“Determination of p-multipliers for 3X3 Deep Foundations (Pile Group) in sand under lateral loads using 3D F.E.M”

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It is certified that

BE Civil Engineering Project entitled

Determination of p-multipliers for 3X3 Deep Foundations (Pile Group) in sand under lateral loads using 3D F.E.M

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DEDICATIONS

This project is dedicated to Allah Almighty, our families, our teachers, MCE and our course mates.

ACKNOWLEDGEMENTS

This project is dedicated to Allah Almighty which made this project not only a source of education and knowledge for us but it also developed in us a sense of confidence and motivation to carry out similar endeavors in the future for the benefit of human beings.

Secondly, we would like to praise the efforts of our project supervisor, Dr. Bilal Adeel whose effort were crucial for the execution of this project and without whom we would not have thought of grasping such a modern and detailed project.

Lastly, we would like to praise the efforts of our parents and Course fellows who efforts are non the less appreciated for the success and finalization of this project. They were a source of support and inspirations for us when time were tough for us.

We will always remember and praise their efforts.

Syndicate Members,

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Abstract

Pile foundations are important for massive structures that are required to be built on relatively weak strata. Study of such structures under lateral loads are limited and requires special attention. Furthermore, study is also time consuming and uneconomical in field testing. 3D analysis by FEM will be used to predict the behavior of soils under different spacing and friction coefficients. Abaqus will be used in order to study such effects in detail and a relation with previous study of Rollins (2005) will be performed in order to validate our results and research.

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CHAPTER 01 INTRODUCTION

1.1 Statement of Purpose

Pile foundations support a wide range of structures, including large skyscrapers, long-span bridges, and offshore structures. The pile response under a lateral load is always considered when designing piled foundations. The sources of these lateral loads are wind forces, wave impacts, slope failure, earthquakes etc.

Due to complexity and non-linearity of pile-soil interaction in group piles it is very difficult to understand the complex responses behind pile-soil interactions. As data from many previous researches are site specific and usually limited to the pile configuration, strata properties like friction angle, pile properties like S/D ratio, Pile type (Driven or Bored), pile head conditions and assumed soil behavior (elastic or Mohr- coulomb) etc. it is difficult to imagine or propose a simple formula or reason as to explain the much complex behavior of pile-soil interactions in group piles.

For our study we are using abacus software to model the 3D pile soil interactions in granular soil in order to calculate p-multipliers. We will also be accessing other p-y curves used for granular soils which includes one represented by (Rollins, Lane, & Gerber, 2005) and comparing them with our proposed results in order to determine the efficiency of our approach. We will be applying static loading on a pile group and will be accessing the effects of different S/D ratio and friction angle on the p-multipliers of the pile group.

We will be using the BNWF model to simulate the group pile response under lateral load. As observed by (Larkela, 2008), the "shadowing effect" and the "edge effect" both reduce soil resistivity.

1.2 Research Objective

The objectives of this study are:

1. To derive the p-multipliers for 3x3 pile group in cohesion-less soils under lateral loads.

2. To compare the results evaluated from Finite Element Model (FEM) with the curves represented by (Rollins, Lane, & Gerber, 2005) for validation.
3. To derive and display the complex 3D pile soil interaction that results in reduced soil resistance towards lateral loads in pile foundations (p-multipliers).
4. Use of three-dimensional 3D numerical simulations via ABAQUS that will account nonlinear nature of soil in modelling.
5. Integration of the present project with Sustainable Development Goal (SDG # 9) which is Industry, Innovation and Infrastructure.
6. Integration of the present project with Sustainable Development Goal (SDG # 11) which is Sustainable cities and Communities
7. Effect of various factors like friction angle, S/D ratio on the values of p-multipliers.

1.3 Scope

3D modeling software like abacus enables us to create solid 3D elements which incorporates more data points than any other model and enables us to include properties like weight, material density, the center of gravity, and mechanical stress. A solid model is not only the most realistic, but it is also the most commonly utilized in numerical modeling to create prototypes.

One advantage is that it provides a visual representation of an object. 3D modelling (at least from an engineering aspect) delivers a large degree of technical detail with nearly no mistakes, if any, in addition to an accurate description of the material object.

3D modeling a pile group to determine various pile soil interactions is not just an economical approach but it also enable us to determine the validity and the safety of structures responding to lateral loading up to maximum realistic output.

1.4 Summary

The basic content of this literature review is

Chapter 1 presents the statement of purpose, objectives, scope, and summary of our write up.

Chapter 2 presents the literature review of previous studies, basic terminologies and conceptual approach that we will take into account in our research.

Chapter 3 will deal with the numerical models that we will create in order to study the relation between bending moments and soil resistance, as well as the relationship between different S/D ratios and p-multipliers for group piles of order 3x3.

Chapter 4 deals with the analysis of data from chapter 3 which will show the different variations in the value of p-multipliers with the changing of spacing and friction angle and the inter relation between different scenario.

Chapter 5 is analysis and discussion of the results and gives some recommendations for the future researches.

CHAPTER 02 LITERATURE REVIEW

2.1 Introduction

In this chapter we will be presenting the design criteria for pile foundation. In design of a group pile the lateral loads have a considerable influence. When pile group comes into interaction with soil, complex pile soil interactions tend to come into play.

The nonlinear nature of the soil, as well as the piles that interact with it, contribute to the complexity. In order to take into account, the nonlinear behavior of soil we use the BNWF approach which is the best case to study pile groups under lateral loading as proposed by (Larkela, 2008).

2.2 Basic Terminologies

2.2.1 Pile Foundation

A pile foundation is a sort of deep foundation that consists of a slender column or long cylinder made of materials such as concrete or steel that is used to support the structure and transmit load at the appropriate depth by end bearing or skin friction. Pile foundations are often used for large constructions and when weaker soil is insufficient to support severe settlement, uplift, and so on

Figure 1 Pile

2.2.2 Pile Group

A pile group is a collection of piles that have a pile cap and work together to bear the weight. Normally, the pile cap would be in touch with the earth. The piles would be constructed to share the pile load in their final form. The pile cap would be built to connect the piles, but its contribution to bearing capacity is not incorporated in the design.

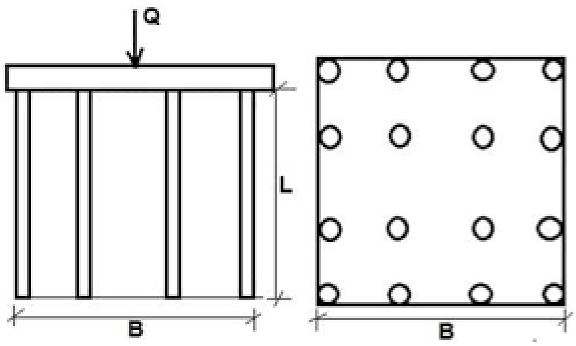


Figure 2 Pile Group illustrations

2.2.3 Lateral Loads

Lateral loading is the application of a load on an object or structural element in a horizontal direction or lateral to the x-axis on a continuous and repeating basis. Lateral loading can tear or deform a material in the direction of force, ultimately leading to material failure.

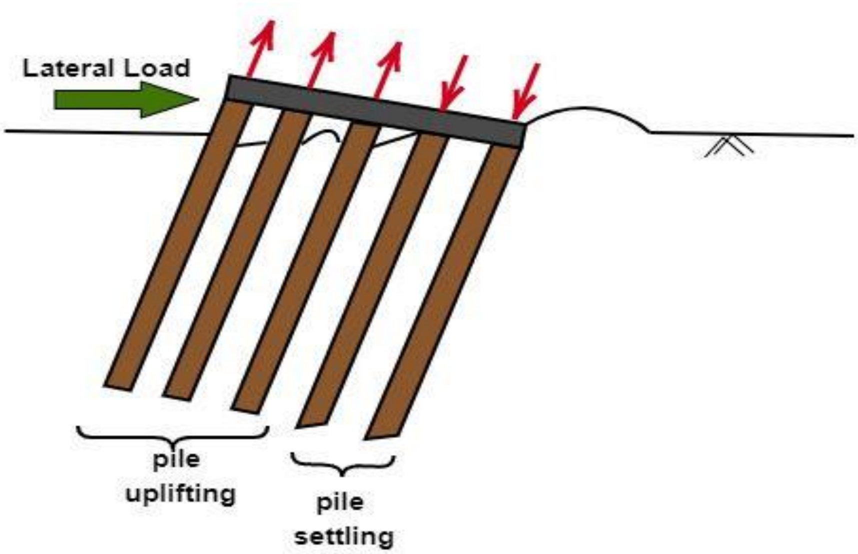


Figure 3 Lateral load Illustrations

2.2.4 Bending Moment

A bending moment (BM) is a measurement of the bending effect that may occur when an external force is applied to a structural part. This concept is significant in structural engineering because it can be used to determine the location and amount of bending that happens when forces are applied.

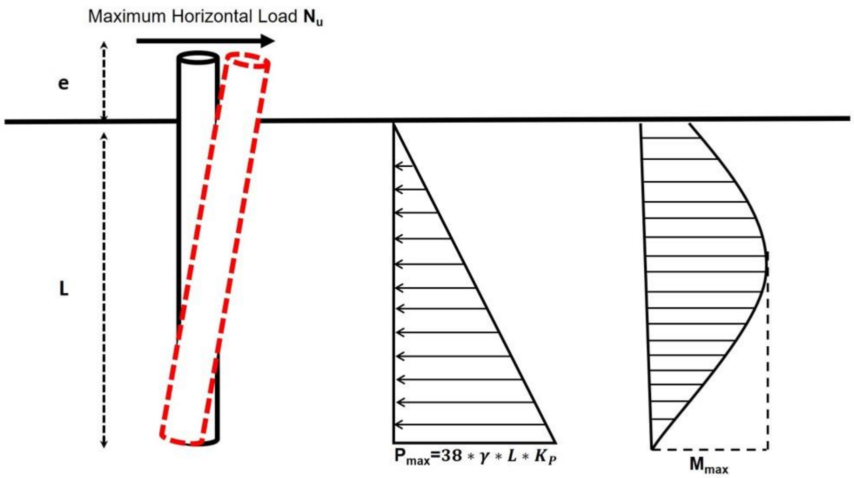


Figure 4 Bending Moment illustrations

2.2.5 p-multiplier

The p-multiplier is defined as the ratio of lateral soil resistance of a group pile case to lateral soil resistance of the identical condition pile but in single orientation.

2.2.6 S/D ratio

S/D ratio is defined as the ration of pile spacing (S), to the diameter of the pile used in the Group (D). It’s an important parameter in pile group study as it is shown to have impact on the performance and efficiency of the pile group.

2.2.7 Finite Element Method

It is a method in which an object or shape are constructed in a modeling software and are provided certain constraints like mass, density, state, elasticity, etc. along with cartesian constraints (x, y, z) in order to define their orientation, translation and rotational aspect in space in order to produce a real-life simulation of the object when subject to external forces, moments, disturbances etc. It can easily produce result comparable to real life problems with little to no errors. Of course, the quality of simulation depends upon the quality of data inserted. (Bathe, 2007)

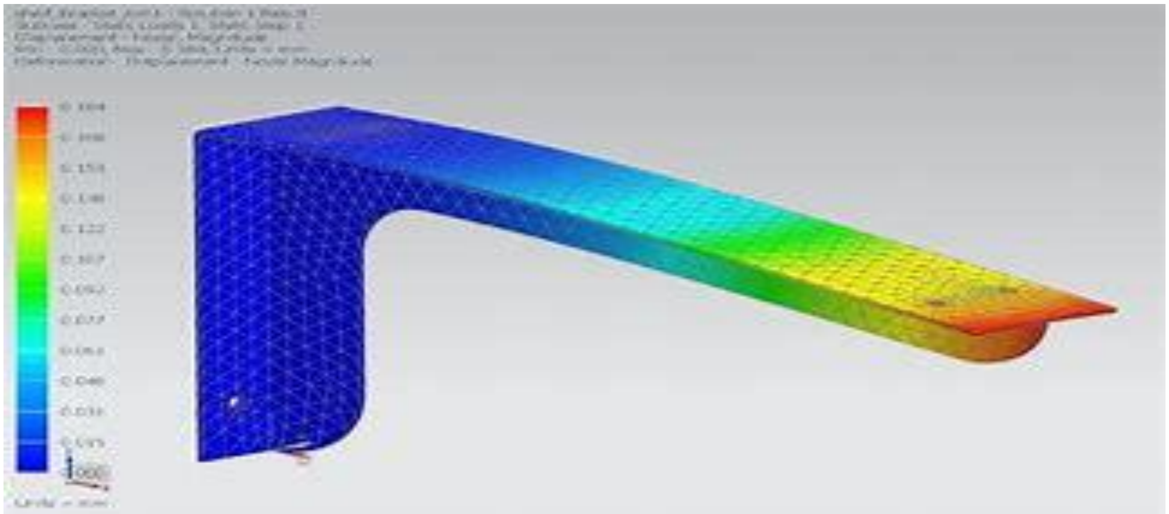


Figure 5 A 3D numerical model

2.3 Previous Studies on pile regarding Lateral loads

The previous studies regarding the study of lateral responses on piles incudes the strain wedge model by (Ashour, 1998), Beam on nonlinear Winkler Foundation (BNWF) by (Brown & Shie, 1990), (Muqtadir, 1986), and (Yang & d Jeremić, 2002).

2.3.1 Strain Wedge Method

The strain wedge model first presented by (Ashour, 1998) focuses on the following Aspect:

The theory of beams on elastic foundations gives an effective solution to the problem of a laterally loaded pile. The precision of such a solution is dependent on the understanding of the interaction between the pile and the surrounding soil. A more accurate depiction of the soil-pile interaction results in a more realistic solution. While classic nonlinear "p-y" characterization is adequate for a wide range of loaded piles, it has been discovered that the p-y curve (or modulus of subgrade response) is affected by pile parameters (width, shape, bending stiffness, and pile-head conditions) as well as soil variables. The strain wedge model evaluates the nonlinear p-y curve response of a laterally loaded pile based on the proposed relationship between the three-dimensional response of a flexible pile in soil and its one-dimensional beam on elastic foundation parameters. Furthermore, the strain wedge model evaluates mobilized soil behavior using the stress-strain-strength behavior of the soil as determined by the triaxial test and the effective stress condition.

2.3.2 BNWF Method

In practice, the BNWF model is most commonly utilized. In the model, the three-dimensional (3D) soil and pile interaction is represented by the p–y curve, where p is the soil resistance and y are the lateral displacement. For convenience, this strategy is also known as the p–y model.

Various form of p-y curves is used for analysis of piles in granular soils, like those presented by (Reese, 1974) and (API, 2007). There explanation is as follows

2.3.2.1 Reese et al. (1974)

Data were collected during the lateral loading of two 24-in. diameter test piles constructed at a site with clean fine sand to silty fine sand soils. There were two forms of loading used: static loading and cyclic loading. The data was evaluated, and families of curves demonstrating soil resistance p as a function of pile deflection y were created.

Based on theoretical investigations, a technique for estimating the family of p-y curves based on sand parameters and pile dimension was developed. Procedures for both static and cyclic loading are suggested. While there is some theoretical support for the procedures, the behavior of sand around a laterally driven pile does not lend itself to a perfectly logical analysis; hence, the recommendations include a significant element of empiricism.

The soil resistance p is found by taking second derivative of moment with respect to depth i.e.

$$p = \frac{d^2}{dx^2} M(x)$$

$$y = \iint \frac{M(x)}{EI}$$

The approach was used at the experimental site to predict p-y curves, and the computed results were compared to the experimental data. The deal is satisfactory.

(Reese, 1974)

The Reese p-y curves contain 4 curves which constitutes both linear and a parabola.

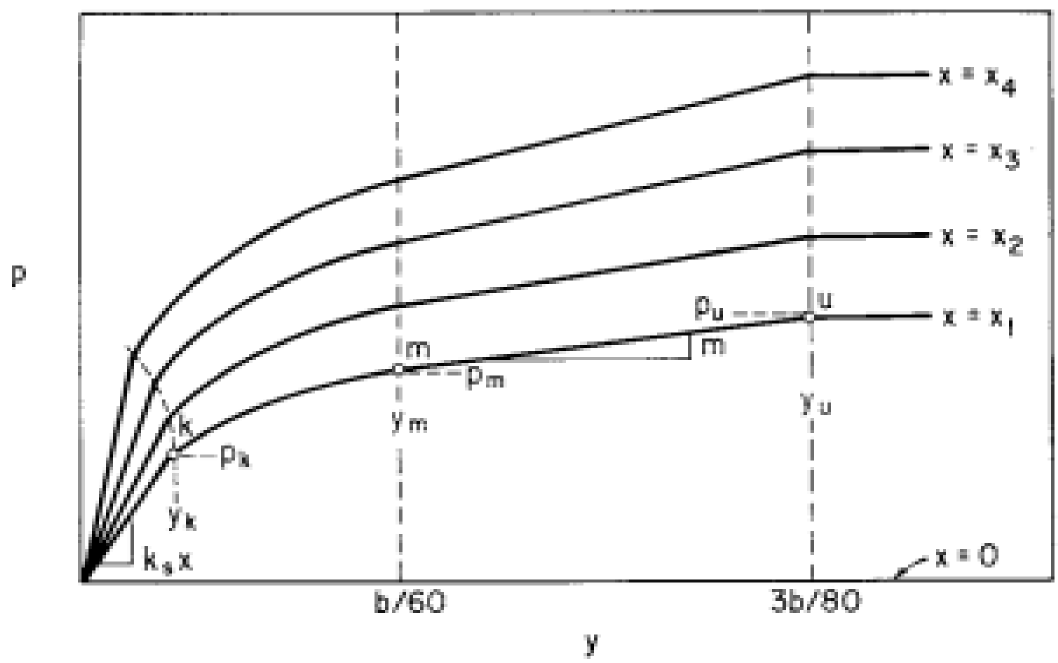


Figure 6 Reese p-y curve

Here,

p = soil resistance

y = displacement

p_u = ultimate resistance of soil

p_m= soil resistance at b/60

Both p_m and p_u are functions of P_{ct}, which is defined as the ultimate resistance near the ground surface and is calculated by following formula:

$$P_{ct} = \frac{K_0 H tan\emptyset sin\beta}{\tan(\beta - \emptyset)\, cos\alpha} + \frac{tan\beta}{\tan(\beta - \alpha)}(D + ztan\beta tan\alpha) + K_0 tan\beta(tan\emptyset sin\beta - tan\alpha) - K_a D$$

where α = ϕ/ 2, β = 45+ ϕ/ 2, Ko = 0.4, Ka= tan2 (45- ϕ /2), and γ is the submerged unit weight; Bp_{ct} and Ap_{ct} are used to determine pm and pu, where A and B are curve-fitting parameters that are functions of the normalized depth, z/D.

2.3.2.2 American Petroleum Institute API (2007)

API (2007) proposed the following tangent hyperbolic function to match the four-curve Reese et al. (1974) model, as illustrated.

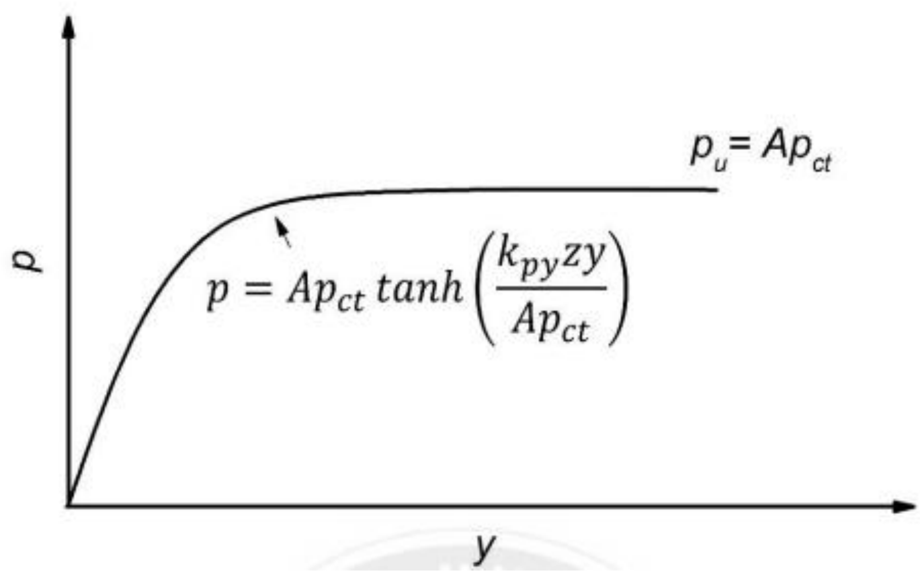


Figure 7 API 2007 Curve

$$p = Ap_{ct}\tanh(\frac{k_{py}zy}{Ap_{ct}})$$

The initial stiffness is k_{py}, and the final resistance is Ap_{ct}, which are both the same as for the Reese curve. However, the definitions of k_{py}, p_{ct}, and A are not the same. The Reese equation for pct is replaced by the following equation:

P_{ct} = (C1z+C2D) γ z

2.4 Pile Groups

Pile groups support a wide range of structures, including large skyscrapers, long-span bridges, and offshore constructions.

Many earlier researches like those of (Brown D.A., 1988) and (Holloway, 1982) showed that piles in the trailing rows of pile groups are less resistant to lateral loads than those in the lead row, resulting in higher deflections. Because of pile-soil-pile interactions that occur in the group, piles in closely spaced groups react differently than single piles. With these interaction effects, the deflections of a pile in a closely spaced group are larger than the deflections of an individual pile under the same weight. The maximum bending moment will also be higher for group pile as compared to a single pile, because soil will tend to behave like it has very less resistance, allowing for more deflection under same seismic loading. This unequal distribution is caused by effects known as "shadowing effect" and "edge effect".

2.4.1 Shadowing Effect and Edge Effect

The shadowing effect reduces lateral load on the trailing pile and so on. While edge effect reduces the lateral load in the same row.

