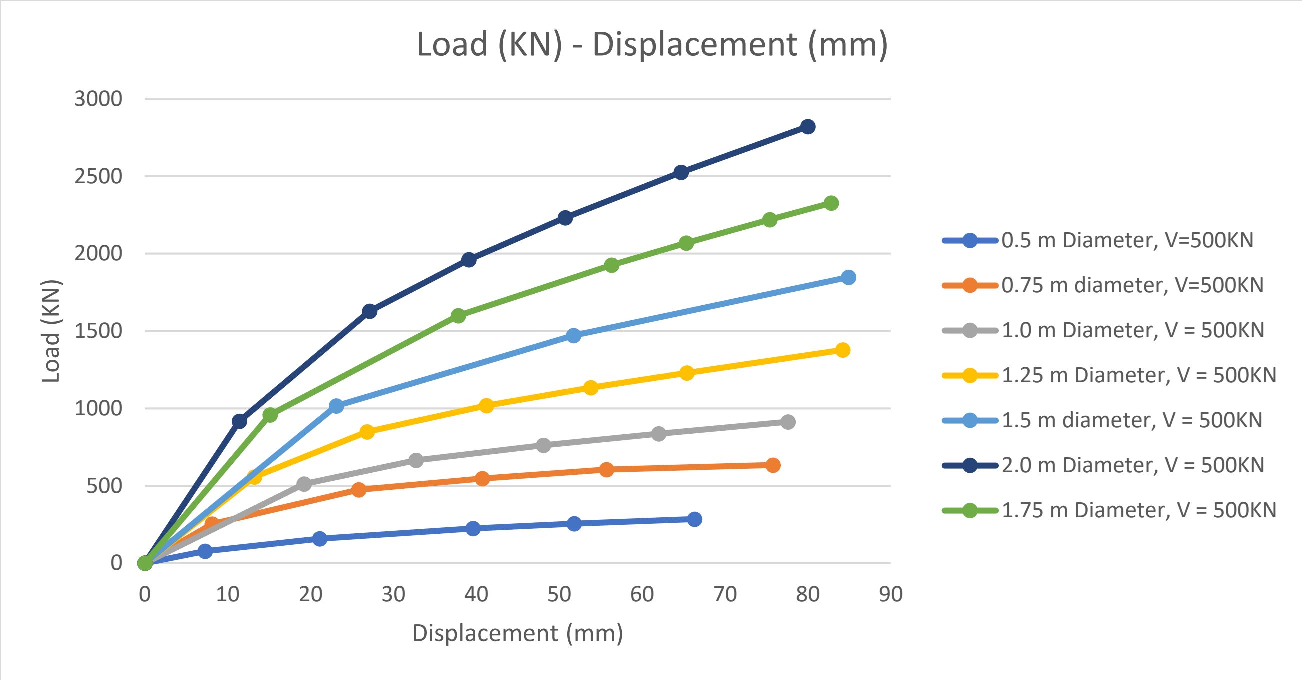

Figure 16 The load-displacement curve of seven different diameters, V=500KN.

The detailed results of load-displacement for every diameter of pile are shown in the Appendices below, the load-displacement characteristics of piles spanning a diameter of 0.5m to 2.0m while subjected to a consistent vertical load of 500KN are illustrated in the graph. The load causes a rapid increase in displacement for the pile with the smallest diameter (0.5m), which reaches a maximum of 800 KN at 80 mm and carries approximately 500 KN at 30 mm of displacement, indicating a lower capacity and greater flexibility. The moderate improvement is evident in the 0.75m pile's support of 750 KN at 40 mm displacement and 900 KN at 80 mm displacement. At 40 mm and 80 mm, the 1.0m pile bears approximately 900 KN and 1100 KN, respectively, indicating increased rigidity. 1100 KN is supported at 40 mm by the 1.25m pile, with a maximum of 1300 KN at 80 mm, indicating further performance enhancement. The 1.5-meter pile is capable of withstanding 1250 KN at 40 mm and 1500 KN at 80 mm, demonstrating a markedly increased capacity and rigidity. The 1.75-meter pile exhibits robust performance, with a maximum support of 1800 KN at 80 mm and an approximate 1500 KN at 40 mm. With a maximum capacity of 2200 KN at 80 mm and a minimum capacity of 1800 KN at 40 mm, the pile with the largest diameter (2.0 m) exhibits the greatest rigidity and least displacement when subjected to strain. In general, piles of greater diameter demonstrate enhanced load-bearing capacity and structural rigidity when subjected to the same horizontal load as smaller-diameter piles.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion:

This study has developed the impact of vertical loading on the lateral behaviour of piles in the sand by using RS pile numerical simulation software.

