Numerical simulation and optimization of pile design

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Abstract - *With a boom in urbanization, the use density of underground areas in predominant towns is regularly increasing, and the congestion of underground areas is turning into more and more prominent. A comparative analysis is also made between the proposed pile foundation material and conventional material. The parametric optimization is performed to determine the effective relationship between dependent and independent variables. Taguchi method, ANOVA techniques are applied on the structure to obtain various parameters optimization. It was observed that the Intensity of displacement in each pile design combination showed an increase with the enhancement in the intensity of blast loads. The maximum displacement of 3.98 mm happens at 2495 N load while at 195 N load the maximum displacement was 1.238 mm. Also, it was further noted in the study that Intensity of stresses in each pile design combination showed an increase with the enhancement in the intensity of blast loads. The maximum displacement of 3.98 mm happens at 2495 N load with 2460 N/mm2 while at 195 N load with 212 N/mm2 the maximum displacement was 1.238 mm. Pareto analysis shows the blast load applied has more significant impact than the pressure applied over the area in performance of the structure with respect to the maximum deviation of the structure.*

Key Words: Pile Design, ANSYS, Optimization, Taguchi method, ANOVA …

1. INTRODUCTION

Underground rail transit has evolved into one of the primary modes of transportation as a result of the growth in urban population [1]. The majority of subway stations, which serve as the transportation centers for underground rail systems, are found in densely populated urban areas with challenging terrain. Ground surface settlement during construction is one of the most significant concerns that plague subway stations frequently [2-4]. These structures frequently have deep piling foundations, which can hinder the development of underground structures like subways and other pipes [5]. For many projects, including high-rise buildings, pile foundations have been built. However, currently, studies on pile foundation underpinning era specializes in the layout and optimization of the underpinning scheme, and research at the corresponding pressure switch mechanism and its effect on subway tunnel production are limited. Moreover, the tunnel production will disturb the shaft friction resistance of the pile basis and its general resistance ability.

1.1 Application of Pile Design

With a boom in urbanization, the use density of underground areas in predominant towns is regularly increasing, and the congestion of underground areas is turning into more and more prominent. There are severa viaduct and high-upward thrust homes with inside the towns. Basin-shaped settling is frequently seen in practice when using the standard pile group foundation, where a uniform arrangement of individual piles is typically established based on the total weight of the superstructure and the designed bearing capacity of each individual pile. Previous research demonstrated that due to the interactive effects between individual piles, the settling of pile groups takes the shape of a basin when individual piles are positioned in the center of pile groups rather than the peripheral section.

1.2 Objective

I. To model the structure of pile column.
II. To analyse this structure by varying the different loading conditions.
III. To optimize the loading parameter for enhancement of structure with different materials.

1.3 Problem Statement

Numerical analysis of pile foundations found an emerging field now days due to its applications. This pile foundation is made of different materials. In present work a pile design foundation made of different material and with different soil condition is investigated to analyses its performance under different loading conditions. A comparative analysis is also made between the proposed pile foundation material and conventional material. The parametric optimization is performed to determine the effective relationship between dependent and independent variables.

2 LITERATURE REVIEW

2.1 Introduction

The Discrete Element Method (DEM) is widely used to investigate granular material behaviour at the element scale as it offers readily accessible information at the micro-scale, which may be used to uncover relevant micromechanics [16-17]. Compared with the experimental technique, the numerical modelling technique has been accepted as a more efficient approach to study the pile installation effect on soil et al. [20] conducted a series of theoretical analysis and numerical simulations of the entire construction process to verify the rationality of the scheme and to reduce the potential construction risk of the technology. Park et al. [21] proposed and verified the application of the modified underpinning method, which can reduce the construction period by 1.5 times and the construction cost by 1.2 times compared with the conventional pile cutting technology. Zhang [22] studied the influence of overlapping tunnel construction on the settlement of the pile foundation underpinning area. Deng et al. [23] analyzed the internal force and displacement response characteristics of complex, statically indeterminate structures composed of bridge superstructure, pile, soil under different jacking loads.

Currently, subway networks are being constructed in all prosperous cities in China. Generally, the greatest challenge encountered in common engineering practices is that the new tunnel has to cross through the pile foundations of existing underground structures (. Under such circumstances, pile underpinning technology or the cutting pile method may be adopted to remove obstructed piles, which poses great difficulty to engineers and technicians.

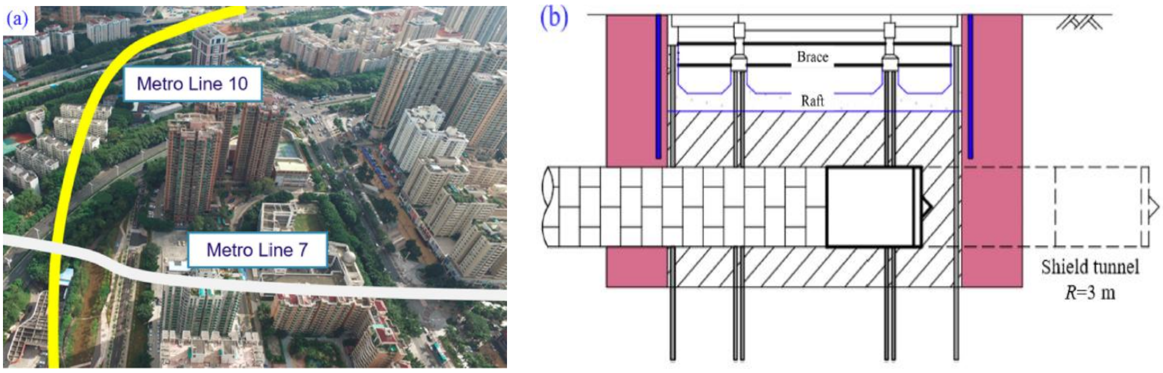

Fig. 1. Typical subway tunnel construction crossing a pile group in a complex urban environment

Moreover, the construction site is an unfavourable seismic section, and the load suffered by the bridge pile foundation is very large. Hence, the active underpinning method needs to be adopted to prevent pier deformation resulting from the settlement of new underpinning piles to ensure the safety of the bridge panel and the original pile during the construction and operation stages.

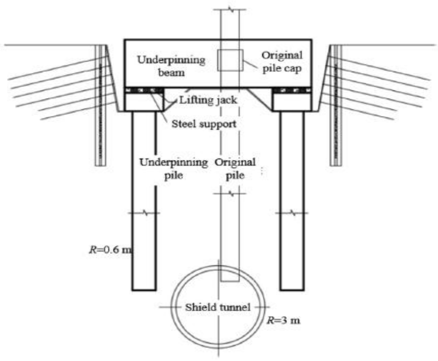

Fig. 2. Pile foundation underpinning scheme of Shenzhen Metro Line 10 passing through the bridge pile foundation group of Guangzhou– Shenzhen highway

Considering the stress conversion mechanism of the pile foundation underpinning process, the key step is to transfer the load of the original pile foundation to the new underpinning pile through the underpinning beam in order to replace the original pile foundation with the new underpinning pile. Fig. And show the maximum principal stress variation of a typical non-underpinning pile and a typical underpinning pile, respectively, before and after the pile foundation underpinning process.