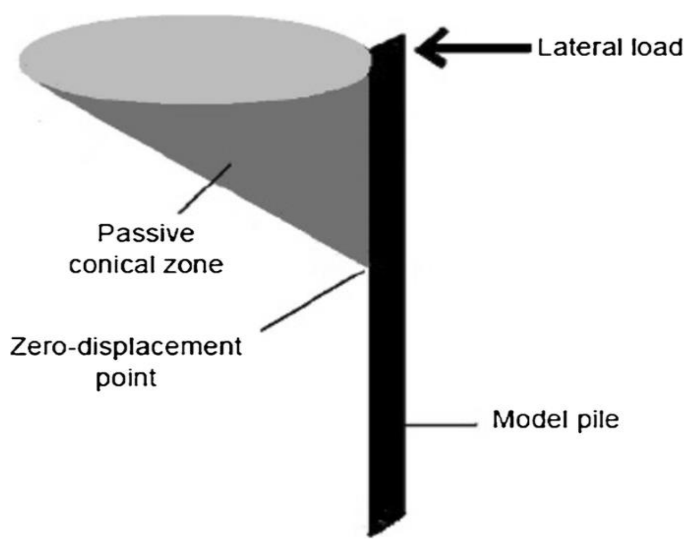


Figure 8 Shadow effect

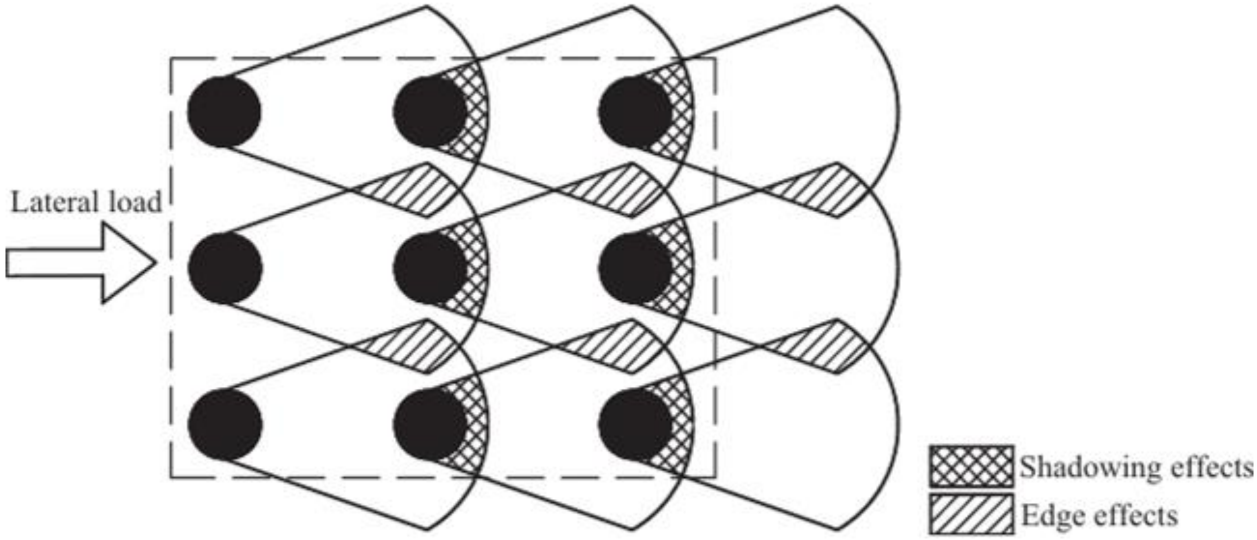


Figure 9 Edge Effect illustrations

2.4.2 p-multipliers

Shadowing and edge effects are anticipated to induce lower lateral load resistance and larger deflections and bending moments in the pile group research, as stated by (Larkela, 2008). The following figure also explains it:

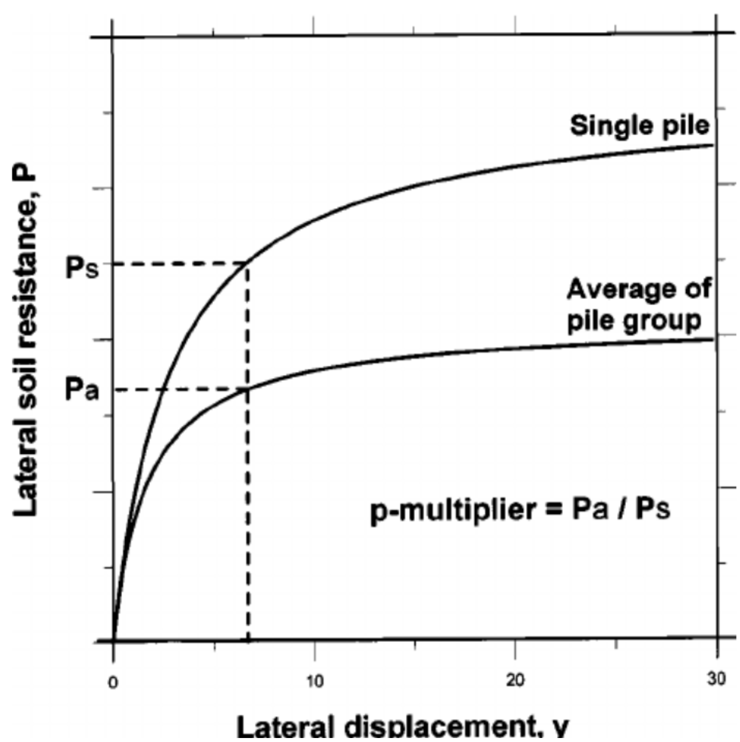


Figure 10 p-multipliers concept

As a result, the p-multiplier may be defined as a ratio of the lateral soil resistance of a single pile case to the lateral soil resistance of the same condition pile but in group orientation. To account for shadow and edge effects, a greater p-multiplier value should be applied to the trailing row, followed by the following trailing row.

2.5 Previous studies on pile Groups

2.5.1 (Holloway, 1982)

The p-multipliers were retrieved from field scale experiments and the following findings were obtained:

- The shadowing effect indicates that the leading row piles were carrying more load than the trailing rows.

2.5.2 (Brown D. A., 1987) and (Brown D. A., 1988)

In 1987, they conducted two experiments on 3x3 pile groups with S/D of 3 on stiff clays, and the following year on medium thick sand. The pile's diameter was 0.273 m. It should be emphasized that the 1988 test comprised of medium thick sand up to 2.9 m, under which lies a layer of firm clay.

Results:

- The load sustained by the leading row was found to be almost identical to that of a single pile under the same lateral displacement. Leading rows bear the largest burden in the group, followed by trailing rows.
- When loaded to the same average load per pile, the deflection of the pile group is much greater than that of a single pile.
- When compared to a single pile, the pile group suffered more bending moments.
- Proposed p-multipliers to account for the drop in resistance caused by the shadowing effect in each row of the pile group.

2.5.3 (Rollins & Sparks, 2002)

In silts and clays, they tested lateral stress on a 3x3 fixed-head pile group. The piles utilized in the testing were made of steel, with a concrete pile cover. The pile's diameter was 0.324m, and the S/D ratio was 3.

Results:

- They discovered that passive resistance on the pile head can greatly increase a pile group's lateral load capacity.
- The leading row piles carry the most lateral load; however, the first trailing row carried less load than the second trailing row.
- In cohesive soils, gaps close to piles can drastically diminish the lateral capacity offered by soil–pile contact.

2.5.4 (Rollins, Lane, & Gerber, 2005)

The site profile is made up of loose fine sand (SP-SM), silty sand (SM), and Young Bay muck. The soil profile is made up of a sand deposit that reaches to a depth of 7.49 m and is supported by soft clay. The water table was measured to be 0.5 m below the surface for the single pile test and 0.1 m below the surface for the group pile test. 11.84 m was dug beneath the excavated earth.

Results:

- Lateral resistance is determined by row position. The exterior piles are 20-40% heavier than the center piles.
- Similar to earlier experimental research, the leading rows bear the highest load in the group, followed by the trailing rows.
- They proposed p-multipliers for the first, first trailing, and second trailing rows are 0.8, 0.4, and 0.4, respectively.

2.5.5 (Rollins K. M., 2006)

They conducted full-scale testing on stiff clay and investigated three pile group configurations: 3x3, 3x4, and 3x5. The pile spacing ranged from 3.3 to 5.65 meters. They explored the impacts of group interaction as a function of pile spacing. In the form of this table, they obtained the following results from their 2006 research thesis.

Reference	Normalized spacing (S/D)	p multipliers (f_m) Row 1	Row 2	Row 3	Row 4
Rollins et al. (1998)	2.82	0.6	0.4	0.4	—
Ruesta and Townsend (1997)	3	0.8	0.7	0.3	0.3
Brown et al. (1988)	3	0.8	0.4	0.3	—
Brown et al. (1987)	3	0.7	0.6	0.5	—
Meimon et al. (1986)	3	0.9	0.5	—	—

Table 1 Comparison of P-multipliers

Results:

- At a given displacement, the leading row carries the highest weight, while the second and third trailing rows carry the lower loads. They determined, however, that the fourth and fifth trailing rows bear about the same load as the third trailing row piles.

2.5.6 (Meimon, Baguelin, & Jezequel, 1986)

The authors used steel pipe piles to conduct full-scale testing on clays. The pile group configuration was 3x2, with S/D of 3 in loading Direction and S/D of 2 in the perpendicular direction. The pile measured 0.27 m in diameter and 7.5 m in depth.

Results:

- Leading rows bear more loads and bending moments than subsequent trailing rows.

- Meimon et al. (1986) were among the first to directly quantify the weight on each individual pile in the group. This contributes to a better understanding of load distribution among piles in a group.

2.5.7 (Weaver, Rollins, & Peterson, 1998)

They conducted static lateral load testing on the very same pile group arrangement (3x3) as (Rollins, Lane, & Gerber, 2005). The pile head circumstances under consideration were free and fixed-head. Both scenarios of with and without pile cap embedment were investigated for fixed-head circumstances.

Results:

- They determined that dynamic resistance was 30-50 percent greater for free-head and fixed-head pile groups without pile cap embedment than static resistance.
- When the pile cap is incorporated in a fixed-head pile group, the dynamic resistance is 100-125 percent more than the static resistance.

2.5.8 (Huang, Hsueh, O'Neill, Chern, & Chen, 2001)

They looked into how pile placement affected pile group reaction. They tested both drilled and driven precast fixed-head pile groupings. The drilled and driven pile groups include 2x3 and 3x4 designs, diameters of 1.5 m and 0.8 m, and depths of 35 m and 17 m, respectively.

Results;

- The pile group reactions are mostly influenced by pile installation.
- Driven pile installation causes the soil to grow thicker, increasing the interaction of piles in a group, whereas bored pile installation has the reverse effect, loosening the soil and reducing group contact between piles.
- For both drilled and driven piles, they suggested p-multipliers. Bored piles have greater p-multipliers than driven precast piles because to less group interaction effect.

2.5.9 (Gandhi & Selvam, 1997)

They looked into the effect of pile driven conditions on the bending moment and lateral displacement due to lateral loading. Pile head conditions were fixed. Laboratory experiments were performed on the aluminum pile in dense grade sand with relative density of 60%. Pile configuration used were 1x2, 1x3, 2x2, 2x3, 3x2, 3x3.

Results:

- The effectiveness of a pile group for a given spacing decreases as the number of piles in the group increases due to an increase in the number of overlapping zones of passive and active wedges.
- For optimum group capacity, the optimal distance between piles in the load direction is around two times the relative stiffness factor T.
- Load factor α is larger in the case of driven piles than in bored piles due to compaction surrounding the driven pile.

2.6 Limitations of Previous Studies

Previous studies on single and group piles usually had the following limitations in regards to the following points:

1. Results for all studies were site specific and are correct for only the proposed site.
2. Results for different soil mediums like granular or clayey have complex variations and due to these reasons produces different values of p-multipliers.
3. Results were sometimes limited in scope in terms of pile configurations and parametric study for different pile group conditions.
4. Seldom did it happen in previous studies that p-multipliers were evaluated from numerical modeling and the effect of different values of friction angle for complex pile-soil interactions was evaluated and shown
5. Previous studies didn’t relate much results on the effect of different values of S/D and Frication angle on p-multipliers.

2.7 Summary

Numerous techniques for computing the p-multipliers for pile groups are described in the group and single piles. The soil resistance (p) is calculated by taking the second derivative of the bending moment with respect to depth.

Secondly, research like those of (Brown D.A., 1988) and (Holloway, 1982) showed that piles in the trailing rows of pile groups are less resistant to lateral loads than those in the lead row, resulting in higher deflections. Because of pile-soil-pile interactions that occur in the group, piles in closely spaced groups react differently than single piles. This causes group piles to experience higher bending moments and decreased lateral resistance. The shadowing effect that means leading row piles were carrying the larger amount of load in comparison with the trailing rows.

Lastly, Lateral resistance is a function of position within a row. Leading rows bear the most load in the group as compared to subsequent trailing rows similar to previous experimental studies.

CHAPTER 03 COMPARIOSN OF 3X3 PILE GROUPS WITH DIFFERENT S/D RATIO AND DIFFERENT FRICTION ANGLE AND VALIDATION WITH 3D MODEL OF ROLLINS ET AL. (2005)

3.1 Basic Concept

A series of 3D FE and BNWF analyses are performed in this chapter to replicate group pile lateral load testing. The 3D FE model, validated against the field lateral load test results, is considered as the reference approach. The mathematically and experimentally determined curves deviations are quantified. The Data we will use to validate our 3D finite element models will be the same as that one used by (Rollins, Lane, & Gerber, 2005) in his study in granular sand medium. The Approach that we use to construct the 3D finite element model will be Beam on Non-Linear Winkler Foundation (BNWF), as employed by both (Reese, 1974) and (API, 2007). We will be making 3 separate models after making the Model for (Rollins, Lane, & Gerber, 2005) which will have different S/D ratio. After our 3D model and analysis is complete, we will obtain the data for bending moment, from which we will calculate the p-multipliers. We will also be comparing the results of bending moments and effects of S/D and φ on p-multipliers.

3.2 Reference Test Data for Lateral Loads in Granular soils

The reference data for lateral loads was obtained from the research paper of (Rollins, Lane, & Gerber, 2005). The data for granular soil consists of the following data:

- Before testing, about 1.2 m of soil above the water table was excavated.
- The soil profile is composed of hydraulically deposited fill and natural shoal sands up to a depth of about 6 m below the excavated ground surface.
- . The hydraulic fill is often made up of fine sand or silty sand.
- . Silty sand and Young Bay Mud exist beneath this beach.
- According to the Unified Soil Classification system, the overlying sand layer is commonly classified as SP–SM material and has a D50 between 0.2 and 0.3 mm.

- At the location, standard penetration testing (SPT), cone penetration testing (CPT), and shear wave velocity recording were all done.
- Six CPT soundings were conducted across the testing location.
- The average cone resistance in the top sand layer was 6 to 9 MPa, whereas the underlying silty sand layer was 4 to 6 MPa.
- The shear wave velocity observed downhole generally ranged from 120 to 150 m/s in the top 6 m.
- Based on the SPT and CPT data, the relative density Dr was calculated.
- • The estimated Dr is normally about 50% in the clear sand layers and around 40% in the silty sands.

• The friction angle was calculated based on a relationship with the relative density.

3.2.1 Test Piles Data, Rollins et. al. (2005)

The data for test piles were as follows:

Pile Type	= Steel pipe ASTM A252 Grade 3
Diameter	= 0.324 m
Thickness	= 0.0095 m
Moment of Inertia	= 1.43x $10^8\ mm^4$
Equivalent modulus Of Elasticity	= 53 Giga Pascal

3.2.2 Soil Data

The soil data consisting of both SPT and CPT is shown in the following figure as calculated and proposed by (Rollins, Lane, & Gerber, 2005)

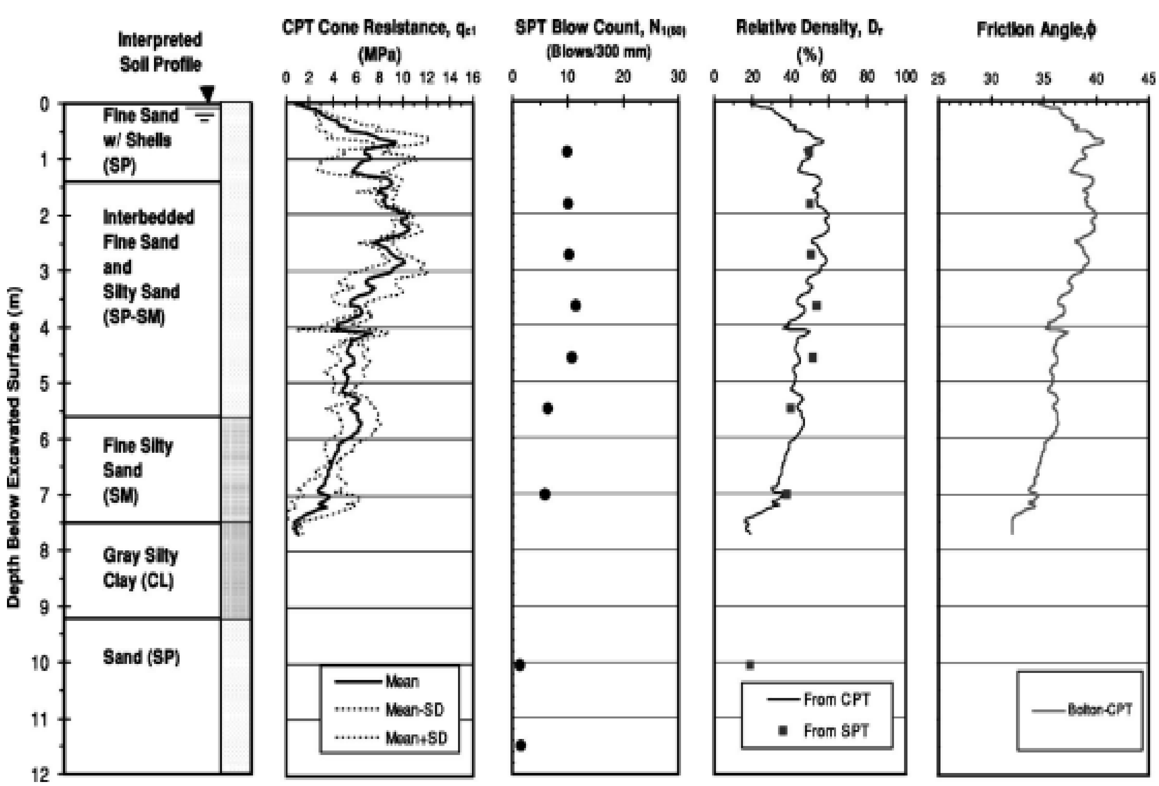


Figure 11 SPT & CPT Data

3.2.3 Pile Arrangement

The pile group is a pile group of order 3x3 with a spacing of 3.3D. As shown in the figure

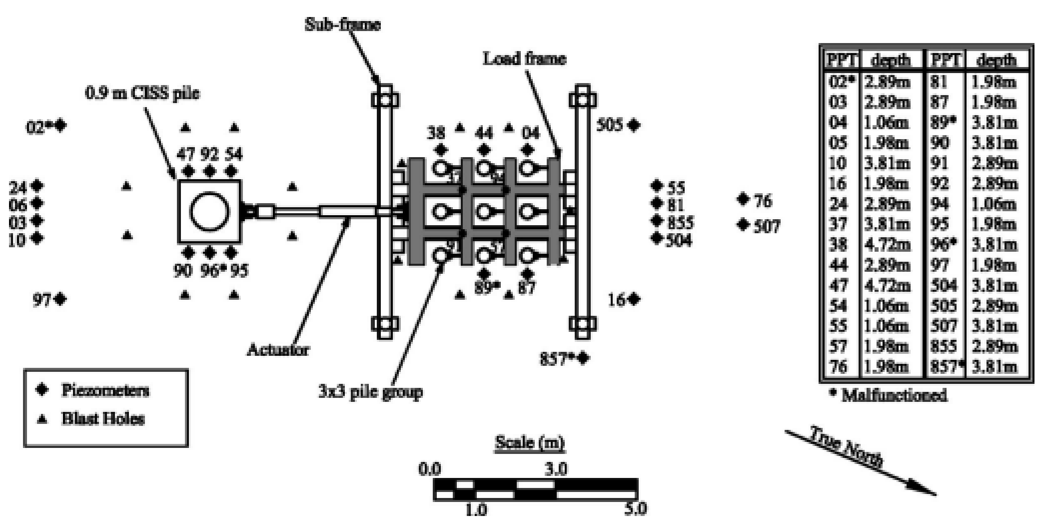


Figure 12 Configuration Of

3.3 Numerical Simulation of Rollins et. al. (2005) Granular Soil Data

3.3.1 Finite Element Model

In Abaqus software we have first constructed the 3D model for the Data of pile used be Rollins et. al. (2005) for granular soil. The 3D simulation we have constructed as a result is shown in the following figure

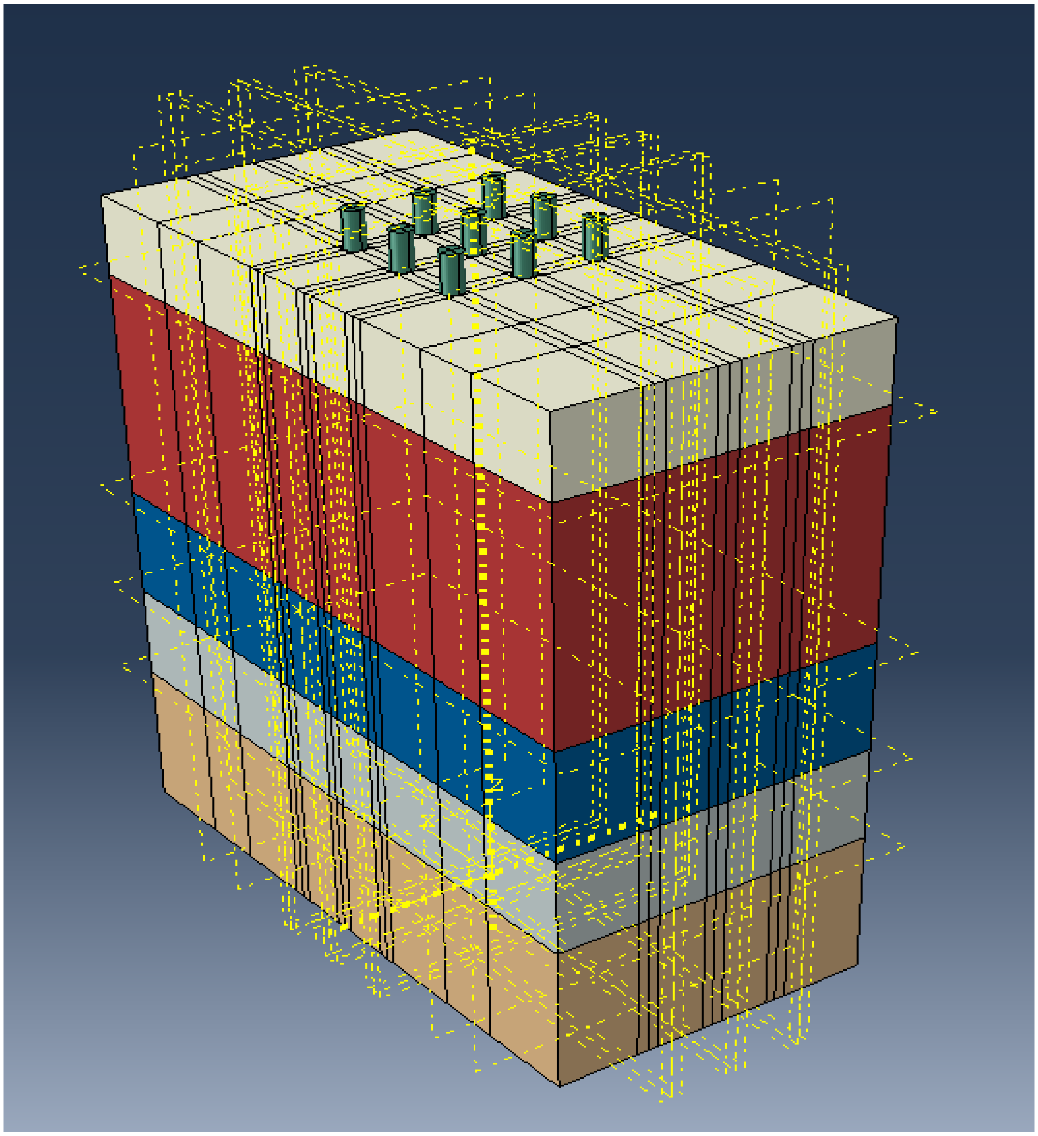


Figure 13 Numerical 3D Model

The model was constructed for six layers of soil strata with different properties of soil according, and piles were constructed with a spacing to diameter ratio (S/D) of 3.3.