A correlation was observed between the RSPILE model and laboratory experiments conducted by Li et al. (2021), which demonstrated that as horizontal force increases, pile head displacement also increases. In general, the RSPILE model forecasted greater displacements than the laboratory experiments. The main cause of this disparity, which is approximately two to three times more pronounced in the RSPILE model, is the utilisation of elastic piles in RSPILE as opposed to rigid piles utilised in laboratory experiments.

In the laboratory investigations conducted by Li et al. (2021), the soil reaction results were greater than those predicted by the RS pile model. The laboratory findings estimated soil reactions that were roughly two to three times more intense than those predicted by the Rs pile model, suggesting that the numerical model adopted a more cautious approach. The distinctions underscore the significance of material properties and model assumptions in simulations.

The investigation additionally assessed the correlation between pile diameter and lateral displacement for piles subjected to both horizontal and combined horizontal and vertical loads. The displacement of horizontally laden piles exhibited consistent patterns in both the RSPILE and VERSET 3D models (Finn and J. Dowling 2016), wherein an increase in pile diameter resulted in a marginal reduction. Increased diameters of piles exhibited improved load-bearing capacity and decreased displacements under combined loading conditions, thereby underscoring the structural advantages associated with such increases.

To conclude, putting a 500KN vertical load on the pile caused it to move 18 mm for a 0.5 m diameter, 19 mm for a 0.75 m diameter, 15 mm for a 1.0 m diameter, 14.2 mm for a 1.25 m diameter, 12 mm for a 1.5 mm diameter, and 10 mm for a 1.75 m diameter and a 2.0 m diameter. The difference in movement between piles loaded horizontally and those loaded vertically and horizontally is about 12%.

5.2 Future work:

Due to the limitation of time and resources, this study only focuses on numerical analysis methods in RS pile software.

Study the long-term performance and durability of piles subjected to combined vertical and lateral loads. This includes examining the effects of cyclic loading and the potential degradation of materials over time.

Conduct full-scale field tests, and centrifuge tests for soil reaction - displacement (p-y) in the lab.

Examine the impact of various pile materials, such as steel, concrete, and composite materials, on the ability to withstand both horizontal and vertical loads. Additionally, analyse the impact of the pile's cross-section shape, such as a square shape, on its ability to sustain both lateral and vertical loads.

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APPENDICES

Table 11 The results of load-displacement for 0.5m diameter of pile, V=500KN

0.5 m Diameter, V=500KN			
Displacement (m)	**Horizontal LOAD (KN)**	**Moment (KN.M)**	**VERTICAL LOAD (KN)**
0	0	0	0
7.27	77.072	37.225776	500
21.1	157.543	76.093269	500
39.6	223.951	108.168333	500
51.8	255.731	123.518073	500
66.3	284.892	137.602836	500

Table 12 The results of load-displacement for 0.75m diameter of pile, V=500KN

0.75 m diameter, V=500KN			
Displacement (m)	**Horizontal Load (kn)**	**moment (kn.m)**	**VERTICAL LOAD (KN)**
0	0	0	0
8.11	253.25	122.31975	500
25.8	475.072	229.459776	500
40.7	546.83	264.11889	500
55.68	603.905	291.686115	500
75.8	634.397	306.413751	500

Table 13 The results of load-displacement for 1.0m diameter of pile, V=500KN

1.0 m Diameter, V = 500KN			
Displacement (m)	**moment (KN.m)**	**Horizontal Load (KN)**	**VERTICAL LOAD**
0	0	0	0
19.2	246.678726	510.722	500
32.7	320.636169	663.843	500
48.1	368.417427	762.769	500
62	403.784619	835.993	500
77.6	441.207942	913.474	500