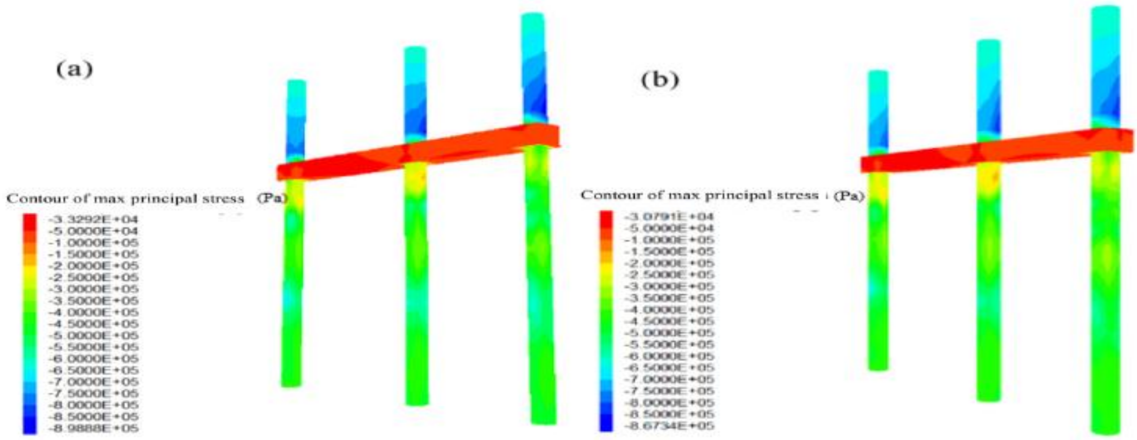

Fig. 3. Stress variation in a typical non-underpinned pile during pile foundation underpinning: (a) before underpinning of pile R25, and (b) after underpinning of pile R25 [24].

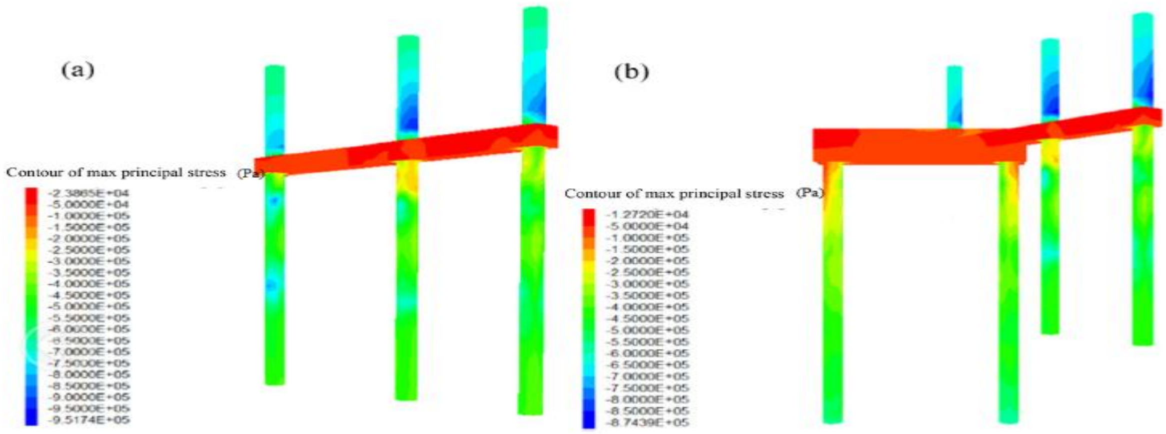

Fig. 4. Stress variation in a typical underpinned pile during pile foundation underpinning: (a) before underpinning of pile R24, and (b) after underpinning of pile R24 [24].

However, currently, research on pile foundation underpinning technology focuses on the design and optimization of the underpinning scheme, and studies on the corresponding force transfer mechanism and its influence on subway tunnel construction are limited.

Yu et al.[25] focuses on the reshaping process of rubble-pile asteroids driven by meteorite impacts. A mesoscale cluster of solid spheres is employed as the principal model for a rubble-pile asteroid, for which little is actually known about their interior structure The Eigen decomposition reveals a connection between the cluster's reactions and the types of external disturbance.

Poulos [26] presented some results of an analysis of piles near slopes in clayey soils. Schmidt [27] performed a series of laboratory model tests with rigid model piles to study the behaviour of piles installed at the crests of four different sandy slopes. It was found that the horizontal ultimate capacity of vertical pile decrease as the slope became steeper. Bouafia & Bouguerra [28] and Mezazigh & Levacher [29] performed centrifuge tests to study the responses of piles in/near a slope under lateral loads.

Chen & Martin [30] conducted extensive Finite Element analyses of piles located near slope crests to evaluate the effects of slope and pile proximity to slope crest on the lateral resistance and p-y curves of the soil-pile system. Their results show that for slope angles less than 45º the effect of slope on ultimate load capacity becomes less than 10% for distances greater than 6 pile diameters, and therefore the slope effect beyond that can be neglected.

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3 Modelling of Pile

3.1 Design of Pile foundation:

It is been obtained that the pile foundation will be modelled with the involvement of various steps into the matter of design of specific relevance of the piles. For the development of the piles foundation the first step to be modelled is the modelling of soil which forms the environment/.surrounding around which the pile and the foundation will be laid. In the first the soil is basically being modelled in the form of cubical structure which forms the surroundings of the structure. Fig shows the design of soil of the structure to be developed.

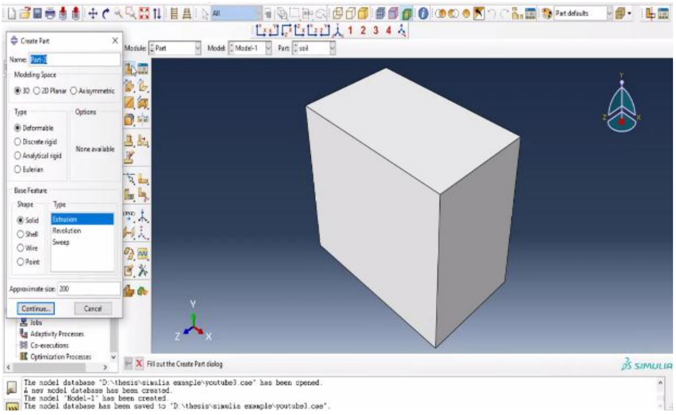


Fig 5. Design of Soil

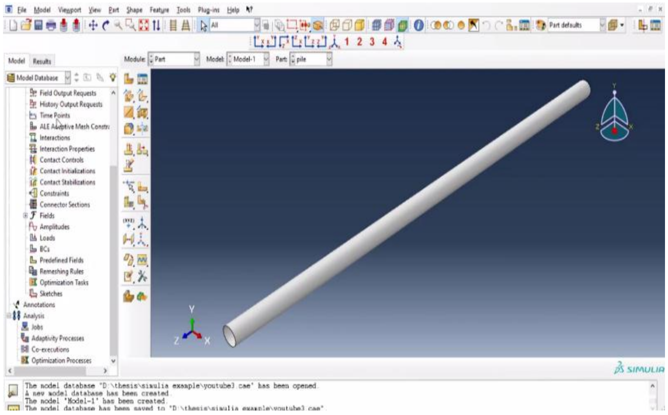


Fig 6. Design of pile

Furthermore, after the design of soil the next step is design of piles. The piles are designed with respect to the cylindrical shape objects which further will be dwelled with the soil. Piles of varying diameters were used for the design of combination of piles and foundation. There was a variation in the length as well as diameter in the design of piles also with respect to that of the soil.