3.3.2 Numerical data analysis

To validate the data for our study of effects of friction angle and spacing on p values and in return, on p-multipliers of pile group, we have compared the data of field test of Rollins et al. (2005) and that of 3D model that incorporates the same soil strata properties as presented by Rollins in his research. The comparison of field test and the numerical model simulation is shown in the following graph. It was done for soil data after pro-blast conditions

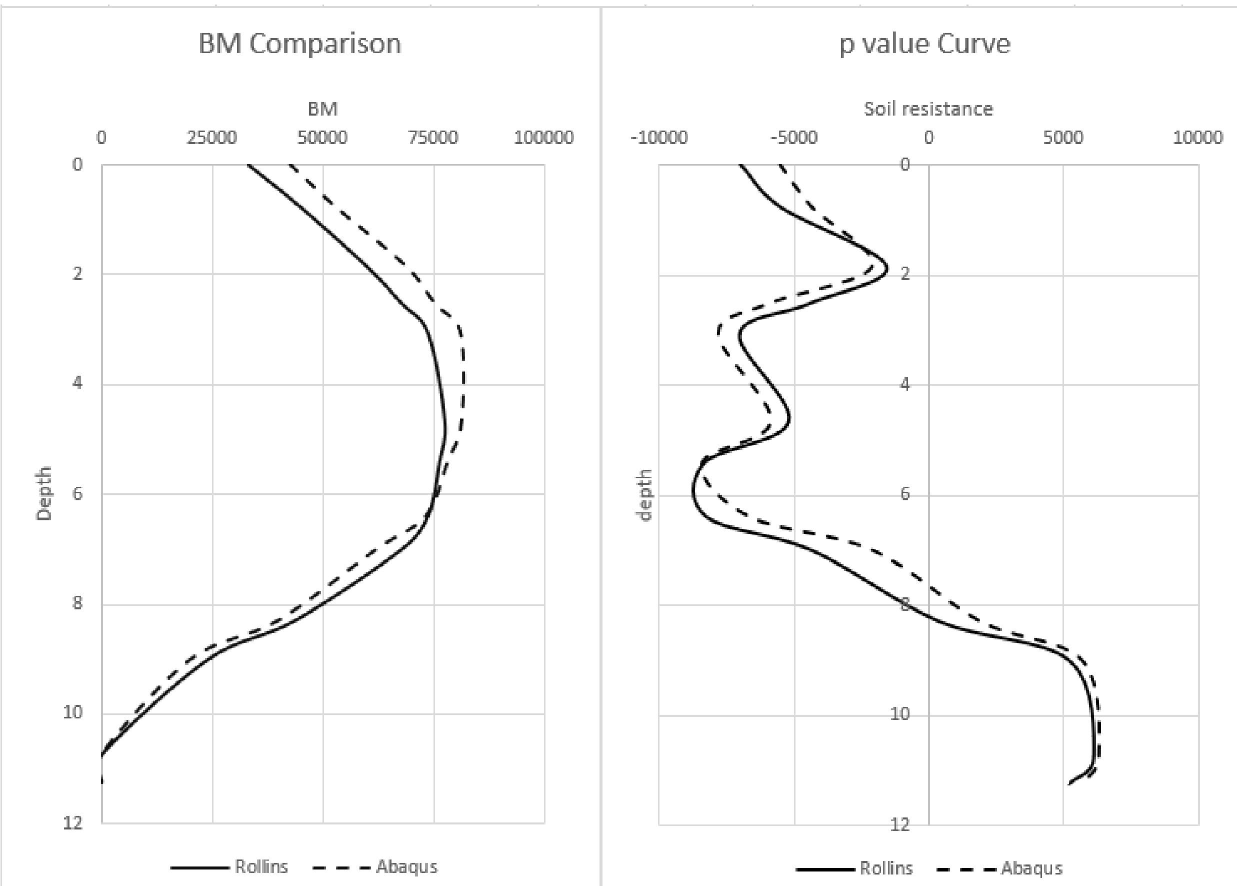


Figure 14 Comparison between Rollins et al. (2005) And Numerical simultaion of it

3.3.2.1 Research Data Validation

The comparison data in the above charts indicates that the Abaqus software was successfully able to reincorporate the live strata conditions in the 3D model and thus was able to produce results up to a maximum degree of realistic output with minor fluctuations. So, we can say that the results that we will evaluate from the other 3D models for different values of friction angle and different spacing will have maximum realistic output.

3.4 Construction of 3D Models for different values of φ and S/D for 3x3 pile group

3.4.1 Preview

For our next step we will be making models for different pile to diameter spacing and friction angle for soil in order to check the effects of the said parameters on the response of pile group subjected to lateral loading. We will be making 3D models for pile of order 3x3 with S-to-D ratio of 3, 4 and 5. These models will be constructed for a friction angle value of 30, 35 and 40 degrees. Once the models are constructed the values of strata will be inserted in the 3D model based on the nonlinear Mohr-Coulomb approach. Mohr-Coulomb is used because it will deal with the soil as a nonlinear non-elastic medium.

3.4.2 Steps for 3D Numerical Modeling

The steps for calculating the values of 3D model are as follows

1. The First step is to create parts in which we define the dimensions of our soil layers and design pile with specific depth and diameter.
2. Next step is to make partitions in the soil layers and in pile in order to get detailed data from the 3D model.
3. Then we add properties such as young's modulus, density, Poisson ratio, Friction angle, Cohesion, Yield Stress, & Dilation Angle
4. Next, we assemble our piles in our soil layers.
5. Now we will define steps in which initially there will be no loading in initial step, and later lateral load will be applied in step 01.
6. We also define what we require as output in Define step. In our study we require Bending moment and displacement
7. Next, we create interactions in which we define how the pile will interact with soil and also enter interaction angle which is function of tangent 2/3 of friction angle in our case. In our case it is hard surface interaction.

8. Now we define loads acting on pile which is gravity load and lateral load in our case.
9. Next, boundary conditions are defined.
10. Next meshing is applied, which is division of components of entire model in to smaller well-defined parts.
11. Now we create a job and run it to get the desired results which are moments and displacement in our case.
12. The step is repeated for both single and group pile with different values of spacing to diameter ratio and friction angle.

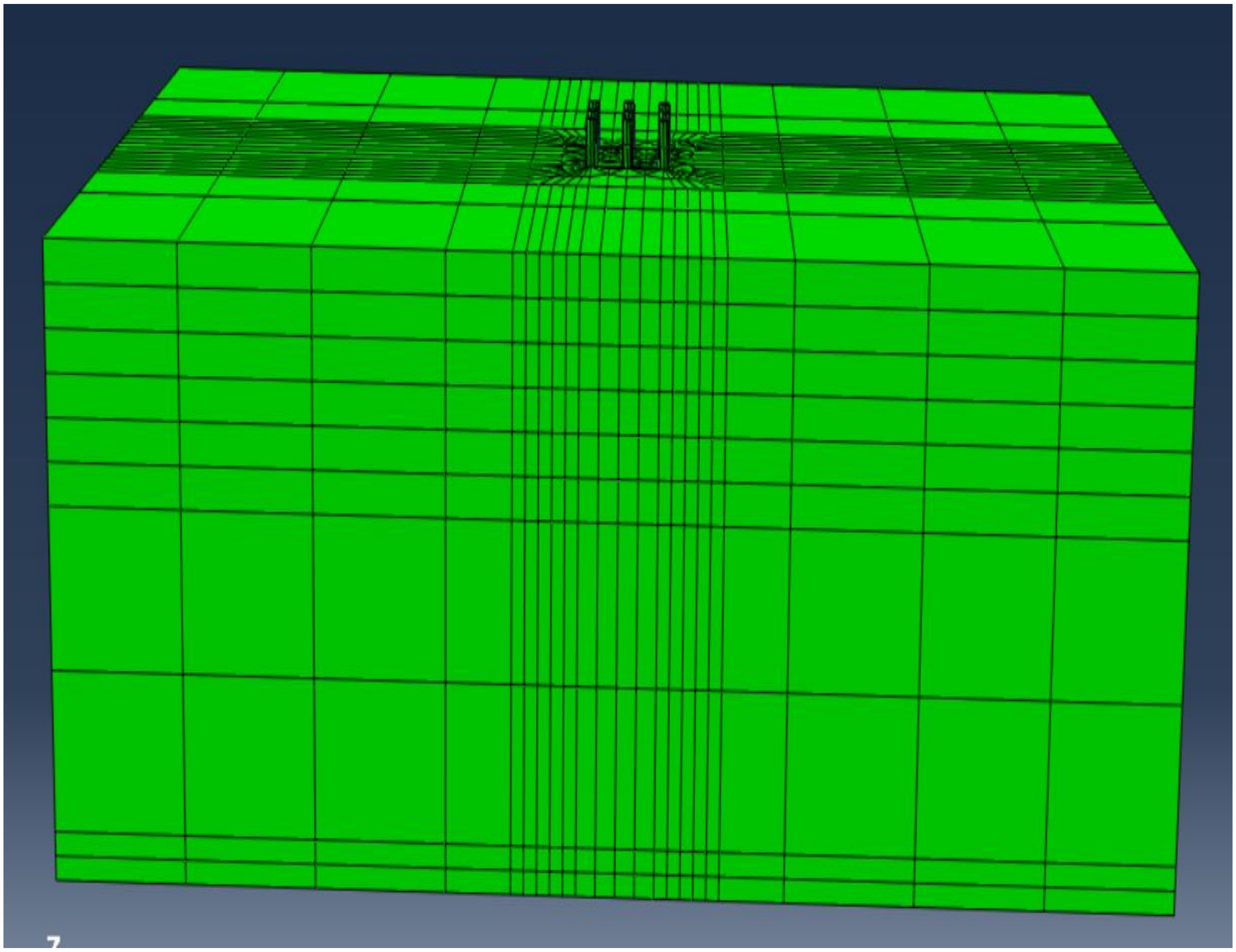
3.4.3 Data for 3D Model

The Data for 3D model for both pile and soil layers were assumed as follows:

- Pile Diameter = 0.3m
- Young's modulus pile = 54.7 GPa
- Top surface Area = 30 x 20 m^2
- Top Strata length = 1.5m,
- 2^{nd} Strata Depth = 1.5m,
- 3^{rd} Strata Depth = 1.5m,
- 4^{th} Strata Depth = 6.5m,

Soil Layers	Depth	Modulus of Elasticity E (Mpa)		
		φ=30	φ=35	φ=40
Strata 1	1.5	24	44	74
Strata 2	1.5	26	46	76
Strata 3	1.5	28	48	78
Strata 4	6.5	30	50	80

Friction Angle	Friction Cofficient
30	0.36
35	0.43
40	0.5



3.4.4 Parametric Study of 3D Numerical Model Simulation

3.4.4.1 φ = 30-degree, S/D=3, 4 & 5

After we have successfully constructed our 3D numerical model, we entered the values of lateral loads on our model. First, we did the simulation on a single pile and then for a fixed value of friction angle, we did the simulations again for different values of spacing which corresponds to the values of S/D of 3, 4 and 5. The data for bending moments and soil resistance was evaluated respectfully. After the values were plotted then p-multipliers were calculated by taking ratio of p of group pile to that of single pile. The results are as follows. For Single Pile:

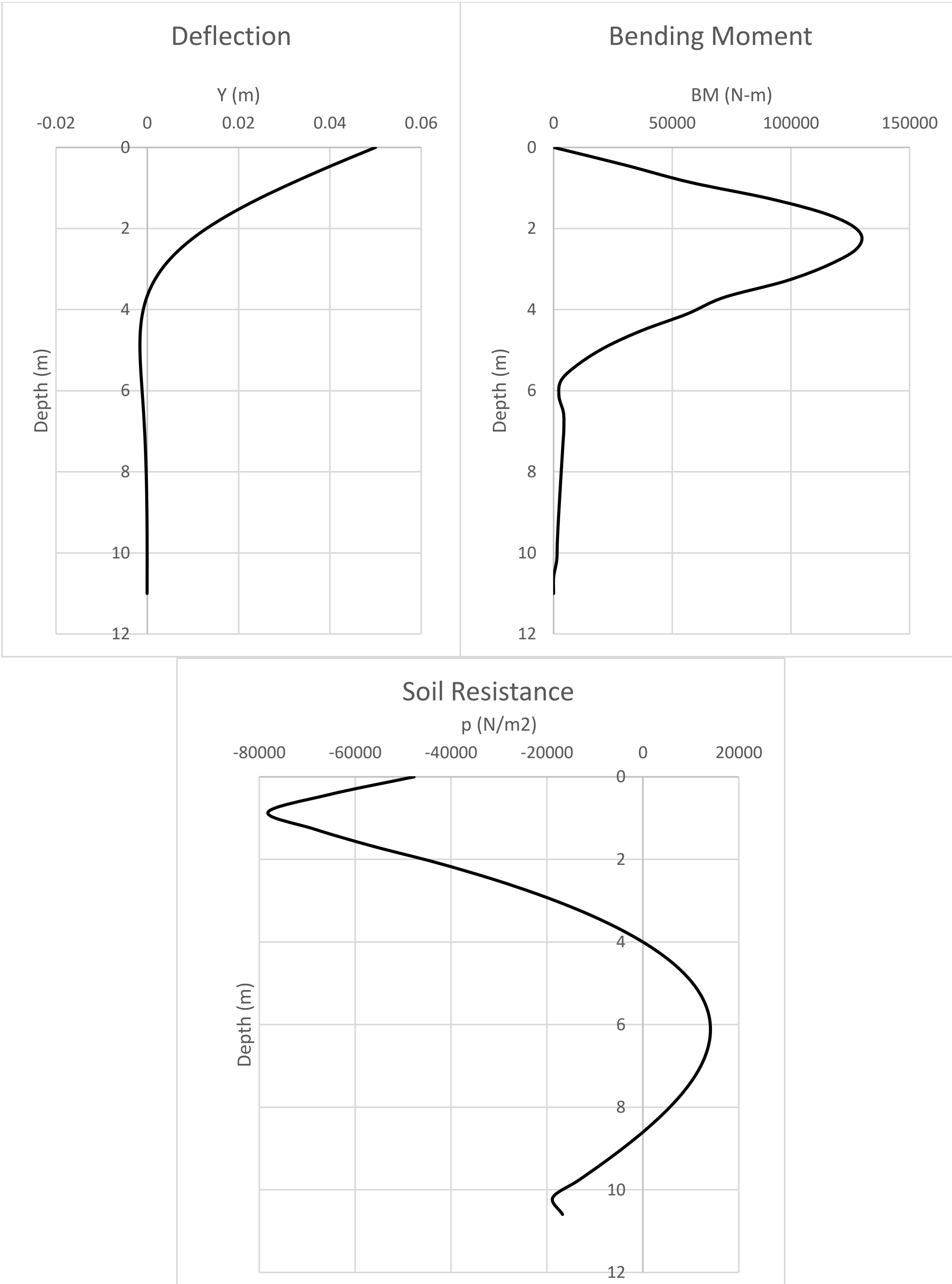


Figure 15 Deflection, Bending Moment & Soil resistance w.r.t Depth at ϕ=30

For group piles the results are:

1. S/D = 3

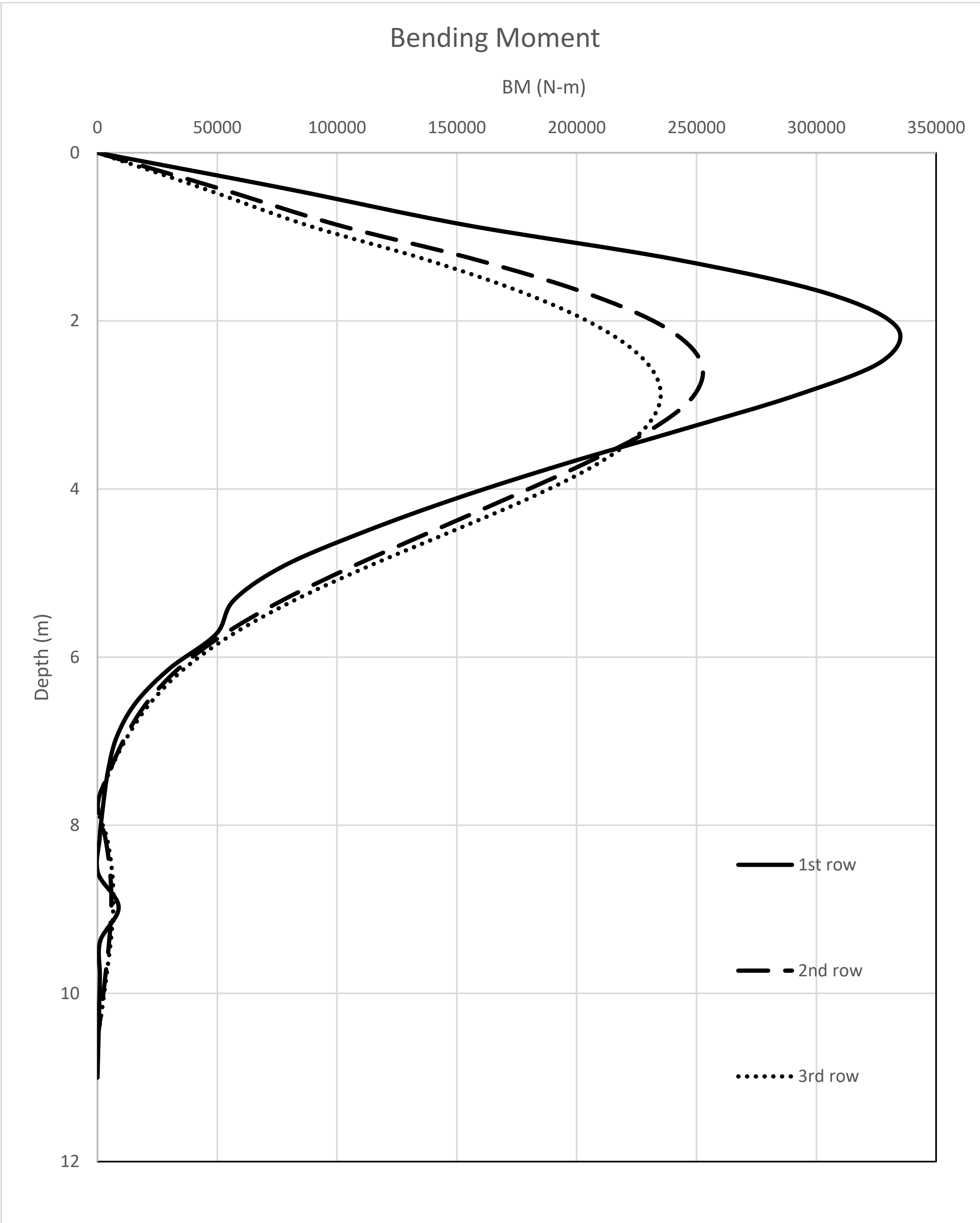


Figure 16 Bending Moment S/D=3, ϕ=30

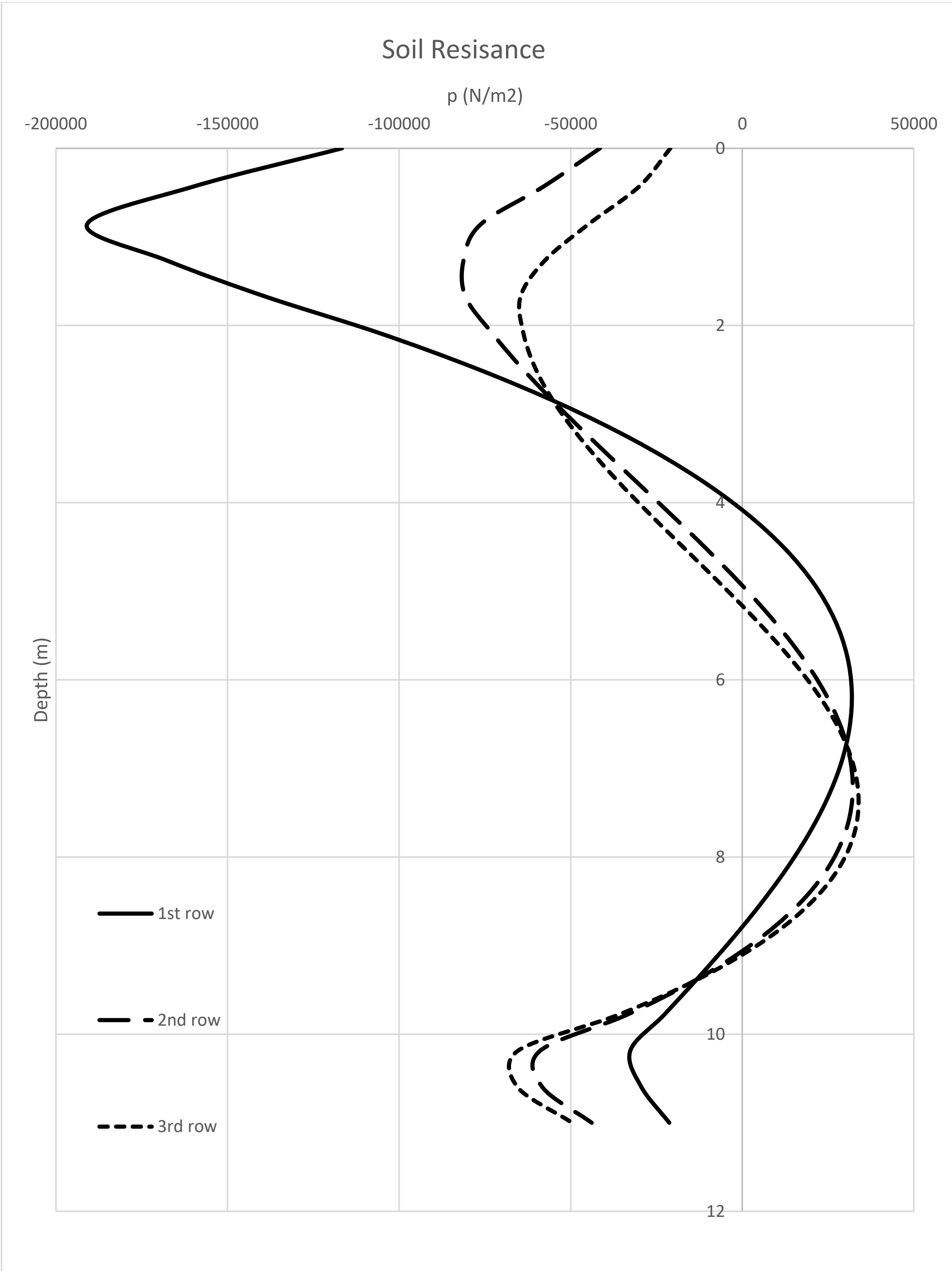


Figure 17 Soil Resistance S/D=3, ϕ=30

2. S/D = 4

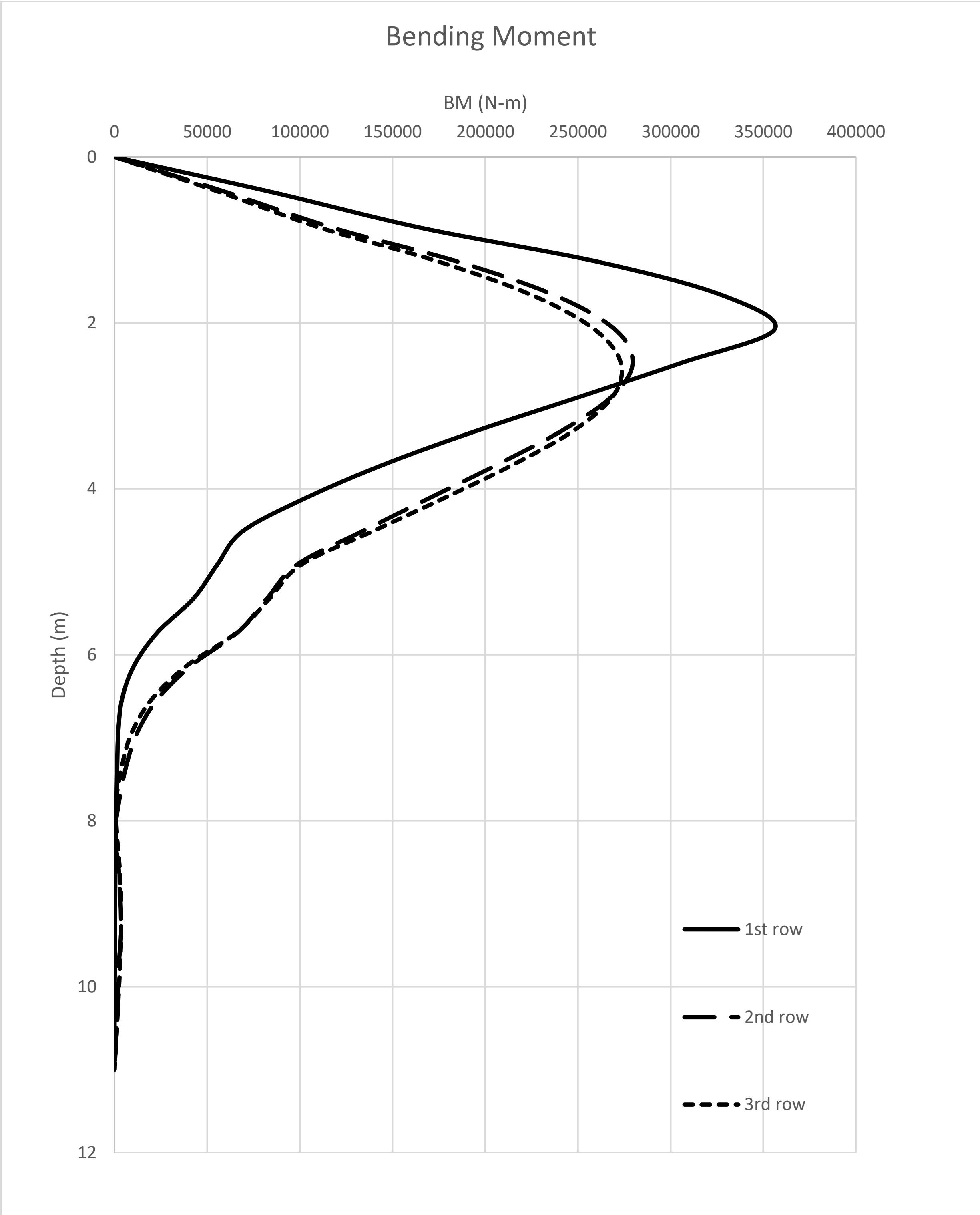


Figure 18 Bending moment S/D=4, ϕ=30

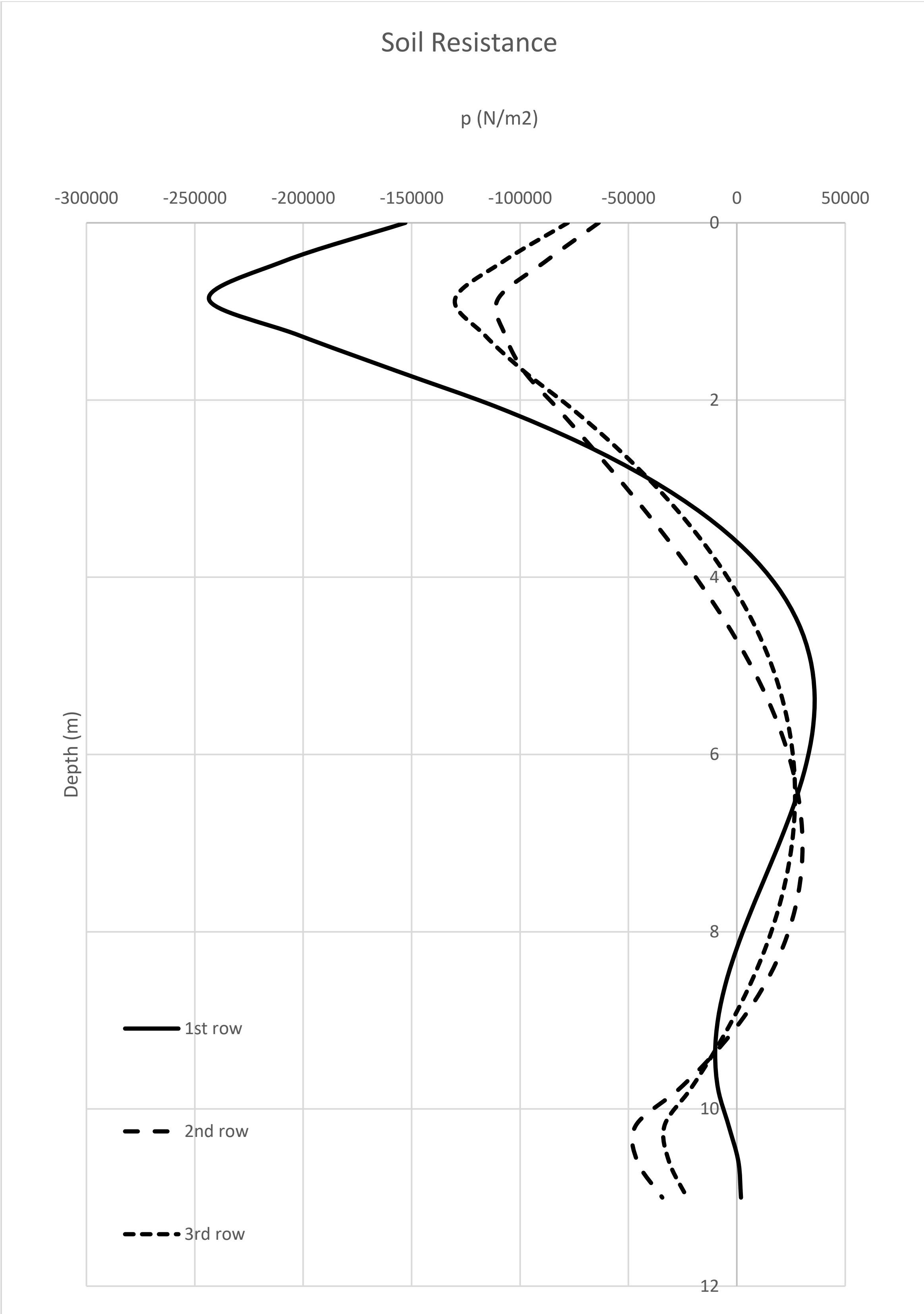


Figure 19 Soil Resistance S/D=4, ϕ=30

3. S/D = 5

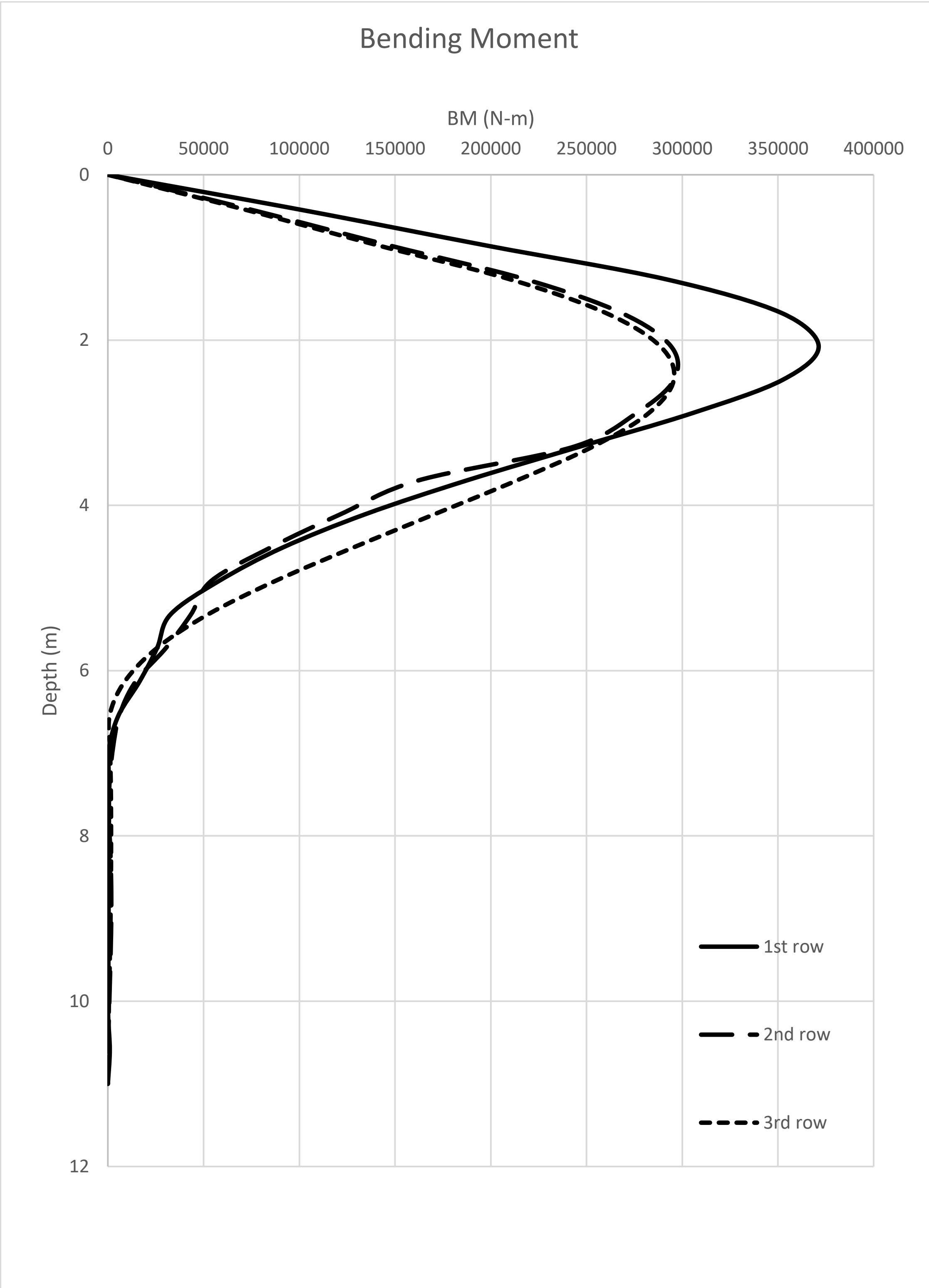


Figure 20 Bending Moment S/D=5, ϕ=30

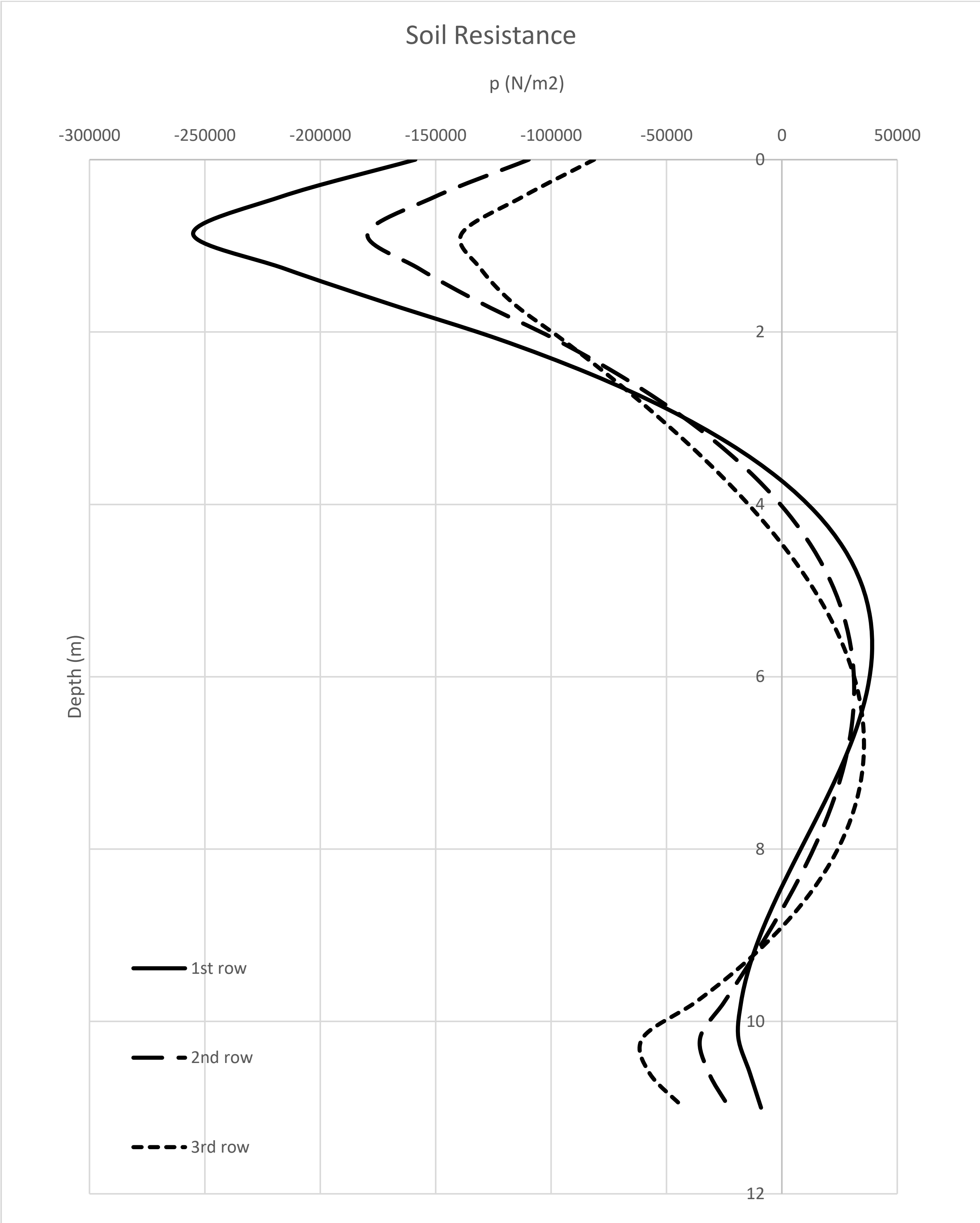


Figure 21 Soil Resistance S/D=5, ϕ=30

The values of p-multipliers for φ = 30 degrees and depth of 1.67m is

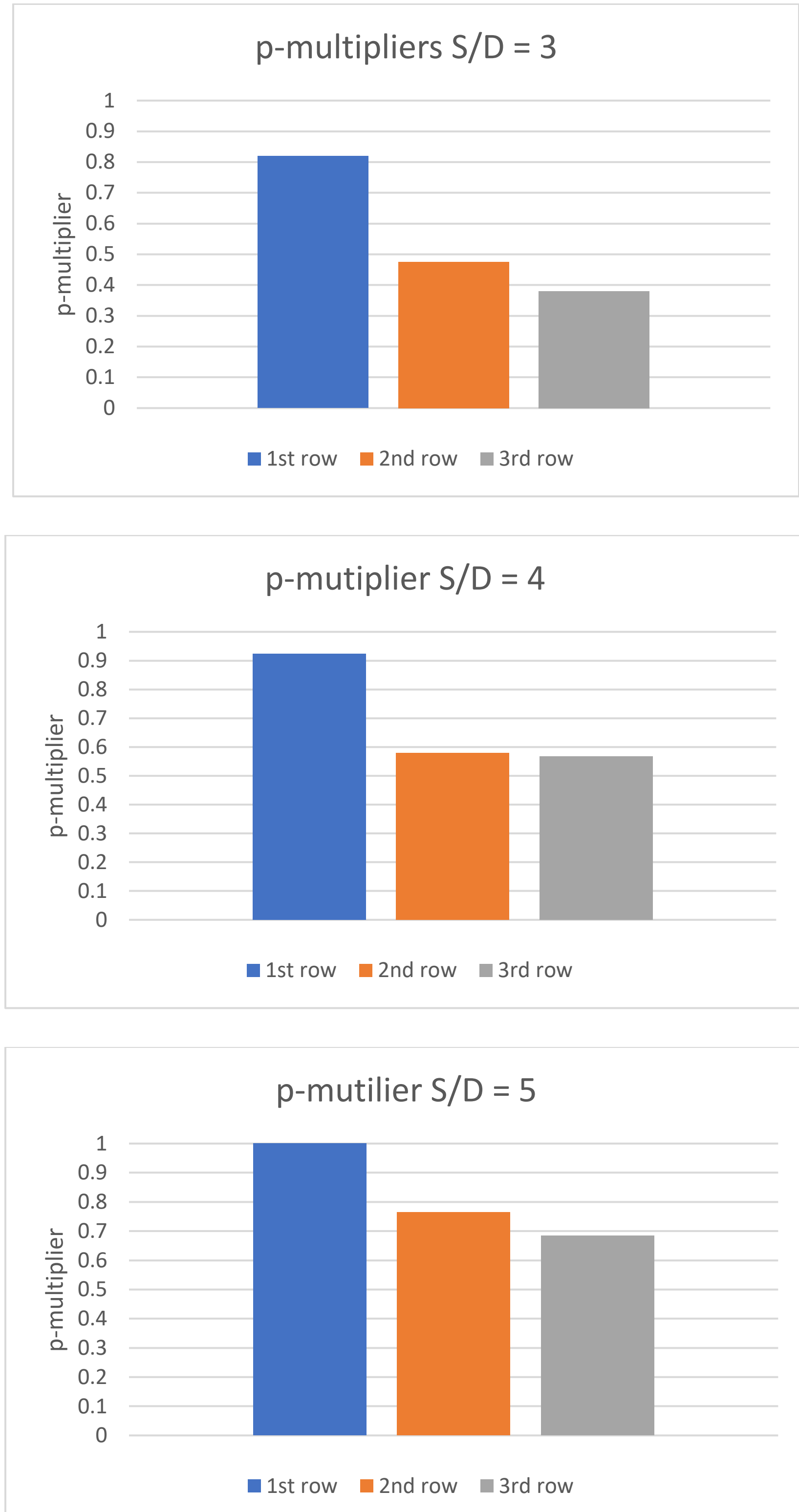


Figure 22 p-multipliers for ϕ=30 at different spacing

p-multiplier comparison from above results:

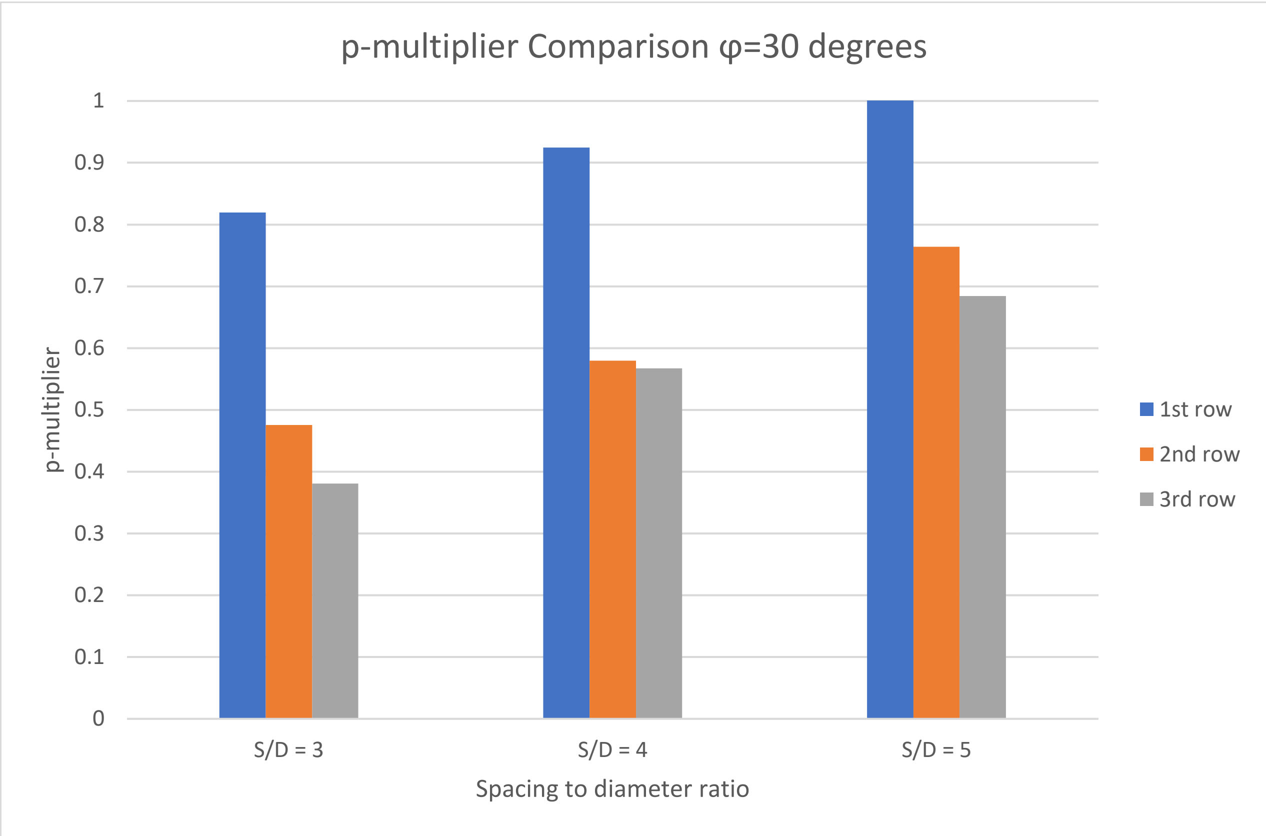


Figure 23 Comparison of p-multipliers

Results:

From the above information it is being shown that increasing the spacing tends to increase the value of p-multiplier which is a good thing as we want maximum soil resistance for the stability of our structure.