Table 14 The results of load-displacement for 1.25m diameter of pile, V=500KN

1.25 m Diameter, V = 500KN			
Displacement (m)	**Horizontal Load (KN)**	**moment (kn.m)**	**VERTICAL LOAD**
0	0	0	0
13.2	556.561	268.818963	500
26.8	849.666	410.388678	500
41.2	1017.822	491.608026	500
53.8	1133.802	547.626366	500
65.4	1229.897	594.040251	500
84.2	1377.609	665.385	500

Table 15 The results of load-displacement for 1.75m diameter of pile, V=500KN

1.75 m Diameter, V = 500KN			
Displacement (m)	**Horizontal Load (KN)**	**moment (kn.m)**	**VERTICAL LOAD**
0	0	0	0
15.1	957.472	462.458976	500
37.8	1598.572	772.110276	500
56.3	1926.148	930.329484	500
65.3	2068.796	999.228468	500
75.4	2220.49	1072.49667	500
82.8	2327.042	1123.96	500

Table 16 The results of load-displacement for 2.0m diameter of pile, V=500KN

2.0 m Diameter, V = 500KN			
Displacement (m)	**Horizontal Load (KN)**	**moment (kn.m)**	**VERTICAL LOAD**
0	0	0	0
11.4	917.781	443.288223	500
27.1	1627.694	786.176202	500
39.1	1961.145	947.233035	500
50.7	2231.66	1077.89178	500
64.7	2525.326	1219.732458	500
80	2821.42	1362.75	500

Risk Assessment Form:

Flinders University **RISK ASSESSMENT FORM**

List identified hazards and detail measures taken to eliminate / minimise the risks:
(boxes on this form will expand to fit text)

Click to add image

Risk Assessment No.	1
Reference to SWP/SWMS No.	

College/Portfolio	civil	Area/Unit		Location	Tonsely pods - flinders university	Area/Unit Manager	
Task/Procedure	centrifuge test	Workers consulted / involved		Date	08/09/2023	Review Date	

Identified Hazard before controls		Risk Assessment			Risk Controls	Residual risk			Implementatio
No.	Description	Consequences	Likelihood	Risk Measure (see matrix)	Control measures	Consequences	Likelihood	Risk Measure (see matrix)	Date controls implemented / reviewed
1	Heavy equipment handling	Major Injury	Unlikely	Medium	check the weight of materials prior to lifting/ moving it use trolly cart to move objects/materials.	First Aid	Possible	Medium	
2	pile driving hazards	Major Injury	Unlikely	Medium	Adequate hearing protection and vibration monitoring should be provided to protect the health of researchers and nearby workers.	First Aid	Highly Unli	Low	
3	load testing	First Aid	Possible	Medium	Researchers need to ensure that the testing apparatus is well-designed and adequately secured to prevent accidents during load application.	First Aid	Possible	Medium	
4	sinking hazard	Minor Injury	Unlikely	Medium	Proper safety measures, such as using appropriate footwear and equipment, should be employed.	First Aid	Possible	Medium	
5	soil contamination	Minor Injury	Unlikely	Medium	Environmental impact assessments should be conducted to minimize the risks of soil contamination.	Minor Injury	Possible	Medium	
6		-Select -	- Select -			- Select -	- Select -		

Review the risk measured, and the controls implemented are still relevant and effective, then please select one of the following:

A The assessment reveals that the potential risk to health and safety from the use of the plant/equipment/procedure is not currently significant. ☐

B The assessment reveals that the potential risk to health and safety from the use of the plant/equipment/procedure is significant. However controls are in place that reduce risk as low as is reasonably practicable. ☐

Note: If the risk level is still **Extreme/High** after controls are in place, then cease the activity, identify and implement further controls and consult with your manager/supervisor until the risk is reduced as low as reasonably practicable.

Risk Assessment Form - revised 15 February 2021 centrifuge test Page 1 of 3