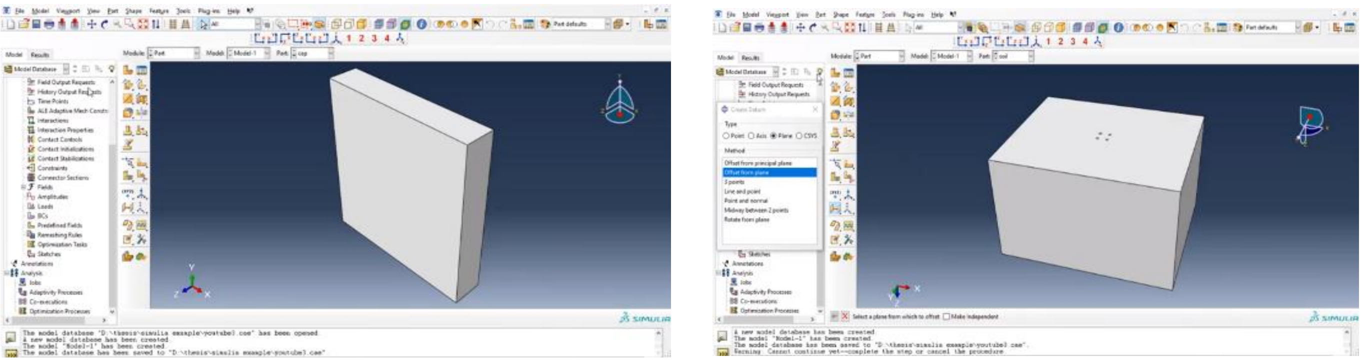
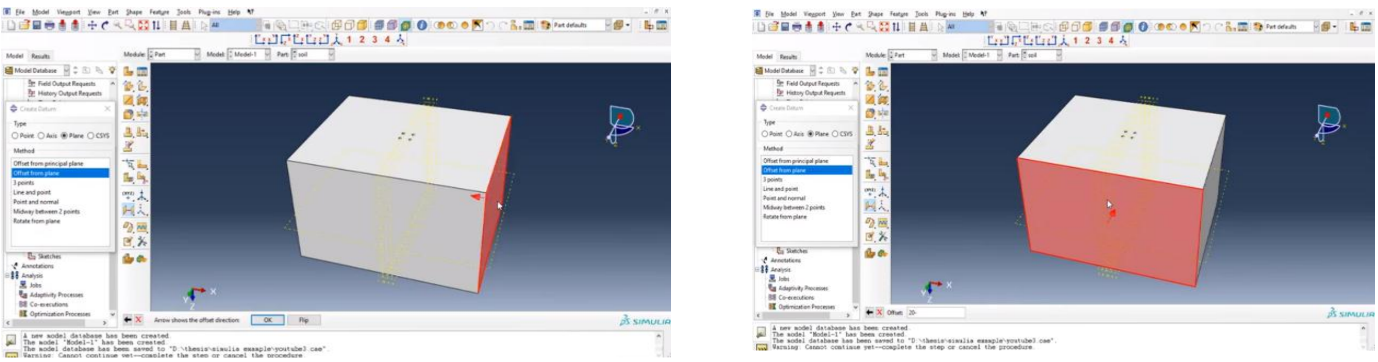
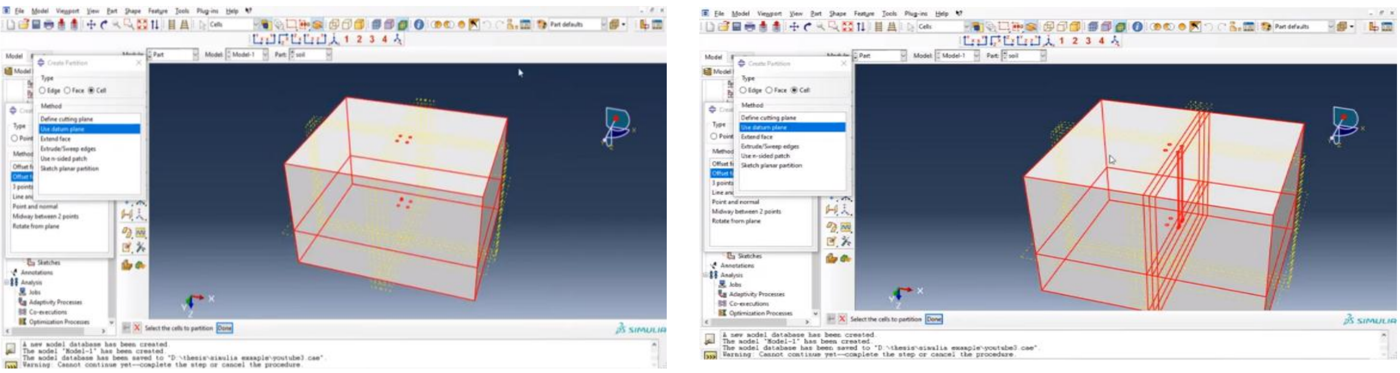


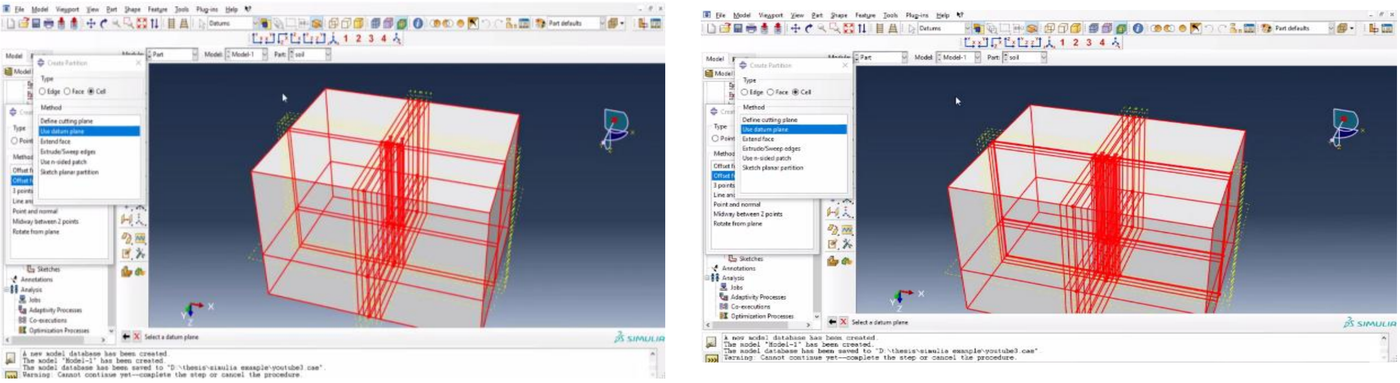
Fig.7 Different sizes of soil for embedding piles