At S/D = 5 the value of p multiplier for the leading row is 1 which means soil resistance for first row is same as that for a single pile case and the p-multiplier for the other trailing rows are comparatively higher from the other S/D cases.

The higher p-multiplier values may be due to the reason that only shadow effect is governing for S/D = 5 and because spacing is 5 times the diameter of pile, there must be little or no edge effect at all.

These results were for friction angle of φ = 30 degrees

3.4.4.2 φ = 35-degree, S/D=3, 4 & 5

For single pile:

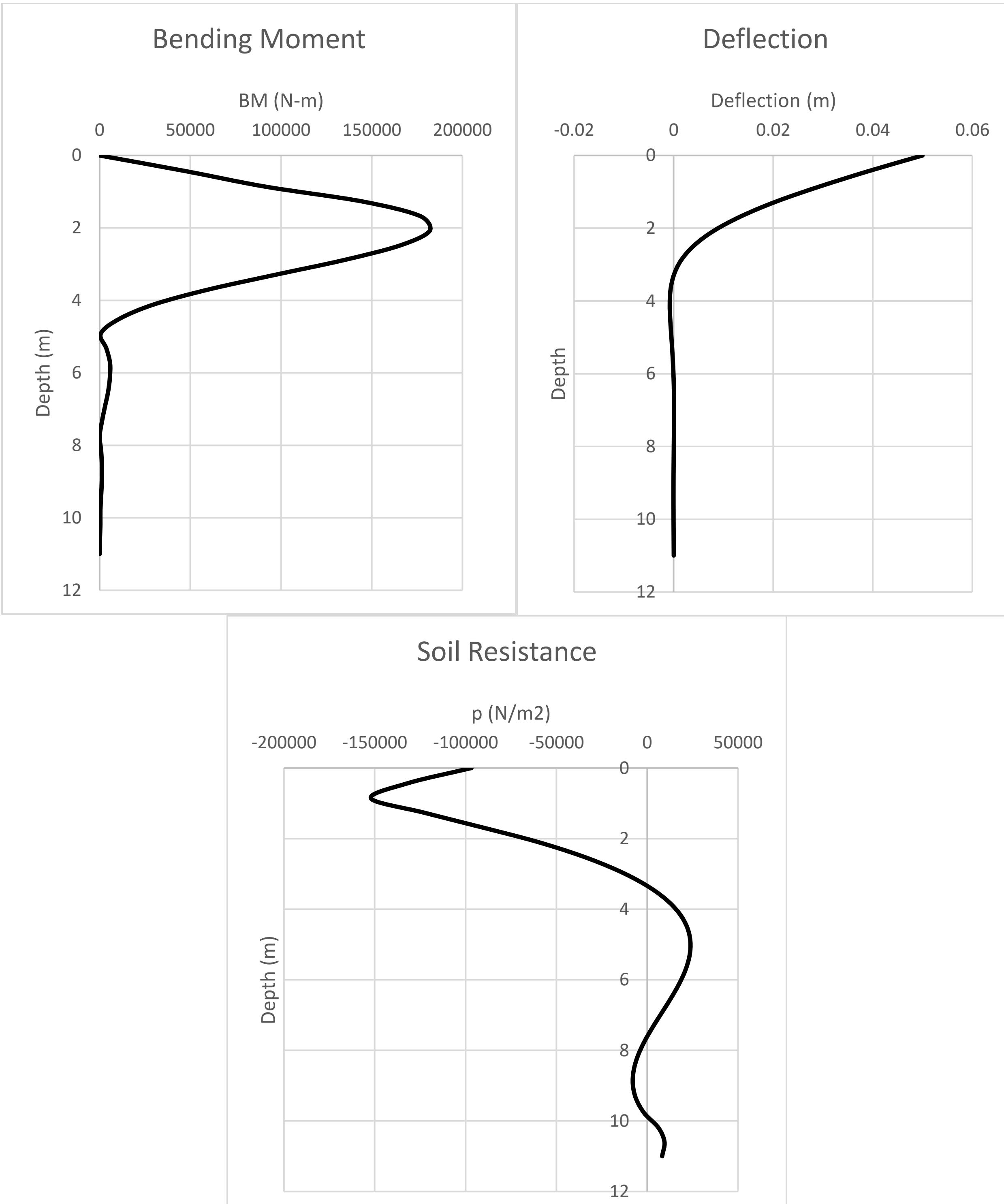


Figure 24 Deflection, Bending Moment & Soil resistance w.r.t Depth at ϕ=35

For Group piles:

1. S/D = 3

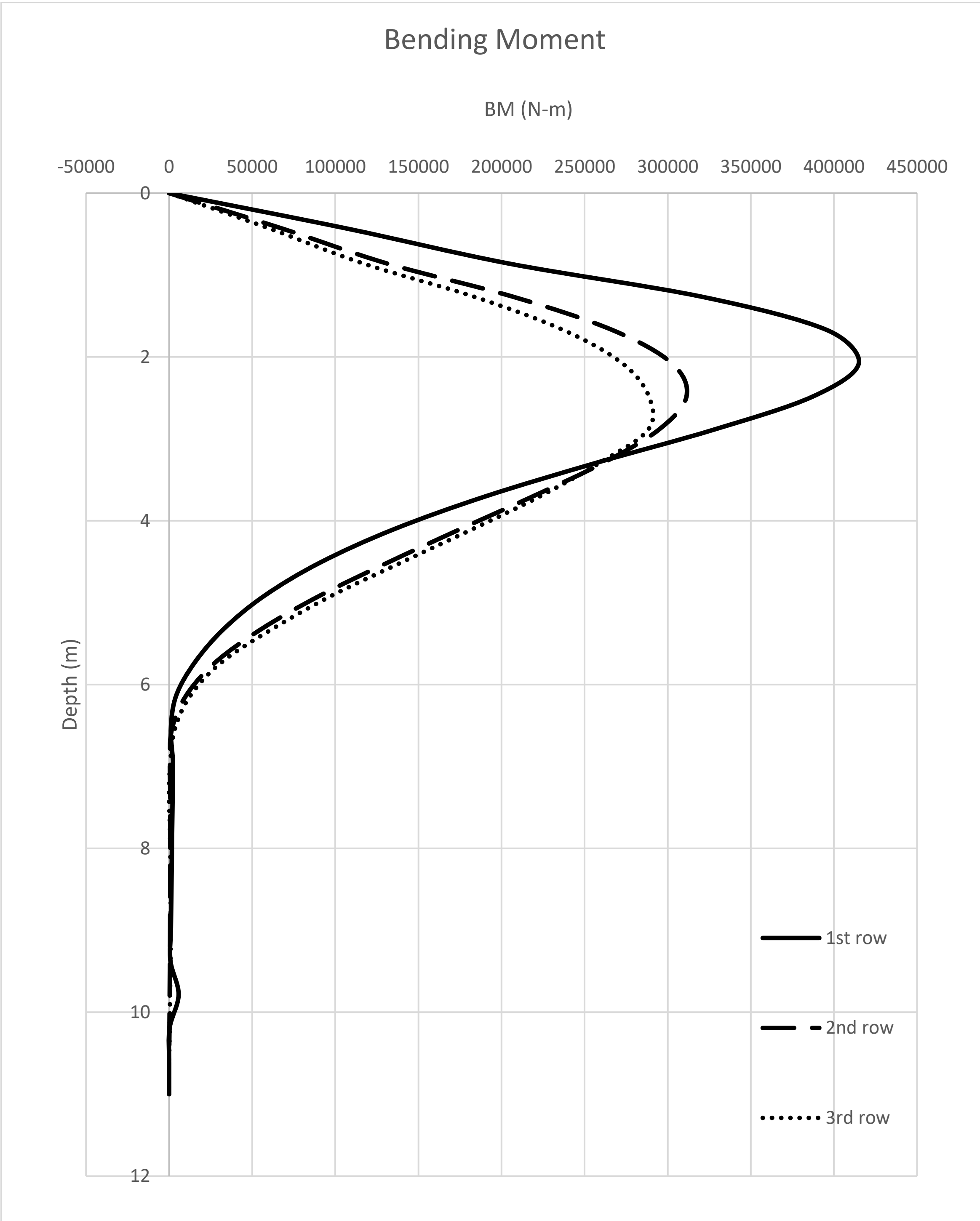


Figure 25 Bending moment S/D=3, ϕ=35

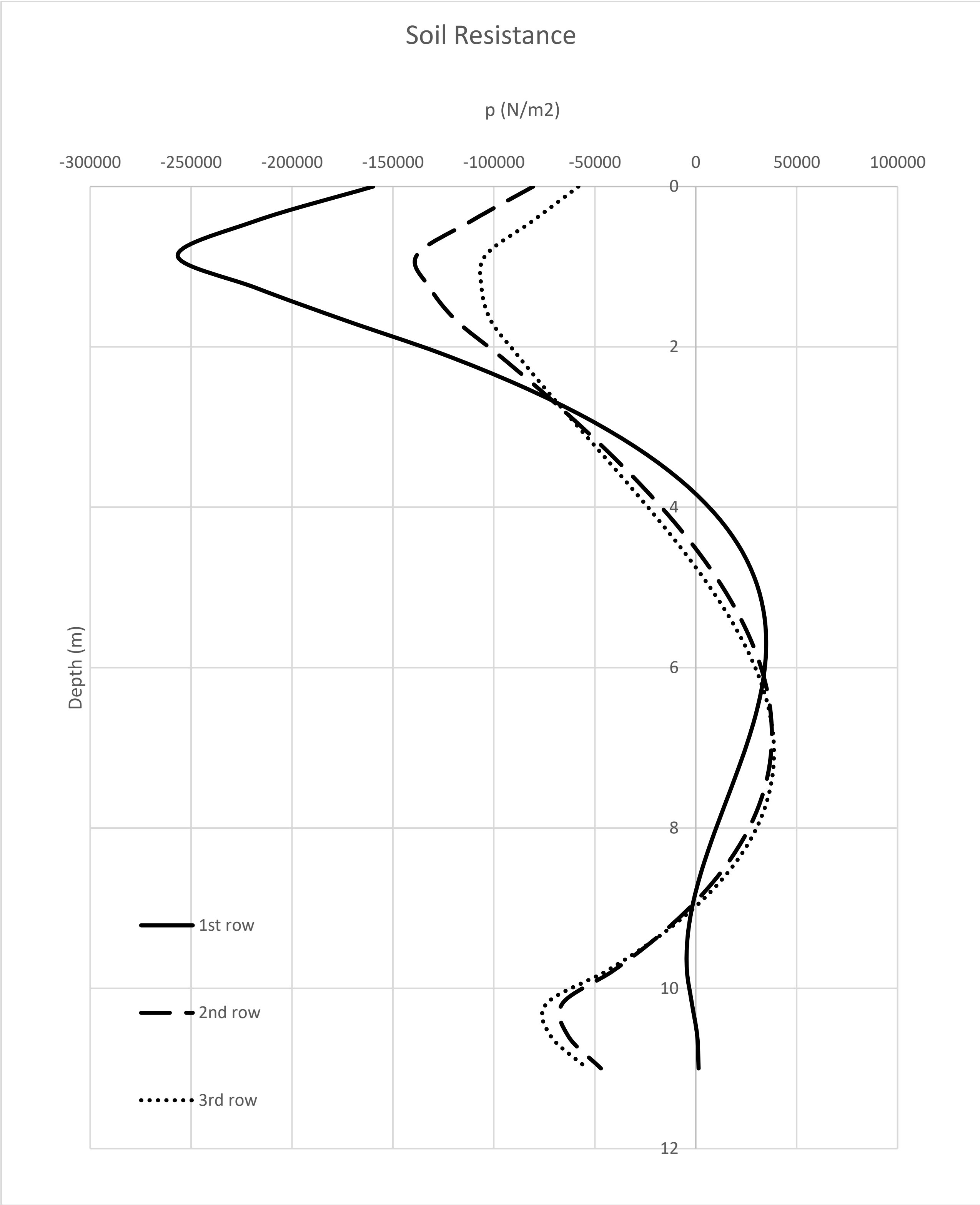


Figure 26 Soil Resistance S/D=3, ϕ=35

2. S/D = 4

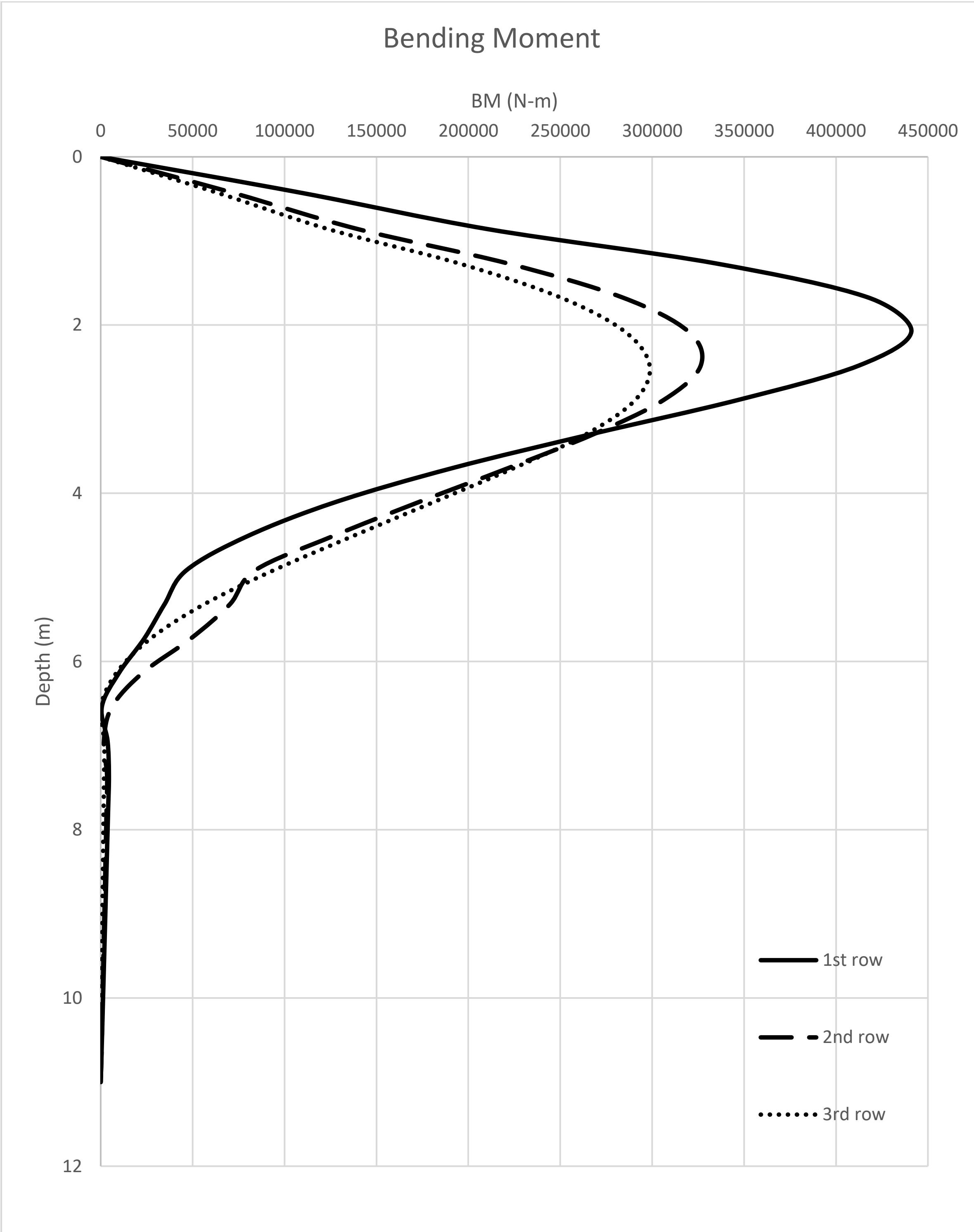


Figure 27 Bending Moment S/D=4, ϕ=35

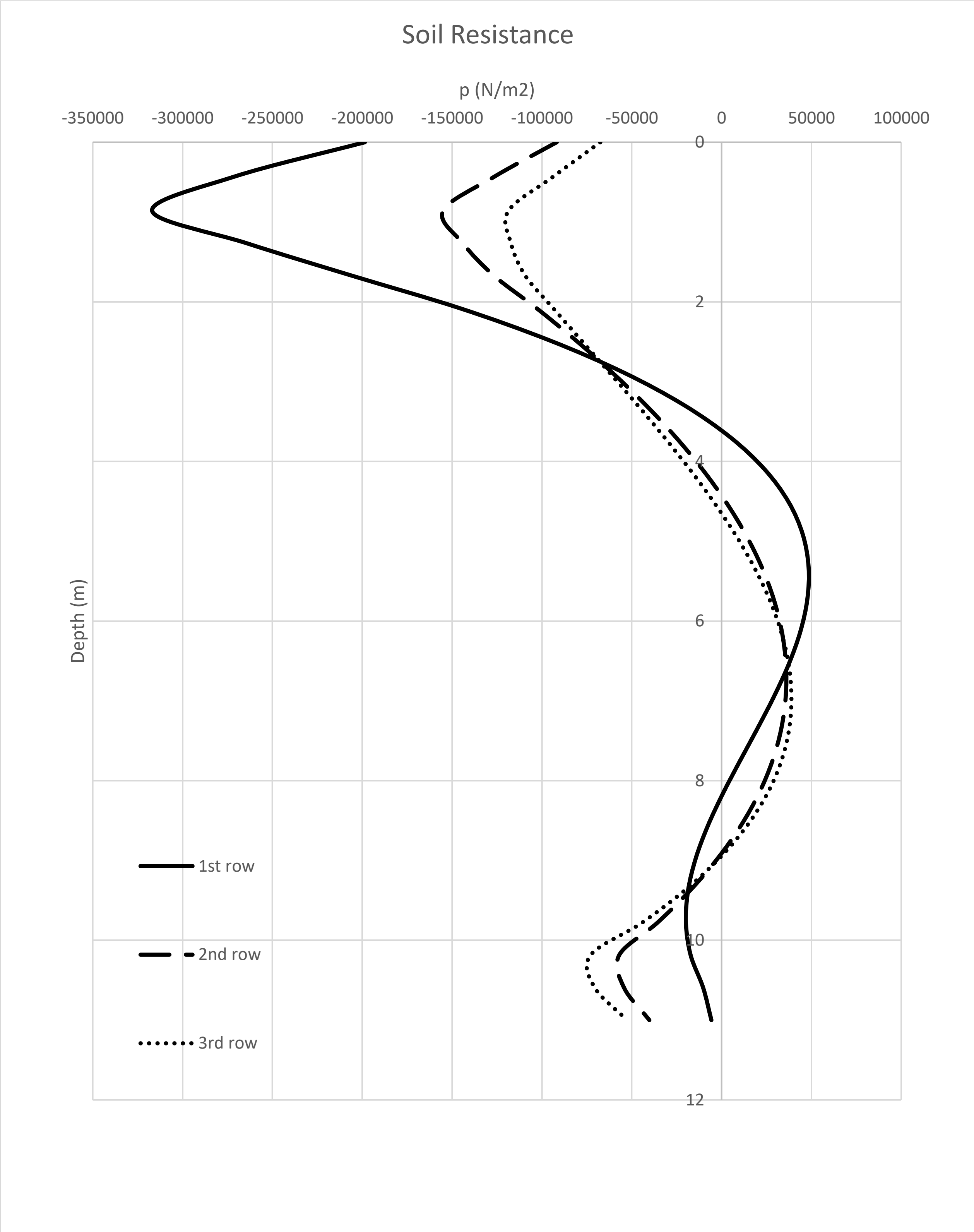


Figure 28 Soil Resistance S/D=4, ϕ=35

3. S/D = 5

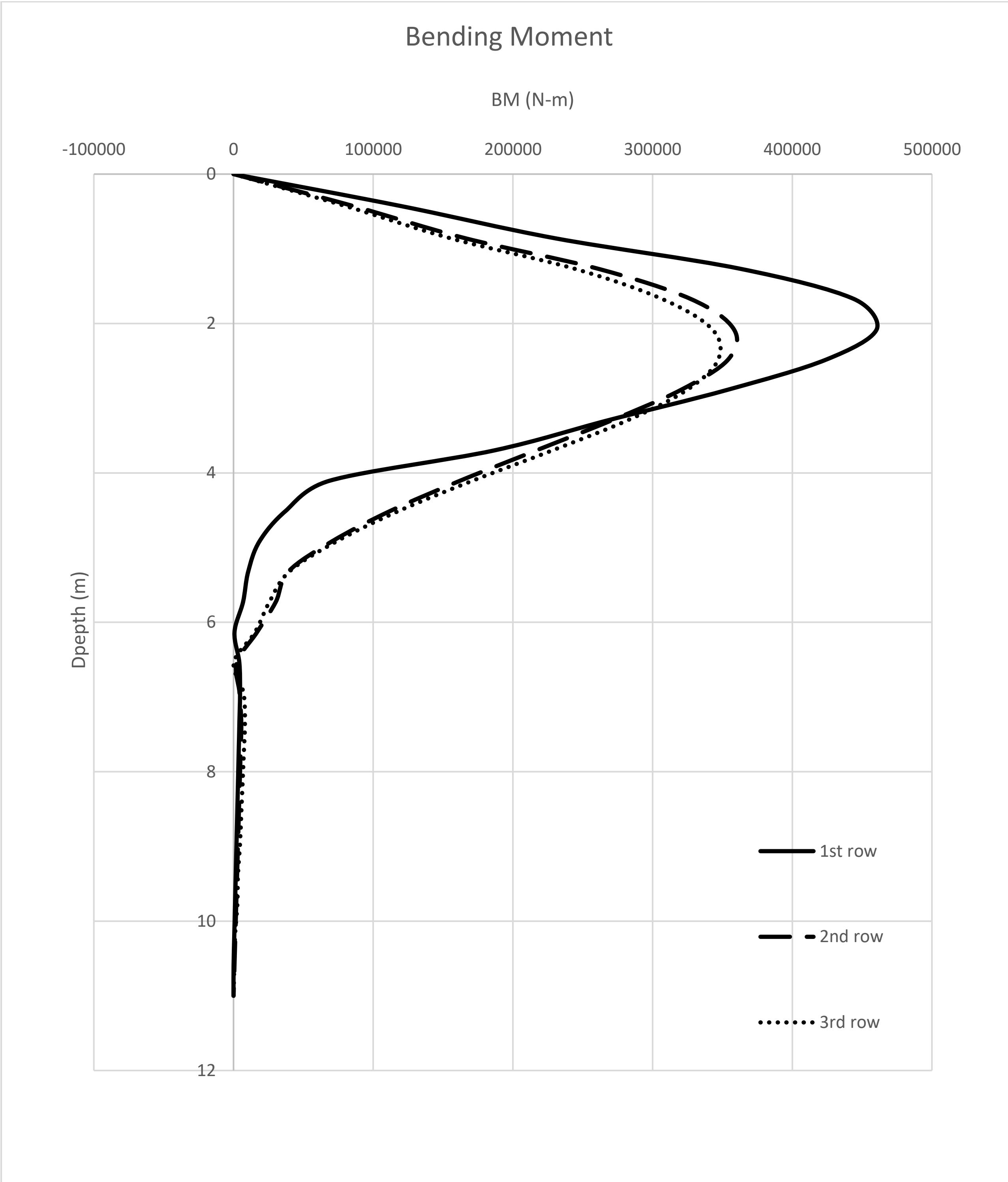


Figure 29 Bending Moment S/D=5, ϕ=35

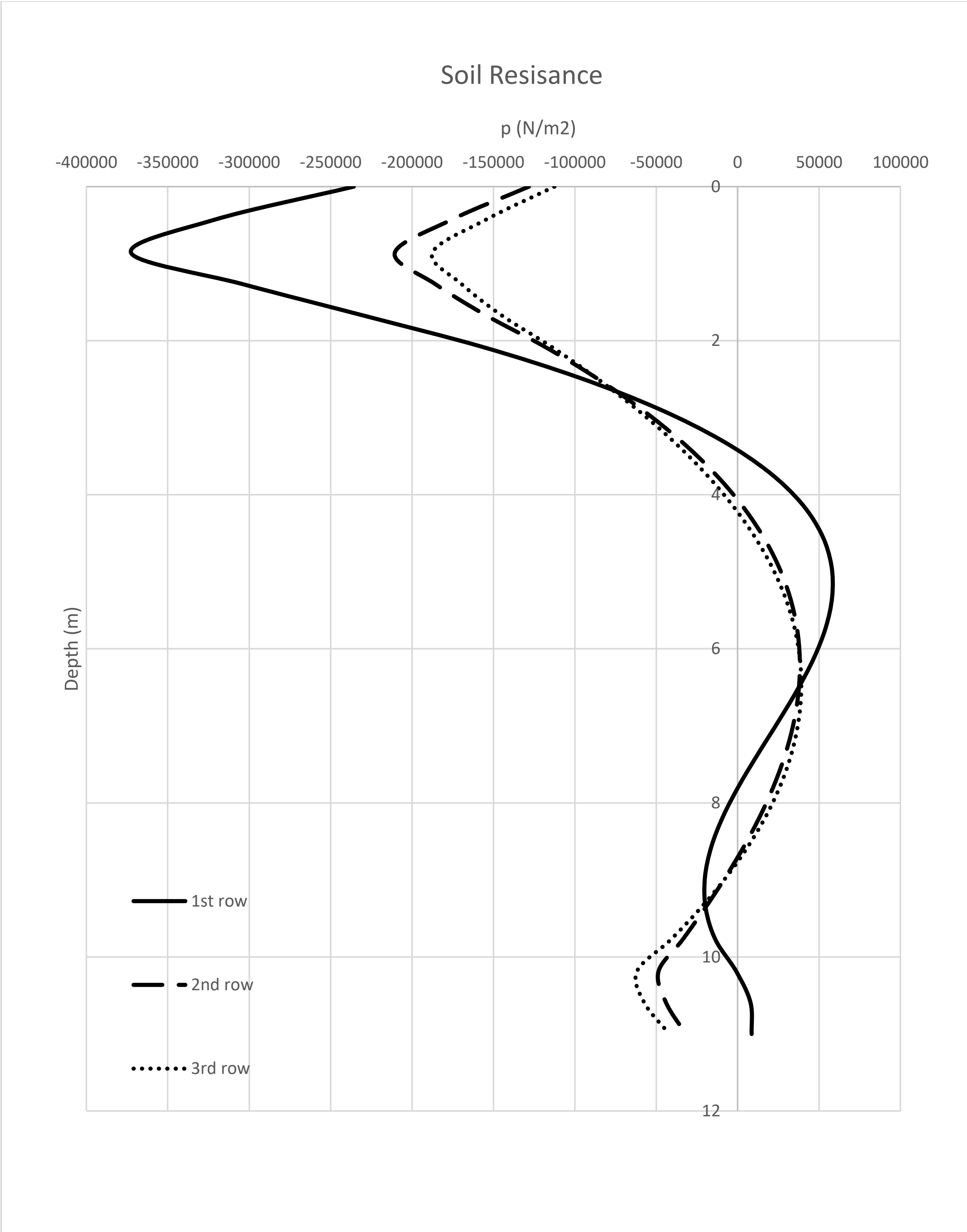


Figure 30 Soil resistance S/D=5, ϕ=35

The values for p-multipliers for φ = 35 degrees and depth of 1.67m is

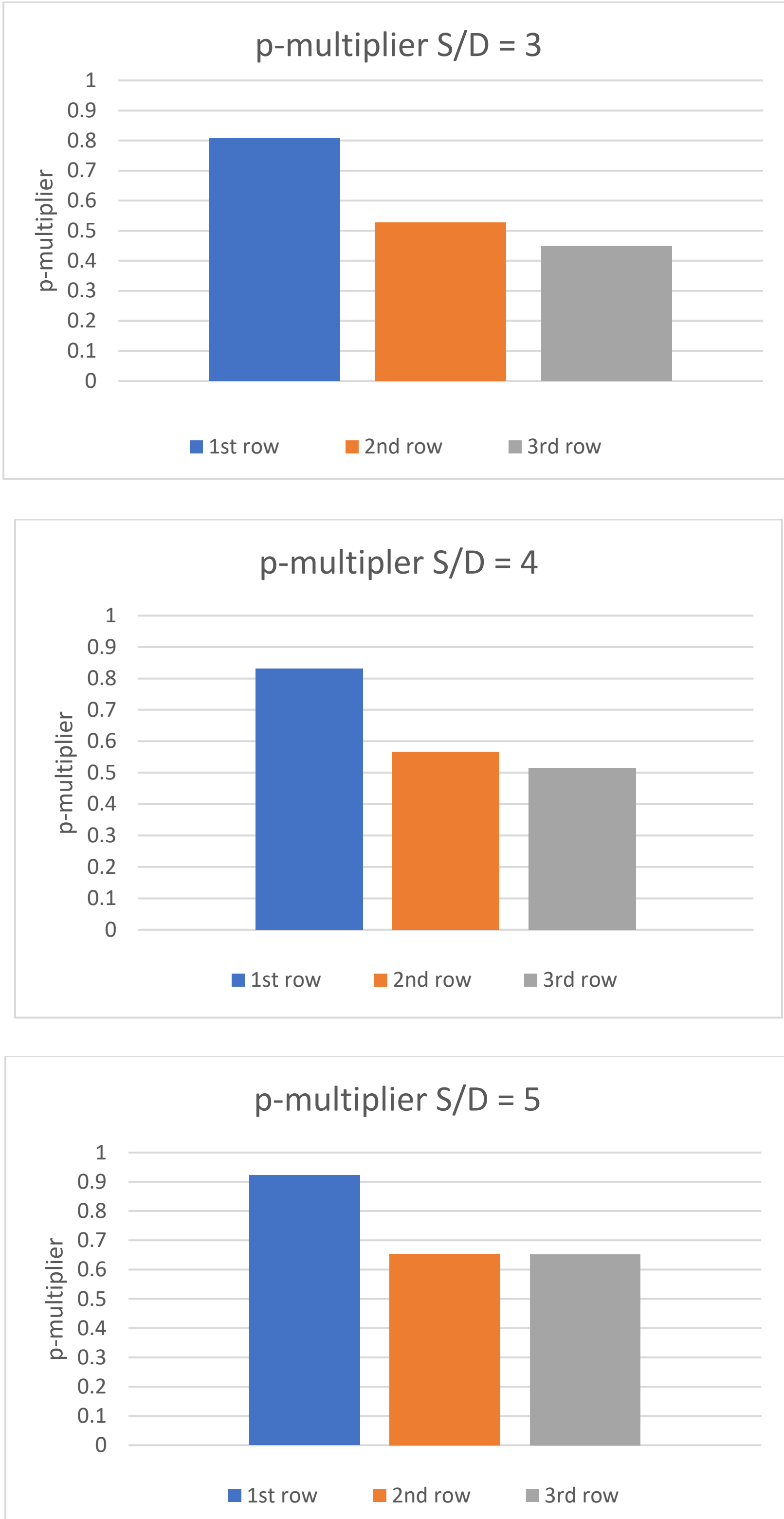


Figure 31 p-multiplier at ϕ=35 degrees at different spacing

p-multiplier comparison from above results:

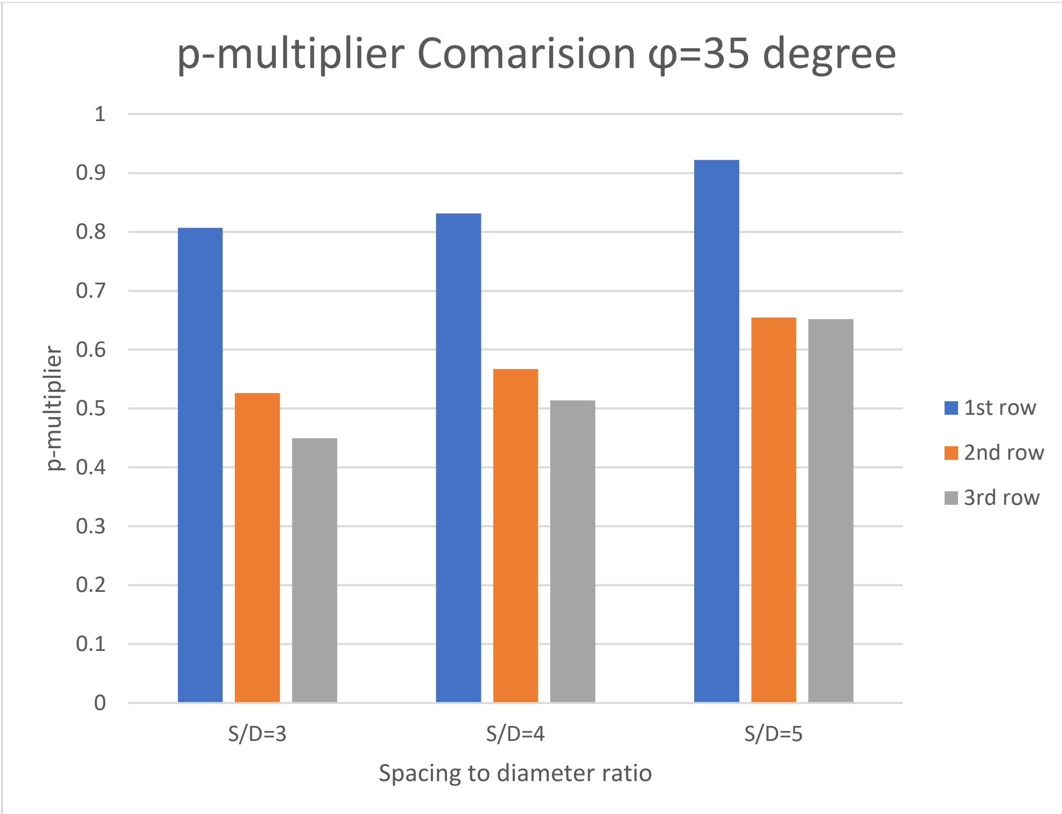


Figure 32 Comparison of p-multipliers

Results:

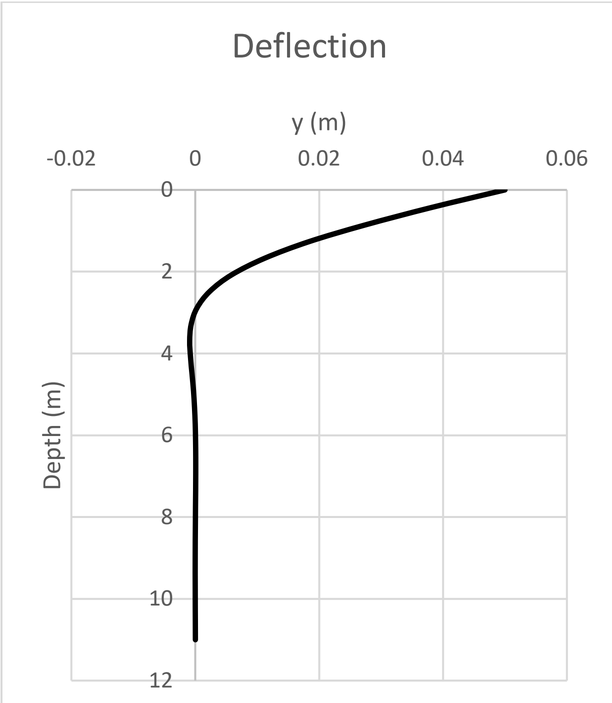
As with the previous case for friction angle of 30 degrees, the values of p-multipliers increase with increase in the spacing between the piles with respect to their diameters.

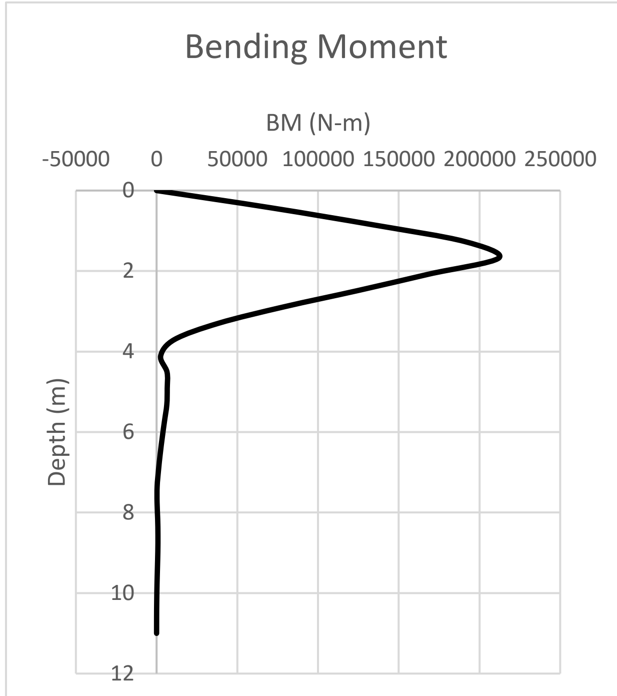
The value of p-multipliers is however less than those measured at a friction angle of 30 degrees however, we cannot be sure here if this is because of friction angle or some other factor so will try to repeat this scenario with a friction angle of 40 degrees.

In relation to previous case the value of p-multiplier for S/D of 5 is not 1 which indicates that friction angle might be causing an increase in overall net shear effect area which may be causing the edge effect to also effect soil resistance when related to previous at φ = 30 degrees

3.4.4.3 φ = 40-degree, S/D=3, 4 & 5

For single pile:





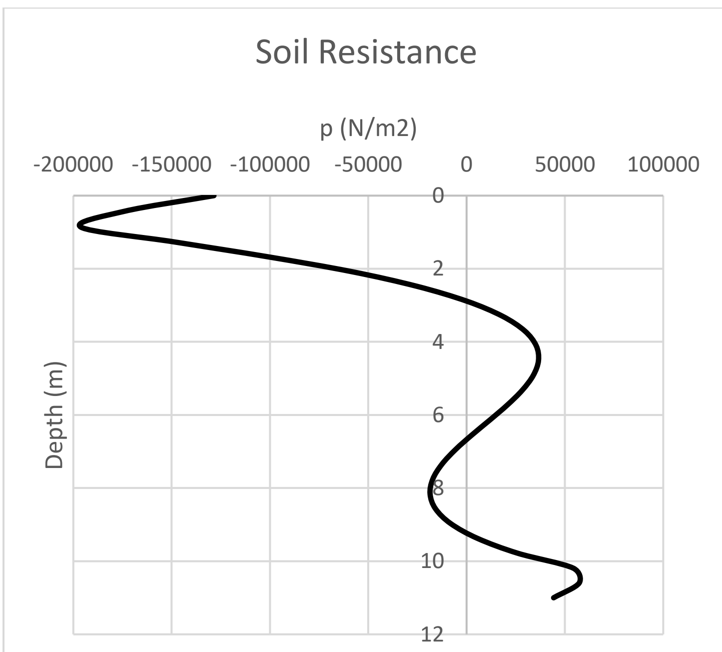


Figure 33 Deflection, Bending Moment & Soil resistance w.r.t Depth at ϕ=40

For Group piles:

1. S/D = 3

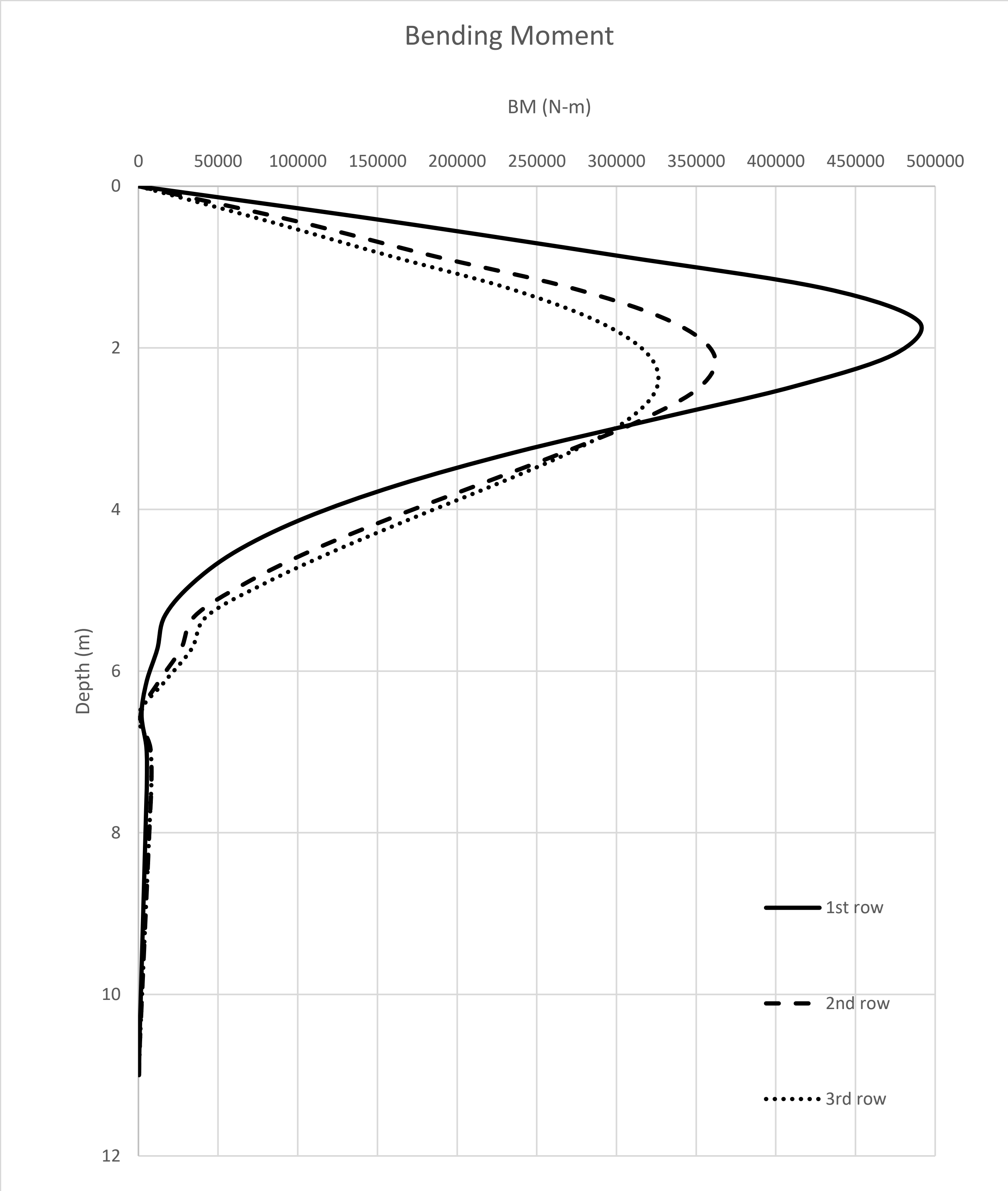


Figure 34 Bending Moment S/D=3, ϕ=40

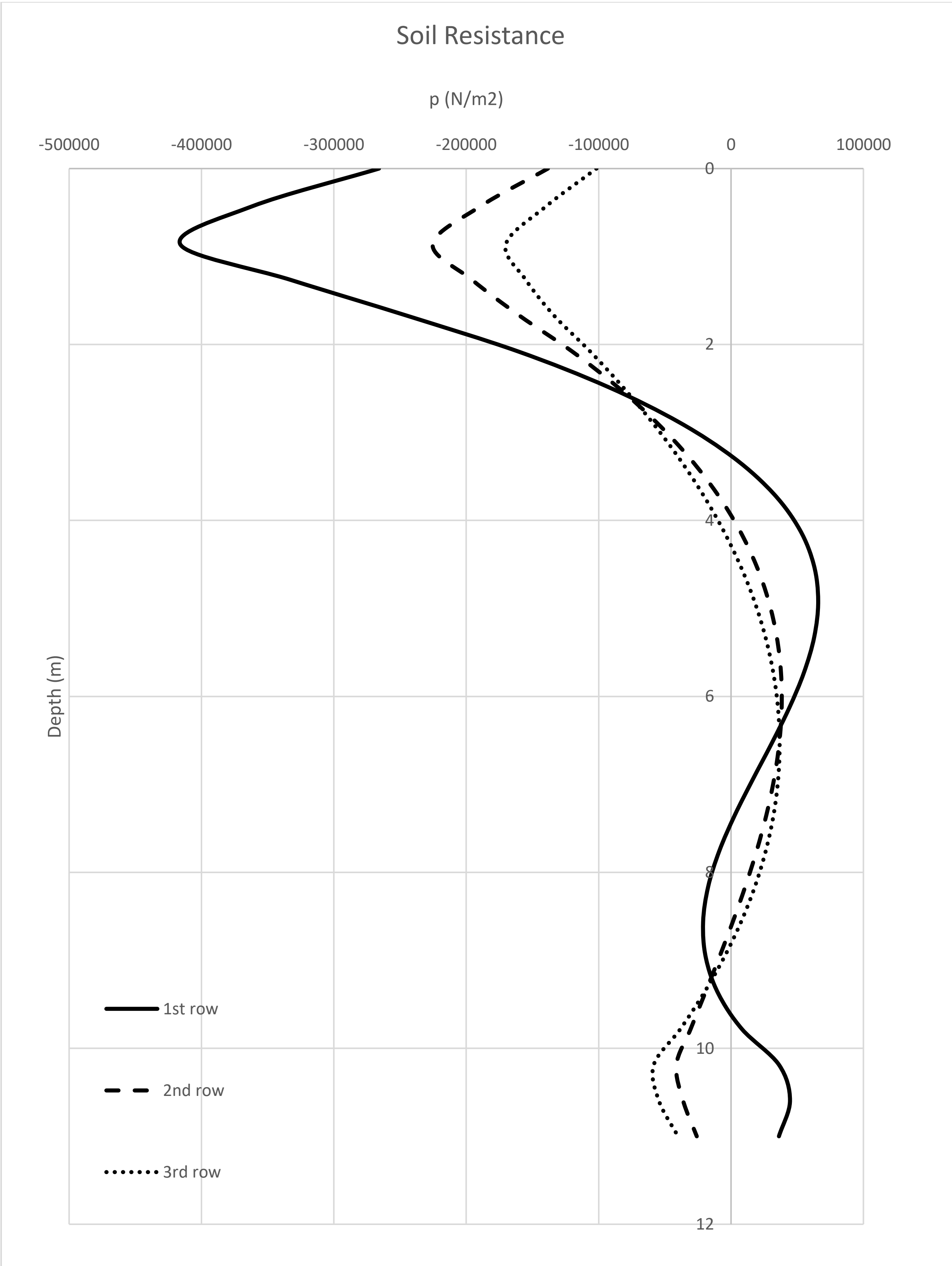


Figure 35 Soil Resistance S/D=3, ϕ=40

2. S/D = 4

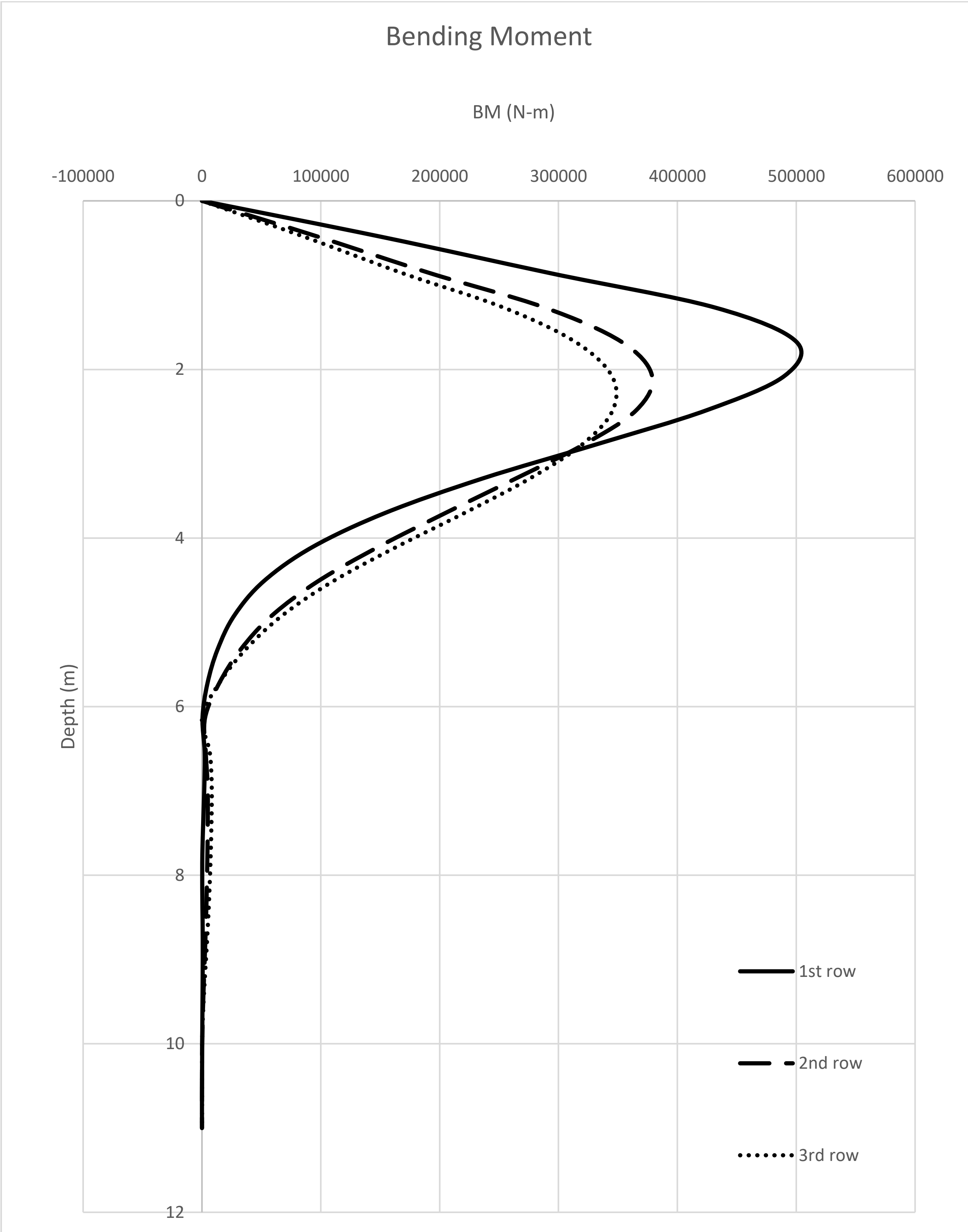


Figure 36 Bending Moment S/D=4, ϕ=40

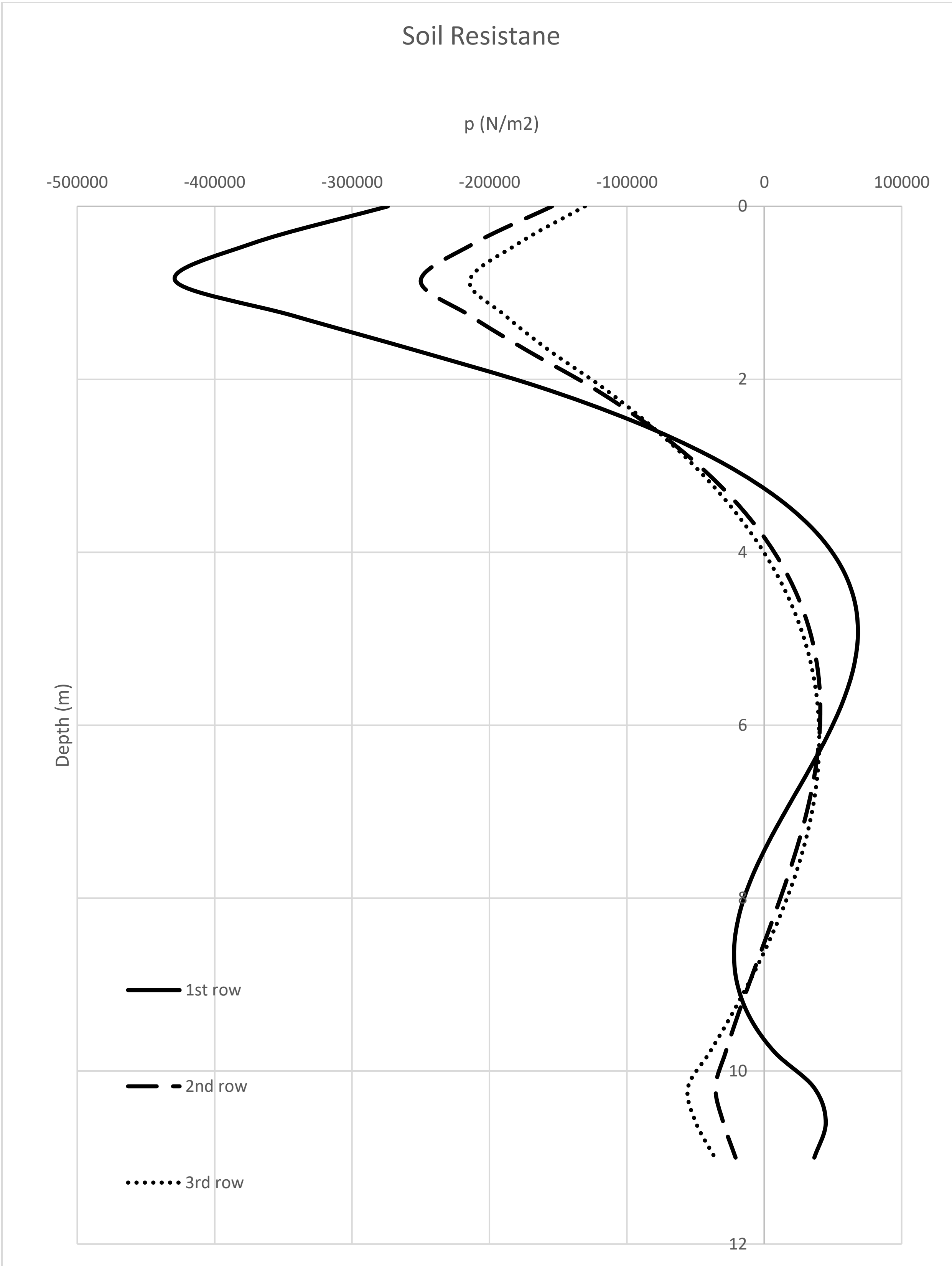


Figure 37 Soil Resistance S/D=4, ϕ=40

3. S/D = 5

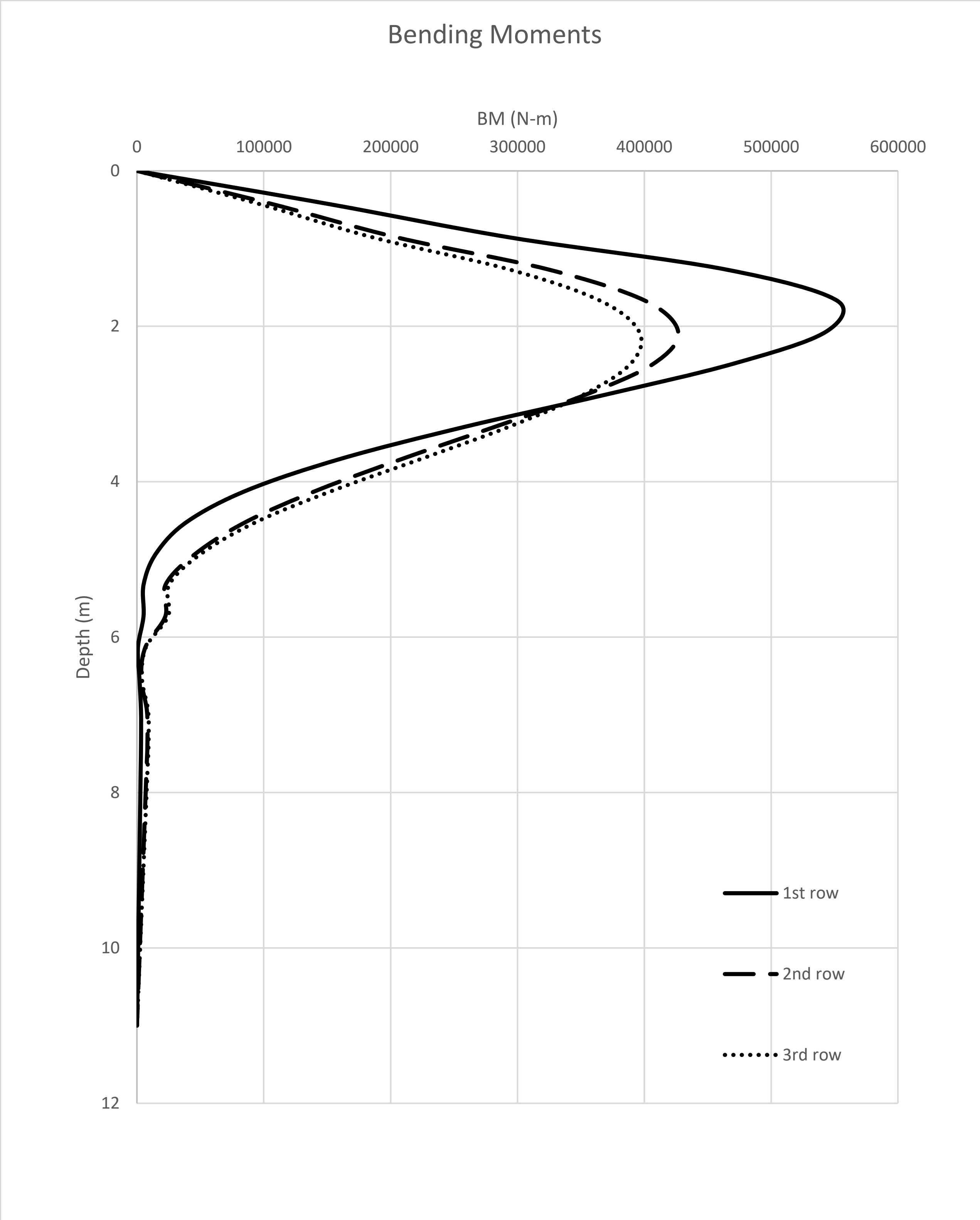


Figure 38 Bending Moment S/D=5, ϕ=40

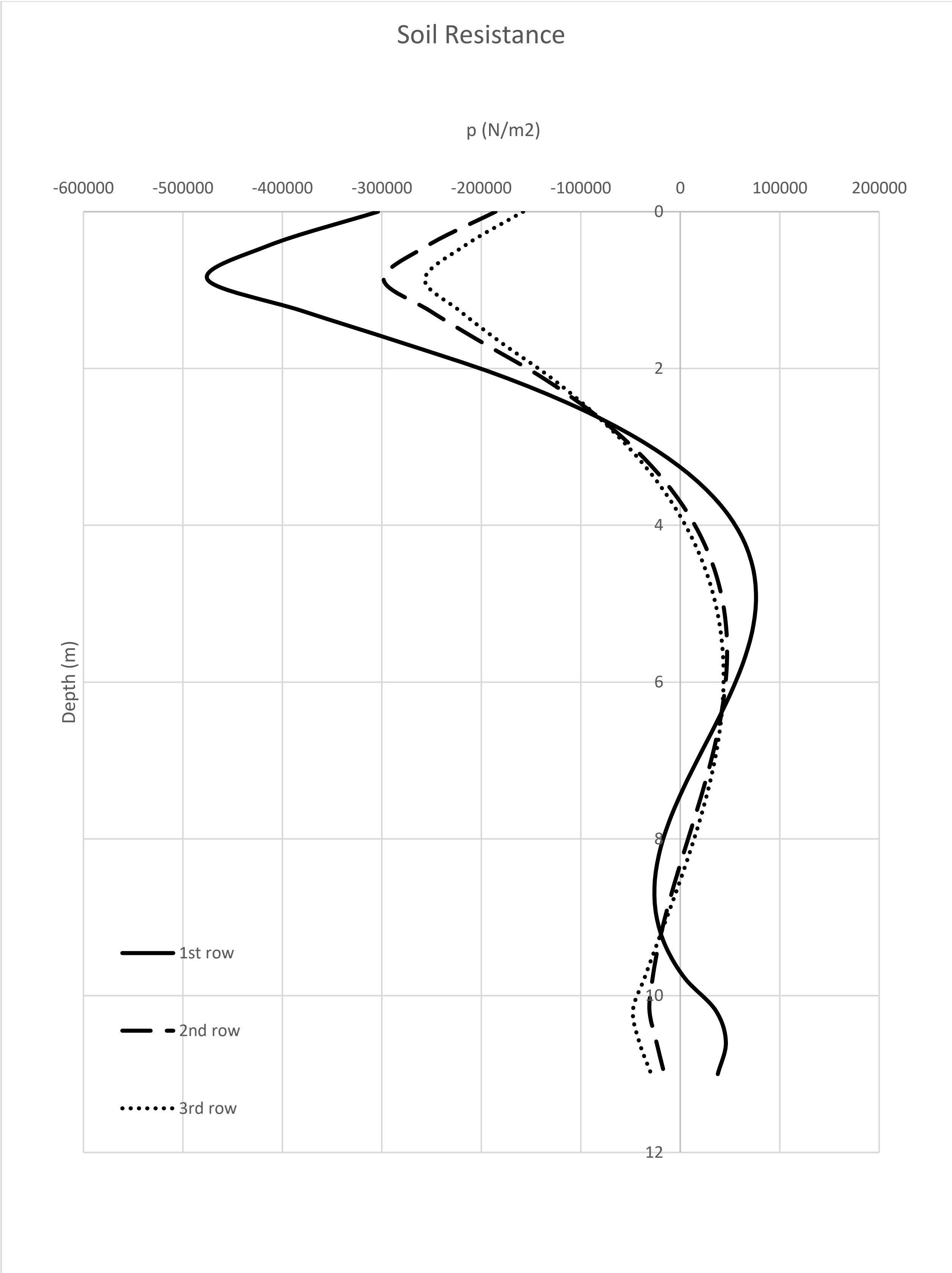


Figure 39 Soil Resistance S/D=5, ϕ=40

The values for p-multipliers for φ = 40 degrees and depth of 1.67m is

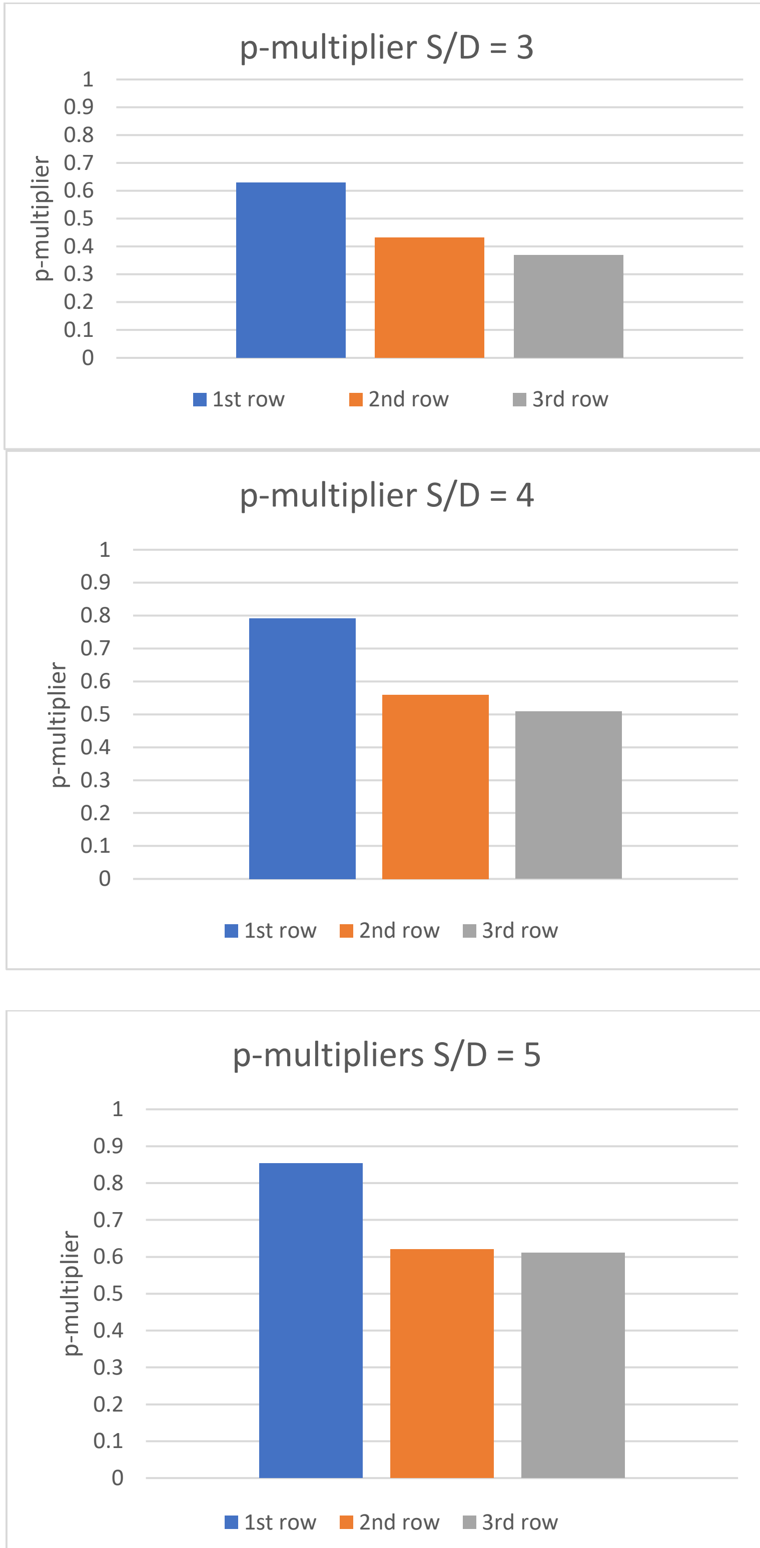


Figure 40 p-multipliers for ϕ=40 at different spacing

p-multiplier comparison from above results:

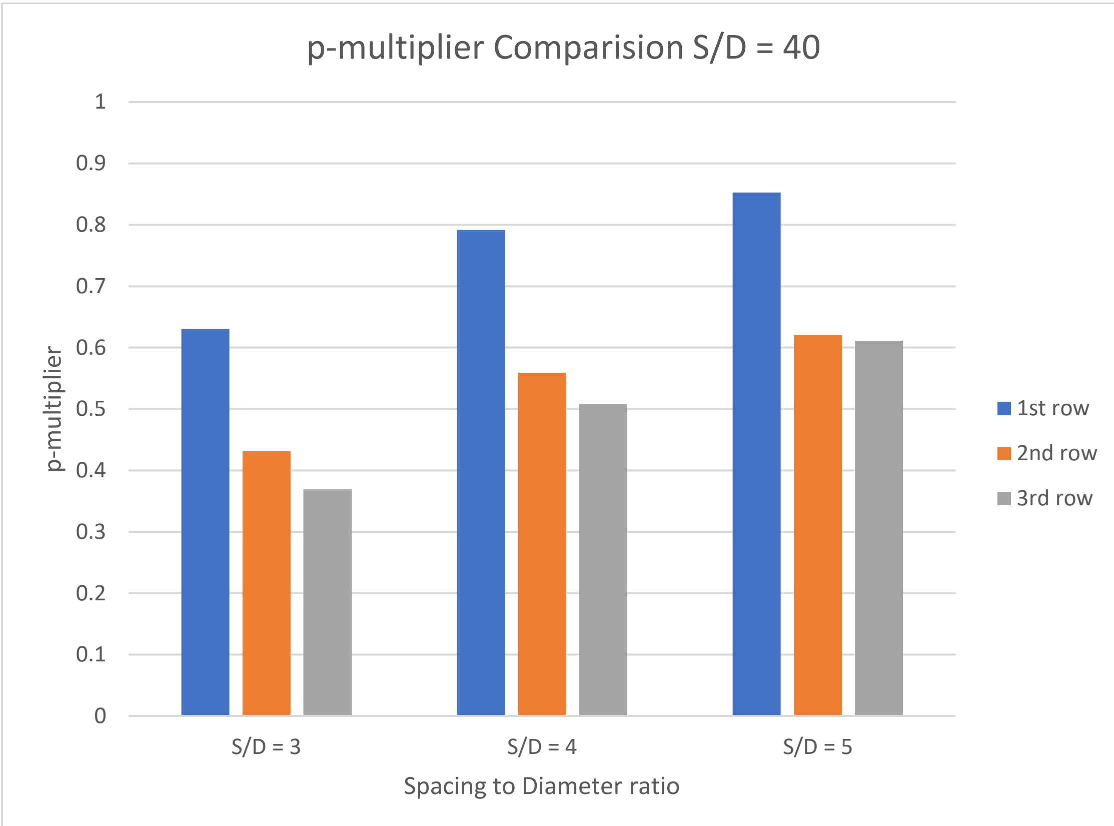


Figure 41 Comparison of p-multipliers

Results:

As with the previous cases the value of p-multiplier is increasing with increase of spacing between the piles with respect to the diameter of the piles used.