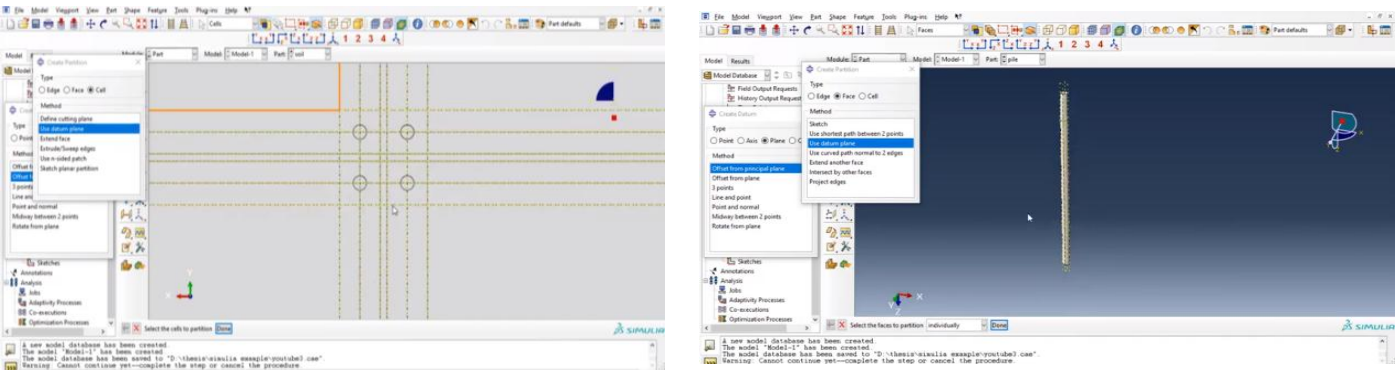
(a) Division for development of cap



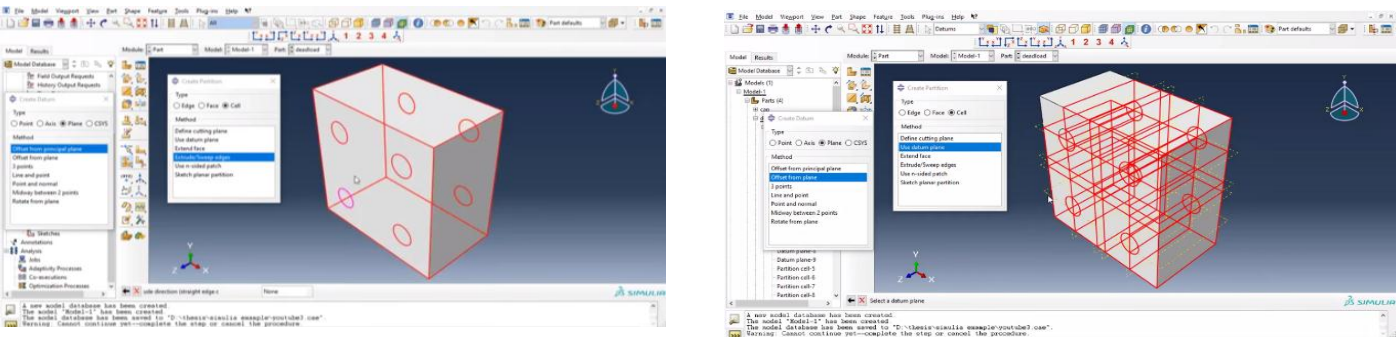
(b) Cross-sectional division for development of cap



(c) Full divisions for development of cap material meshing and alignment



(d) Development of cap for inserting Piles



(e) Development of cap with pile sized cavity

Fig 8. Development of Cap 1

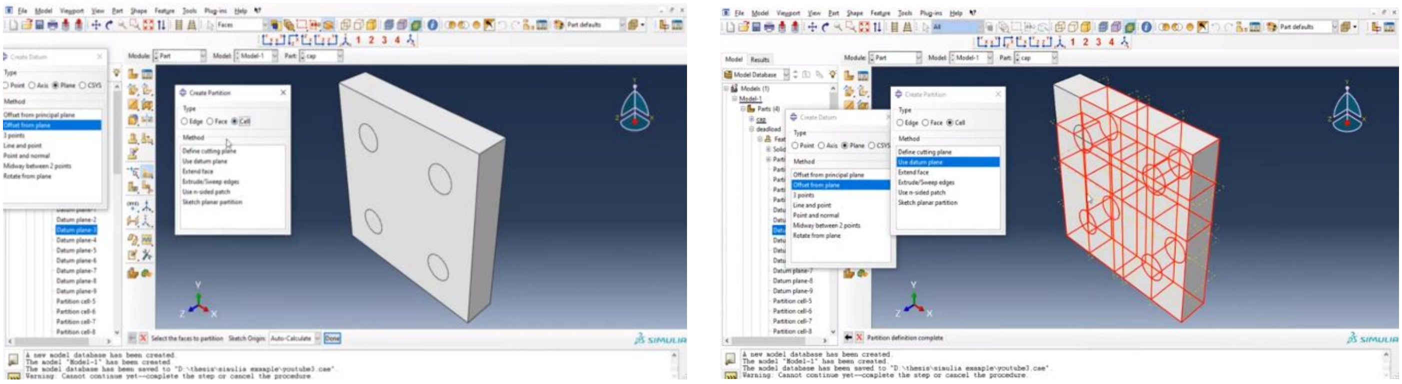


Fig 9. Development of Cap 2

Further to development of the piles different caps with pile shaped and sized cavity holes were formed. Specifically two different pile cavity shaped caps were modelled which could be placed above and below the pile in respect to the soil. Furthermore the material is specifically assigned to different models namely soil, piles and caps respectively. Each material property assigned is different from the other one and the values obtained were demonstrated as per the research papers.

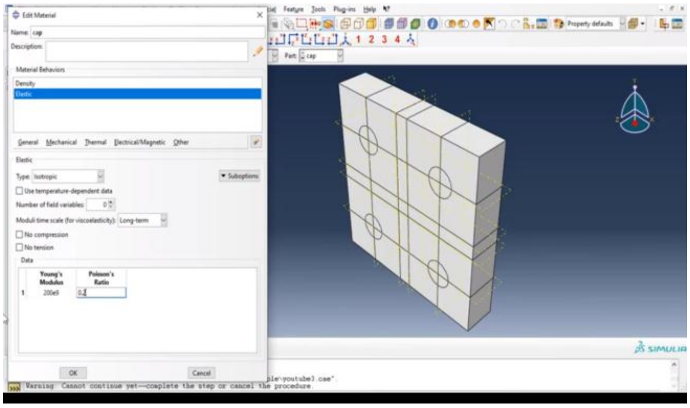


Fig 10. Assignment of material in respective models

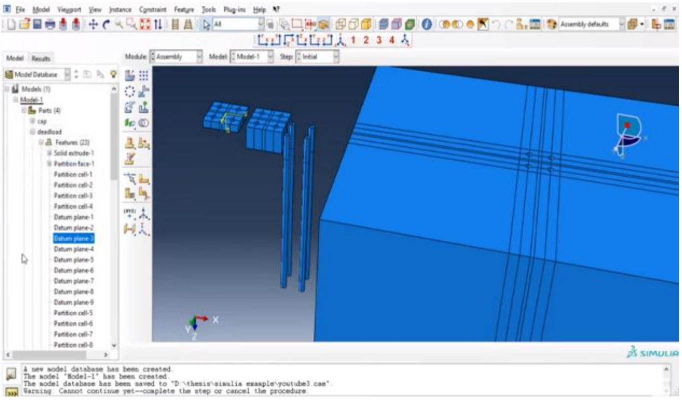


Fig 11 Assembly of all components for pile design

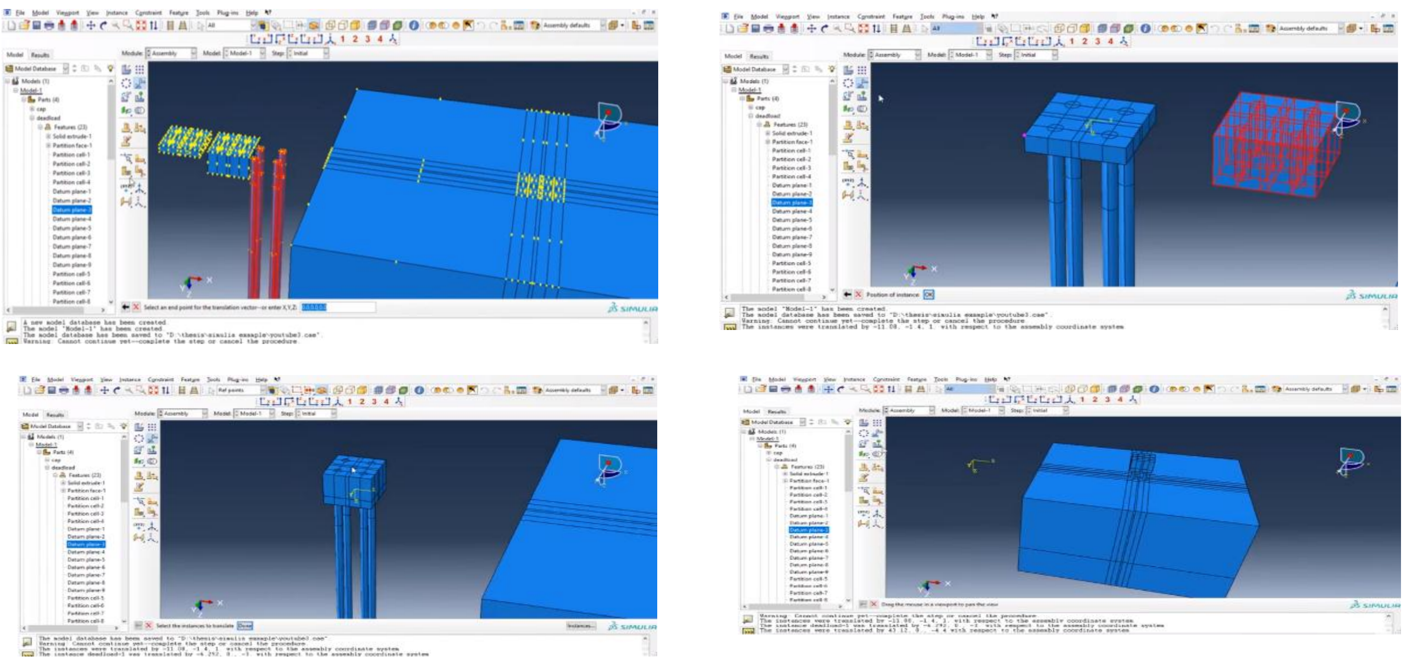
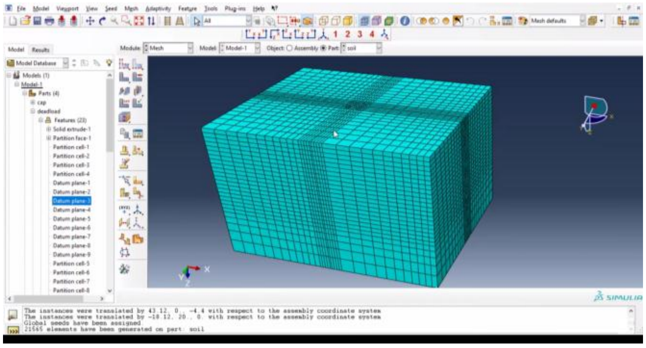


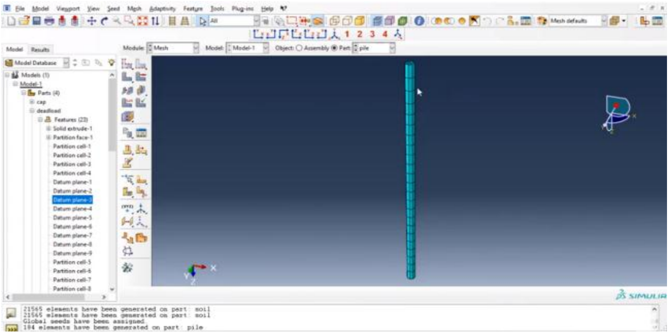
Fig 12 Assembly of all members for pile design

Furthermore, after assignment of materials and section to each elements like pile, soil, caps etc. separately they will be attached/assembled together with different techniques, inorder to develop the full model of pile design.