The values of p-multipliers are the lowest for all studied cases when compared with values of p-multipliers for friction angles of 35 and 30 degrees.

These values of p-multipliers were for a friction angle of 40 degrees.

3.5 Summary

Values for different conditions of spacing and friction angle was evaluated from 3D model in this chapter and their relationship between them was elaborated briefly. In the next chapter we will do an enhanced study and comparison with detailed analysis to further increase the present knowledge of the p-multipliers.

Chapter 04 ANALYSIS OF DATA FOR P-MULTIPLIERS AND INTERPRETION OF THE GENERAL TREND FOR GRANULAR SAND MEDIUM

4.1 Introduction

In this chapter we will do a thorough study of our evaluated results from the 3D finite element model. This chapter also represents the general trend that was seen in the values of p-multipliers and certain variations in the overall values of p-multipliers that was not described in the previous chapters.

The numerical data will be used to represent the trend of p-multiplier first for a simple single case and then there will be a comparison between the cases evaluated in the previous studies.

Finally, we will represent the final results of our study in a form that will clarify what we have done with our study.

4.2 Analysis of Calculated and Evaluated Data

4.2.1 Trend of p-multiplier in a single simulation

For a single case, we first ran the simulation in the 3D numerical model and then we extracted the data for deflection and bending moment at equal intervals of depth for a total of 11m. After that soil resistance was calculated by taking second derivative of bending moment. To obtain a smooth curve we also applied polynomial fitting with degree five to get a smooth curve for soil resistance. Now, since all the data is extracted, we will show what is the trend of p-multiplier value by taking reference from the above study. The reference data will be for φ=30 degrees and for group pile with S/D = 3.

Now we will take the data from the above-mentioned cases and see what is the trend of p-multiplier for a single case.

When the calculation was performed following data was received:

For ϕ=30 degree & S/D = 3

SR. #	Depth	p for single pile	P Group pile			p-multiplier			
			Leading row	1st Trailing row	2nd Trailing row	Leading row	1st Trailing row	2nd Trailing row	
	m	N/m2	N/m2	N/m2	N/m2	-	-	-	
1	0.00	47738.38	38891.24	13827.09	6986.80	0.81	0.29	0.15	
2	0.43	65445.58	53274.22	19287.42	10008.96	0.81	0.29	0.15	Region of maximum bending moment or critical point
3	0.86	78194.64	63654.05	25427.73	14977.67	0.81	0.33	0.19	
4	1.27	68506.53	55906.04	27078.31	19170.99	0.82	0.40	0.28	
5	1.67	56590.42	46363.60	26901.35	21535.60	0.82	0.48	0.38	
6	2.08	43055.95	35457.70	24362.48	21276.02	0.82	0.57	0.49	
7	2.48	31159.79	25895.80	21386.70	20099.26	0.83	0.69	0.65	
8	2.89	20830.95	17611.38	18076.67	18153.17	0.85	0.87	0.87	
9	3.29	12000.11	10538.77	14536.46	15587.17	0.88	1.21	1.30	
10	3.70	4595.01	4610.81	10869.59	12550.38	1.00	2.37	2.73	
11	4.10	1459.45	237.88	7180.51	9192.63	0.16	4.92	6.30	
12	4.51	6238.07	4073.52	3573.64	5663.93	0.65	0.57	0.91	
13	4.92	9814.60	6964.41	151.92	2112.98	0.71	0.02	0.22	
14	5.32	12266.01	8977.00	2980.39	1310.34	0.73	0.24	0.11	
15	5.73	13668.24	10178.63	5719.79	4456.89	0.74	0.42	0.33	
16	6.13	14095.05	10637.29	7963.51	7178.26	0.75	0.56	0.51	
17	6.54	13621.75	10419.70	9607.57	9324.86	0.76	0.71	0.68	
18	6.94	12323.33	9593.28	10548.82	10747.97	0.78	0.86	0.87	
19	7.35	10274.32	8225.25	10683.90	11298.64	0.80	1.04	1.10	
20	7.76	7549.69	6382.49	9908.96	10827.41	0.85	1.31	1.43	
21	8.16	4224.14	4132.14	8120.46	9185.14	0.98	1.92	2.17	
22	8.57	372.45	1541.29	5214.78	6222.58	4.14	14.00	16.71	
23	8.97	3930.31	1322.74	1088.66	1790.88	0.34	0.28	0.46	
24	9.38	8609.15	4392.86	4361.65	4259.33	0.51	0.51	0.49	
25	9.78	13588.89	7601.64	11238.97	12076.39	0.56	0.83	0.89	
26	10.19	18796.01	10882.95	19648.26	21810.95	0.58	1.05	1.16	
27	10.59	16757.63	9813.08	19439.43	21853.18	0.59	1.16	1.30	
28	11.00	12067.84	7092.43	14629.34	16529.38	0.59	1.21	1.37	

Table 2 p-multiplier at various depth points for a single simulation

For a single case it is clear that the value of p-multiplier is not the same at every point. But the only region which is a concern for us is the region where the bending moment is exceptionally very high as compared to other region which is in our case is lying between 0.43 to 2.89 m. At this point the drop in the value of p-multiplier is a great concern as it not only shows a high chance of failure in the soil strata but indicates that the soil resistance decreases for the given moment and thus should be accounted for when designing a certain pile.

For future comparison we will only be looking at the values of p-multipliers at a depth of 1.67m as it is the transition point having both higher moment and soil resistance values in all the simulations data that we have evaluated so far.

4.2.2 Trend of p-multiplier for same friction angle but different spacing in group piles

For the same value of friction angle but different spacing values the result from the evaluated data was that spacing increases the value of p-multipliers.

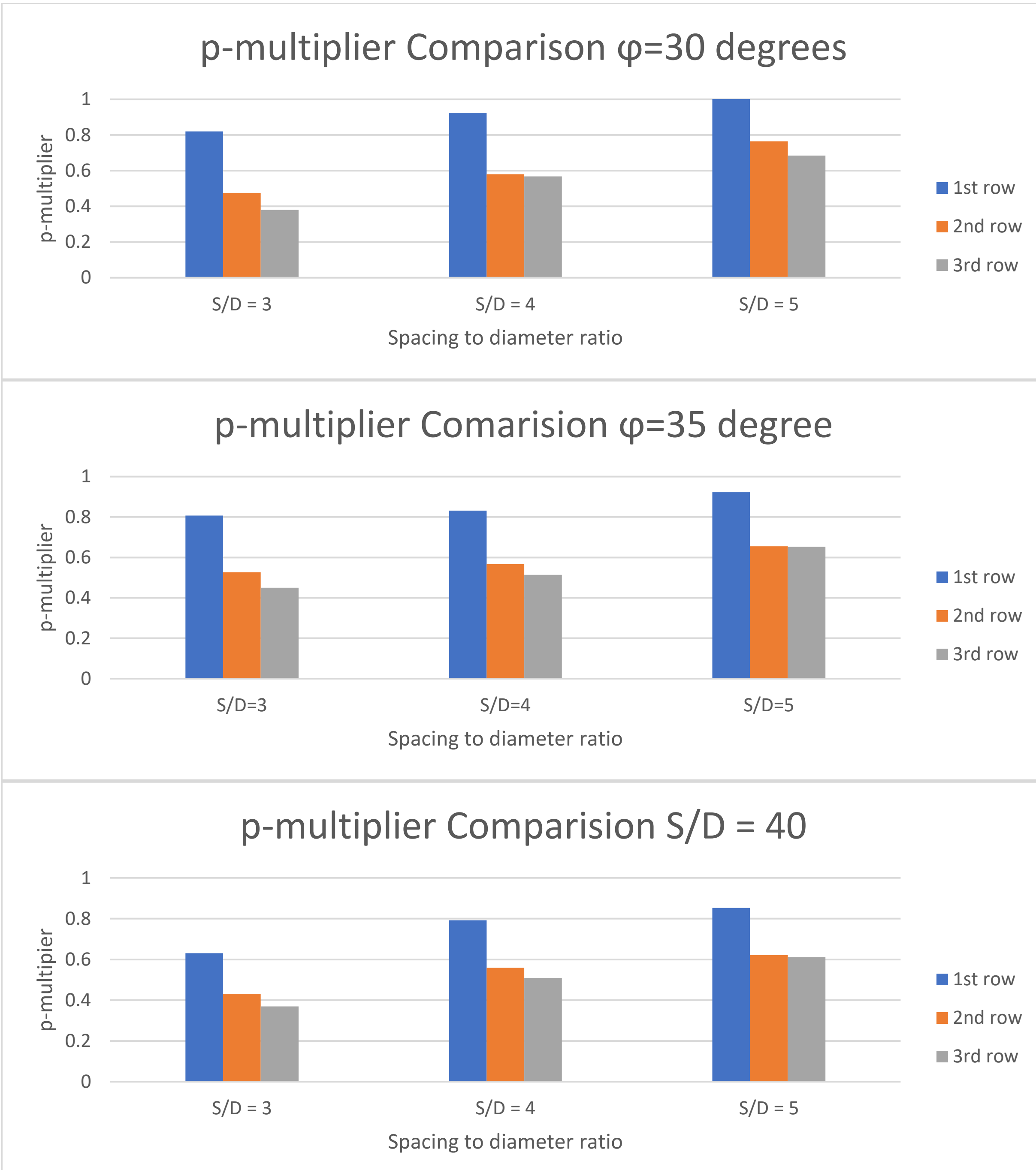
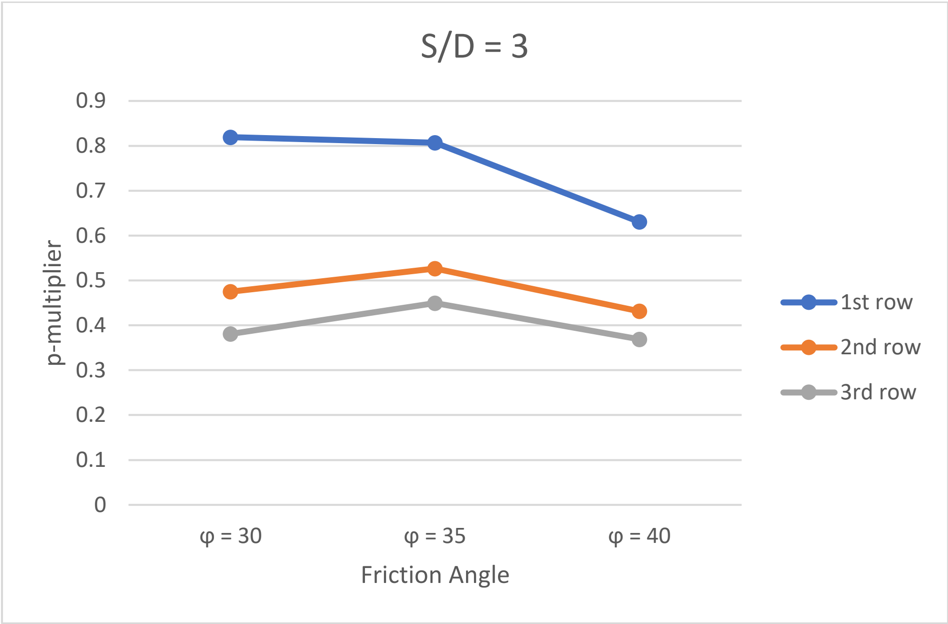
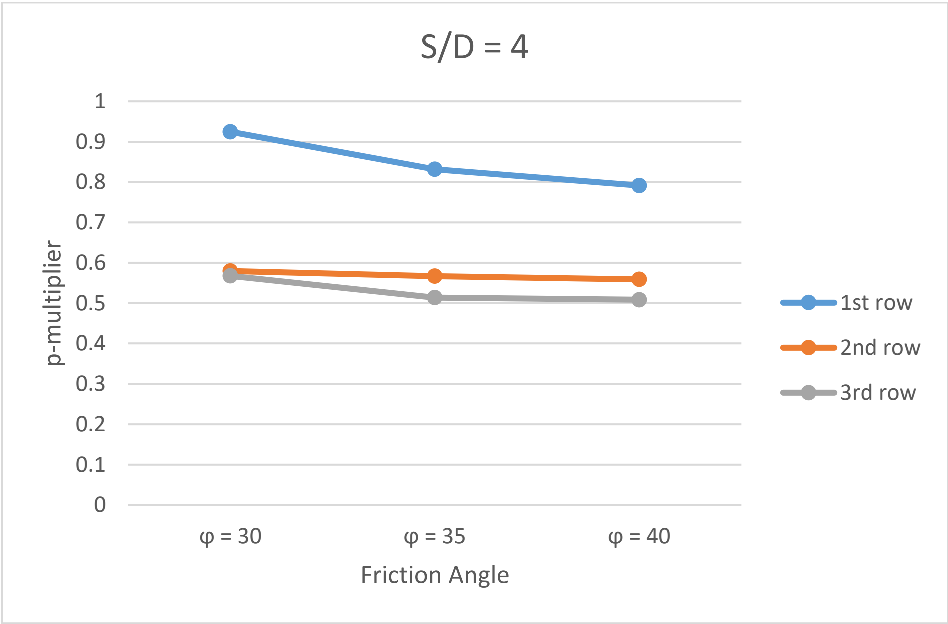


Figure 42 Comparison of p-multiplier for same friction angle but different spacing

4.3.3 Trend of p-multiplier with same spacing but different friction angle

For same spacing but different value of friction angle, the result trend of p-multiplier is shown to be decreasing with increase in friction angle. This is also elaborated from the above graphs. So, it can be said that the value of friction angle is also a design parameter to be considered while design or testing a pile group in 3D simulation.





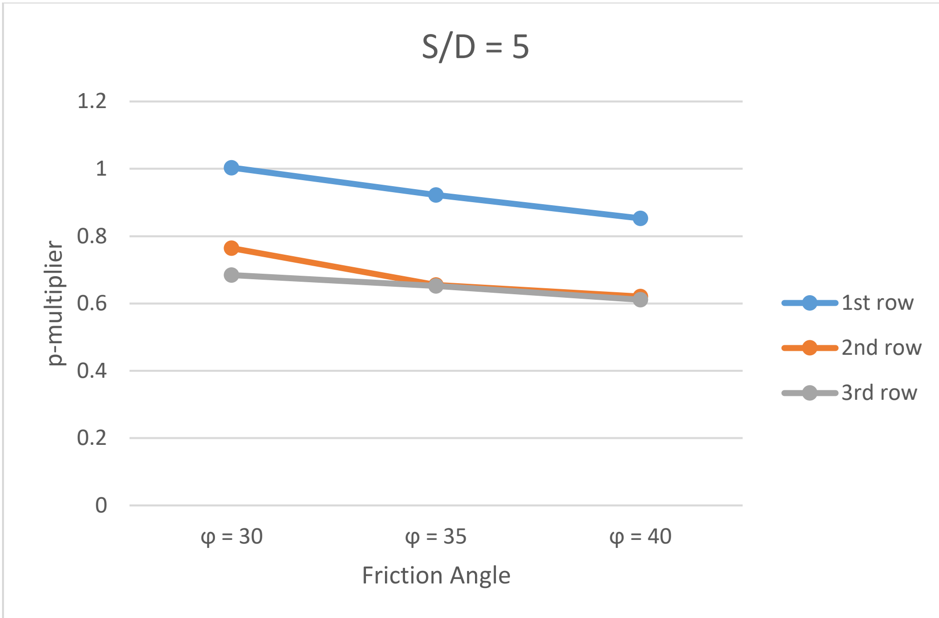


Figure 43 Comparison with same Spacing

4.3.4 Calculation of p-multiplier

In order to calculate the value of p-multipliers we first need the data for bending moment at certain designated points (which are 28 in our case) of depth along pile in our study. Once the data for bending moment is calculated, we need to derive the data for soil resistance at same designated points on pile.

The value of soil resistance is calculated for the given bending moments by first fitting our data by polynomial fitting at degree 5 in order to generate a smooth curve later and then taking second derivative of polynomial fitted data to get the values of soil resistance at designated depth points.

$$p = \frac{d}{dx^2}(M)$$

The value of soil resistance is calculated for both single and group piles under consideration and then the value of p-multiplier is calculated by the following formula:

$$p - multiplier = \frac{p\ (group\ pile)}{p\ (single\ pile)} \quad for\ x = 0\ to\ n$$

The comparison of p-multiplier is already done in the above chapters.

4.4 Conclusion

The following conclusion can be drawn from our study:

- For same value of friction angle the value of p-multiplier was increasing with increase in spacing
- For same spacing the value of p-multiplier decreases with increase in friction angle
- The value of p-multiplier changes with depth.
- A value of p-multiplier greater than one indicates that no reduction factor is needed for those points and the behavior of soil is identical to the single pile case
- p-multiplier is a concern at points with higher bending moment and soil resistance which is usually identified from graph
- It should be the approach that the p-multiplier should be extracted at different points along the critical bending moment region in order to find the case with more concerning values of p-multipliers.
- The notable values of p-multipliers in our study are

Friction angle	Spacing	p-multipler		
		1st row	2nd row	3rd row
ϕ=30	*S/D* = 3	0.82	0.48	0.38
	S/D = 4	0.92	0.58	0.57
	S/D = 5	1	0.76	0.68
ϕ=35	*S/D* = 3	0.8	0.52	0.45
	S/D = 4	0.83	0.57	0.51
	S/D = 5	0.92	0.65	0.65
ϕ=40	*S/D* = 3	0.63	0.43	0.37
	S/D = 4	0.79	0.56	0.51
	S/D = 5	0.85	0.62	0.62

Table 3 values of p-multipliers

CHAPTER 05 DISCUSSION AND RECOMMENDATIONS

5.1 Introduction

After evaluating our final study, we will now be doing a discussion and giving some recommendations on the results we were able to extract from our 3D models.

5.2 Discussion

First and foremost, conclusion of this research was that we were able to give a general trend for values of p-multipliers for various values of spacing and friction angle. It was not only a study gap from previous study but it was also rarely experimented and researched on a 3D numerical model.

Also, during data evaluation, we found that many previous researches only discussed the value of p-multipliers for a single critical point and didn't show the value of p-multiplier for other points. Although we also discussed the p-multipliers along various points in depth for a single pile case with reference to first case of S/D = 3 with friction value of φ = 30 degrees, we still addressed that the value of p-multiplier can be greater than 1 for both leading and trailing rows both in inside and outside regions of critical bending moment.

We also found that beyond a certain value of friction angle and spacing the value of p-multiplier can become equal to or greater than for leading row while it will be reduced for other trailing rows depending on the mentioned conditions.

The values and calculation of p-multipliers are much complex than anticipated and it proves that the values of p-multipliers are specific to site and strata properties and cannot be used to relate with p-multipliers propose for other sites.

Higher values of bending moment occur in the region close to the point of application of load and in strata having low relative density and bearing capacity as analyzed during soil layer properties analysis in the software. Relatively hard strata were not affected much from bending moment.

5.3 Recommendations

For our study we defined a few parameters in the start that we took throughout the whole study. We will discuss them now and give some recommendations.

First of all, we applied the lateral load as point load at the top of pile. We did this in order to incorporate maximum impact of a single natural disaster like earthquake, flood etc. at a single point. As we know the maximum damage occurs when epicenter is close to earth surface where soil strata is relatively weak so in order to get maximum effect of earthquake on pile, we applied the load as point load rather than Uniformly Distributed Load or Variable load. Here we recommend that in future we or someone else should repeat this project but for a variable loading and compare it with our results to see the effects on p-multipliers using Abaqus.

Secondly only gravity load was applied on the pile, there was no existing structural load on the pile. Here we suggest that one should also apply structural load along with the gravity load on the pile in order to see if it effects the value of p-multipliers that we have evaluated from our study without any superimposed structural load.

Next, we did this only for 3x3 configuration. We suggest that one should do it for other configurations as well like for 4x4, 4x3, 5x5, etc.

Finally, we did our research based on non-linear elastic perfectly-plastic behavior of the soil. We suggest that in the future one must compare it with soil behavior taken not as nonlinear elastic perfectly-plastic in order to study the differences between both of the approaches.

5.4 Summary

We finally conclude here by presenting our research on the previous study gap which failed to address the effects of p-multipliers when friction angle and spacing was changed for a single site. We were able to not only present a valid solution, but we ended up creating more research opportunities which will help us understand and grasp the concept of p-multipliers and complex pile soil responses. It will not only promote the use of software for evaluation of pile responses but will also help humanity reach the two sustainable design goals that were the objectives of this study.

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