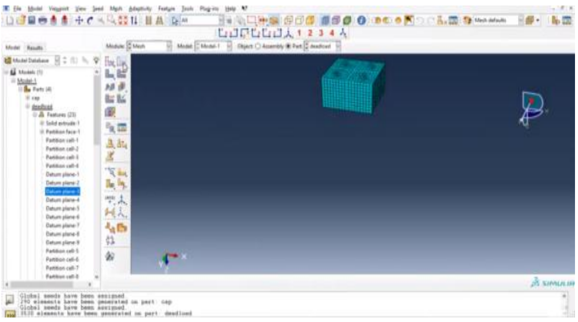
4 Pile Design Analysis

4.1 Meshing

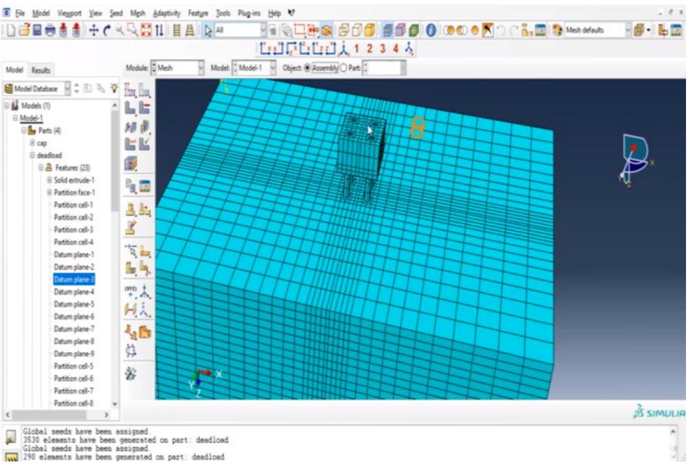




(a) Meshing of soil (b) Meshing of pile



(c) Meshing of cap



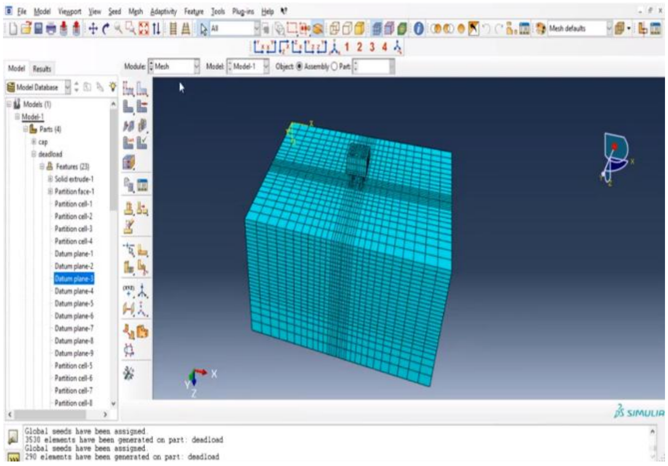


Fig 13 Meshed model of the assembled pile design

For the development of FEM model of piles foundation analysis, the next process to be done is to mesh/discretize the whole structures. The divisions performed at the time of modelling of soil, caps will be useful for distinction of different mesh sizes as per the requirement of failure modes and analysis of the structure.

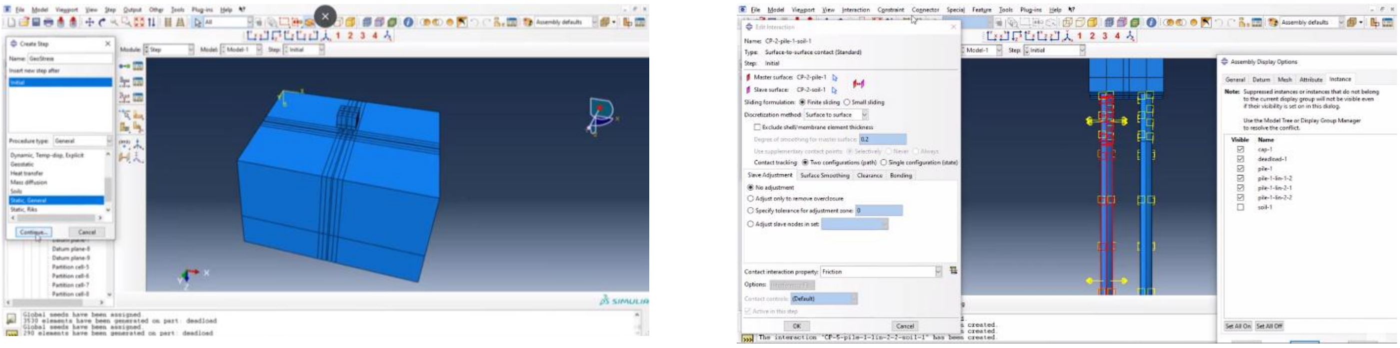


Fig 14 Contact definition for pile design

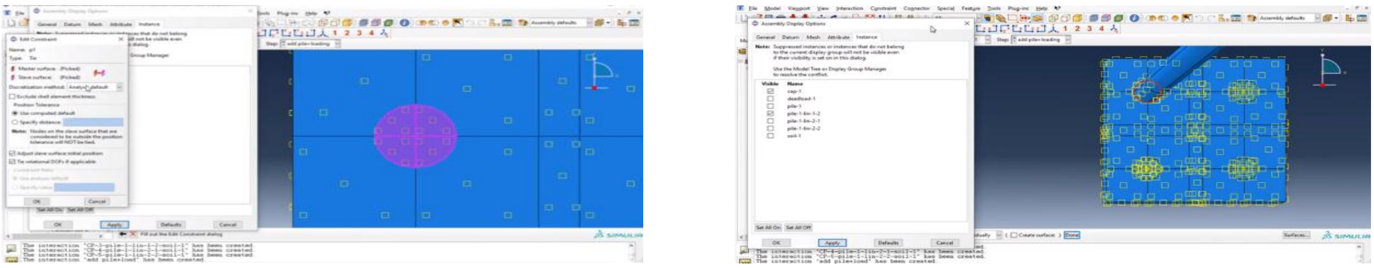


Fig 15 Contact definition for pile design

5 PARAMETRIC OPTIMIZATION OF PILE DESIGN SUBJECT TO STATIC LOADS

5.1 Introduction

Every industrial process/product optimization begins with Taguchi's optimization concept. However, due to its failure to resolve multi-objective optimization problems, this ideology is under fire everywhere. To combat this, literature emphasizes the use of the Taguchi technique in combination with the desire function approach, TOPSIS, fuzzy inference system (FIS), principal component analysis (PCA), and Grey relational analysis. The basic goal is to reduce a number of objectives to a single, equivalent objective function that can then be optimized using the Taguchi method. These methods, however, are predicated on some presumptions.

5.2 Taguchi's S/N ratio for performance evaluation

A loss function exists that describes the deviation from the target (desired level) and is then converted to the S/N. The converted S/N ratio is likewise described as nice assessment index. The least version and the greatest layout are acquired via way of means of reading S/N ratio. The better the S/N ratio, the extra solid the potential nice. It additionally reduces the sensitivity of the gadget overall performance to supply of version.

Table 1 Identifying control factors and their levels

Item	Control factor	Units	Level 1	Level 2	Level 3	Level 4
A	Theoretical Load	N	195	980	1764	2452
B	Applied Load	N	212	1018	1781	2460

There are three S/N ratios of common interest for optimization of static problems:

Nominal-the-best/target-the-best

In this approach, the closer to the target value, the better and the deviation is quadratic

The formula for these characteristics is;

$$\frac{S}{N} = -10\log\frac{y}{S_y^2}$$

Lower-is-better (LB)

The lower is better approach held when a company desires smaller values. The formula for these characteristics is;

$$\frac{S}{N} = -10\log\frac{1}{n}\sum y^2$$

Higher-is-better (HB)

It is required when a manufacturer desires higher values of a characteristic. The formula for these characteristics is;

$$\frac{S}{N} = -10\log\frac{1}{n}\sum\frac{1}{y^2}$$

Here, y is the average of observed values; S_y^2 is the variance of ; and N is the number of observations.

However, Taguchi approach is taken into consideration simplest for single-goal optimization problems. It can't be applied for buying the unmarried most excellent placing of system parameters thinking about multiple overall performance parameter.

Taguchi's experimental technique has been accompanied to limit the test trails, and L16 orthogonal array has been used to carry out the experimental runs. Besides, ANOVA has been accomplished to discover the importance of system variables. Blast Load, Bonding Strength and Thickness are taken as enter parameters and most displacement as a Output parameters.

Taguchi Array	L16(4^3)
Factors:	3
Runs:	16

Table 2 Design of experiment L16 orthogonal array

Sr. No	Theoretical Load (N)	Applied Load (N/mm²)	Total settlement (mm)
1	195	212	1.298
2	195	1018	1.314
3	195	1781	1.396
4	195	2460	1.389
5	980	212	2.125
6	980	1018	2.198
7	980	1781	2.179
8	980	2460	2.199
9	1764	212	2.919
10	1764	1018	2.979
11	1764	1781	3.011
12	1764	2460	3.121
13	2452	212	3.987
14	2452	1018	3.978
15	2452	1781	3.790
16	2452	2460	3.980

Response Table for Signal to Noise Ratios

Larger is better

Table 3 Signal to Noise ratios

Level	Theoretical Load	Applied Load
1	-1.434	4.710
2	11.033	7.644
3	9.709	8.247
4	11.183	9.888
Delta	12.617	5.178
Rank	1	2

Response Table for Means

Table 4 Means

Level	Theoretical Load	Applied Load
1	0.9721	2.5604
2	3.8712	2.8074
3	3.4209	3.1248
4	3.6775	3.4492
Delta	2.8991	0.8889
Rank	1	2

The Level 2 of A and level 4 for B gives the maximum settlement which shows in Fig. Interestingly A2B4 is the best combination for maximum settlement. It can be seen that theoretical load of 980N and applied load 2460 N and gives the optimum result for maximum settlement of 3.980 mm.

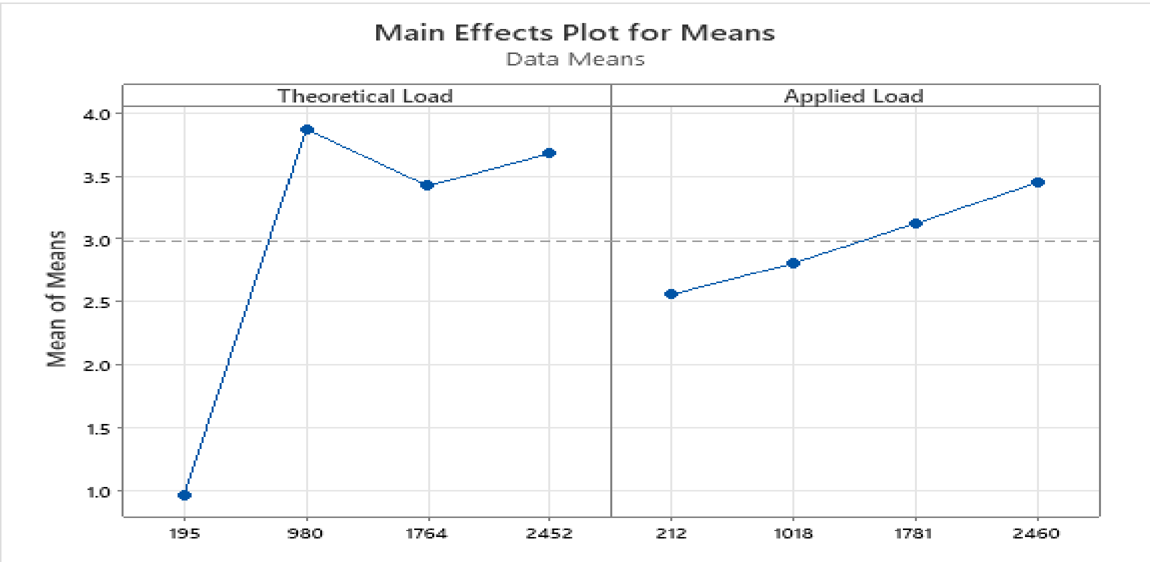


Fig. 16 Main effect plot for means

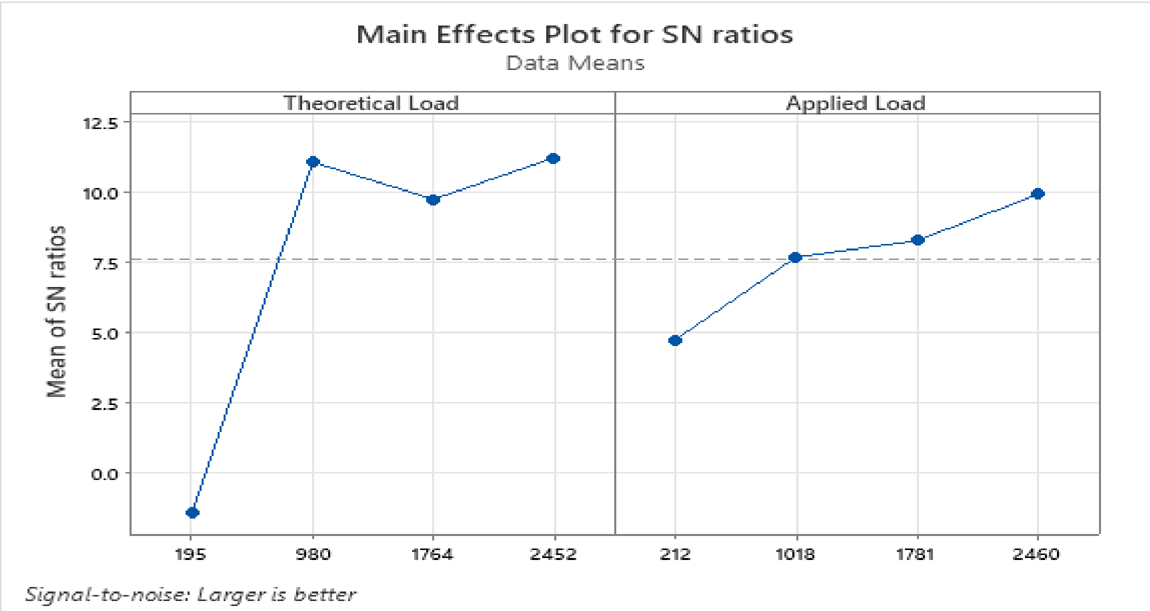


Fig. 17 Main effect plot for SN ratios

Regression Equation

In regression model, theoretical load and applied load are independent variable and maximum settlement is a dependent variable.

In this model, the relationship between theoretical loads, applied load and maximum settlement were analysed.

Total settlement = 1.056 + 0.001029 Theoretical Load + 0.000396 Applied Load

Table-5 Maximum Displacement Numerical vs Regression equation

S. No	Total Settlement	
	Numerical	Regression Equation
1	1.298	1.265
2	1.314	1.296
3	1.396	1.327
4	1.389	1.354
5	2.125	2.072
6	2.198	2.104
7	2.179	2.134
8	2.199	2.161
9	2.919	2.879
10	2.979	2.911
11	3.011	2.941
12	3.121	2.968
13	3.987	3.587
14	3.978	3.619
15	3.790	3.649
16	3.980	3.676

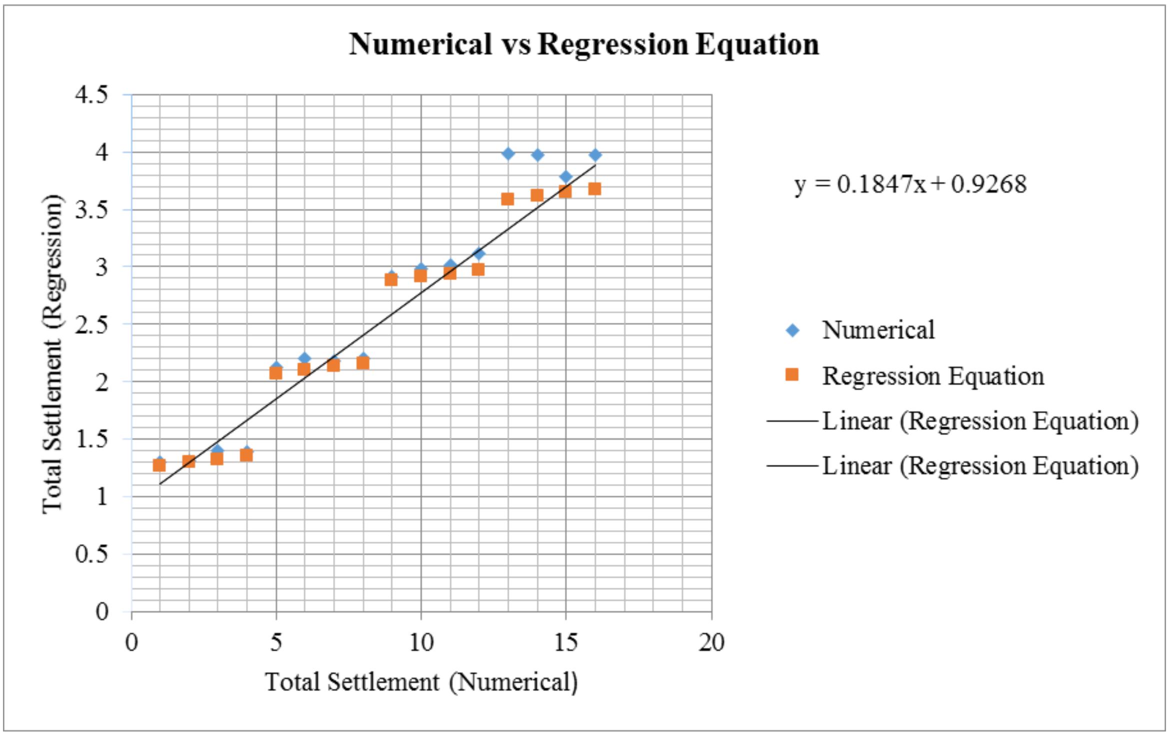


Fig. 18 Comparison between numerical and regression model

ANOVA analysis

By adjusting the theoretical load and applied load, the goal of the analysis of variance is to identify the key variables that significantly influence the maximum settlement. The level of significance of the factors and how the parameters affect the answer are both clearly shown by ANOVA analysis. Blast load, bonding strength, and thickness are the three primary factors taken into account in this study. The R2 value (34.37 percent) for maximum displacement is clearly shown by the ANOVA analysis. A high R2 value shows that the theoretical and numerical models are more compatible. Here, the theoretical load's 0.030 P value is important. The main output of ANOVA analysis on variance arranged in Tables 6 and 7. Larger F value (5.94) indicates that the variation of the process parameter make a significant changes on maximum settlement.

Table-6 ANOVA for maximum settlement

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	13.878	6.939	3.40	0.065
Theoretical Load	1	12.107	12.107	5.94	0.030
Applied Load	1	1.771	1.771	0.87	0.368
Error	13	26.495	2.038		
Total	15	40.373			

Table –7 Coefficient for maximum displacement

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.056	0.888	1.19	0.256	
Theoretical Load	0.001029	0.000422	2.44	0.030	1.00
Applied Load	0.000396	0.000425	0.93	0.368	1.00

Table 8 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.42761	34.37%	24.28%	6.41%

Pareto chart shows indicate the theoretical load plays a significant role for the maximum settlement followed by applied load. Fig represent the normal probability plot for maximum settlement. It shows the data are following normal distribution curve, which fits the model suitable for prediction of maximum displacement values. In Fig. we can see only one value as a outlier, so it prove the feasibility of numerical analysis.

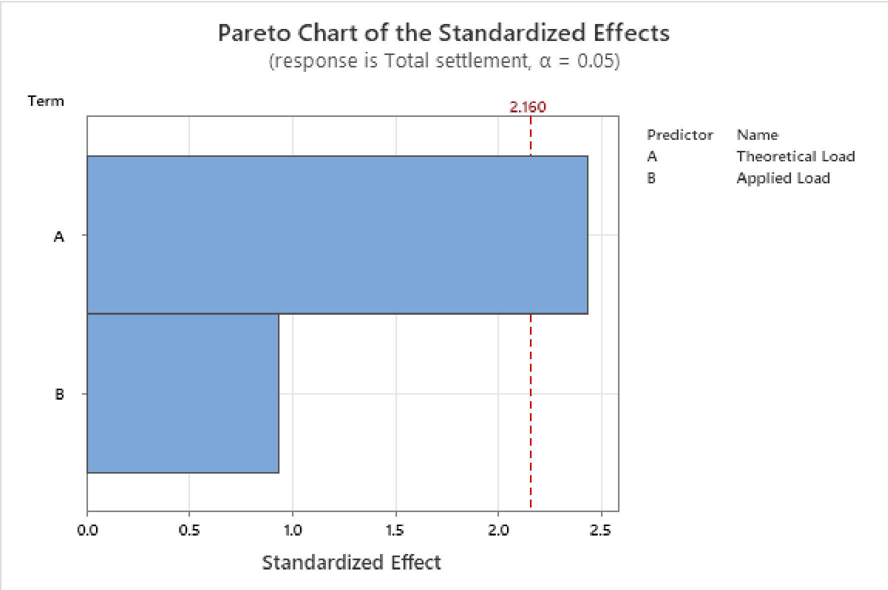


Fig. 19 Pareto chart

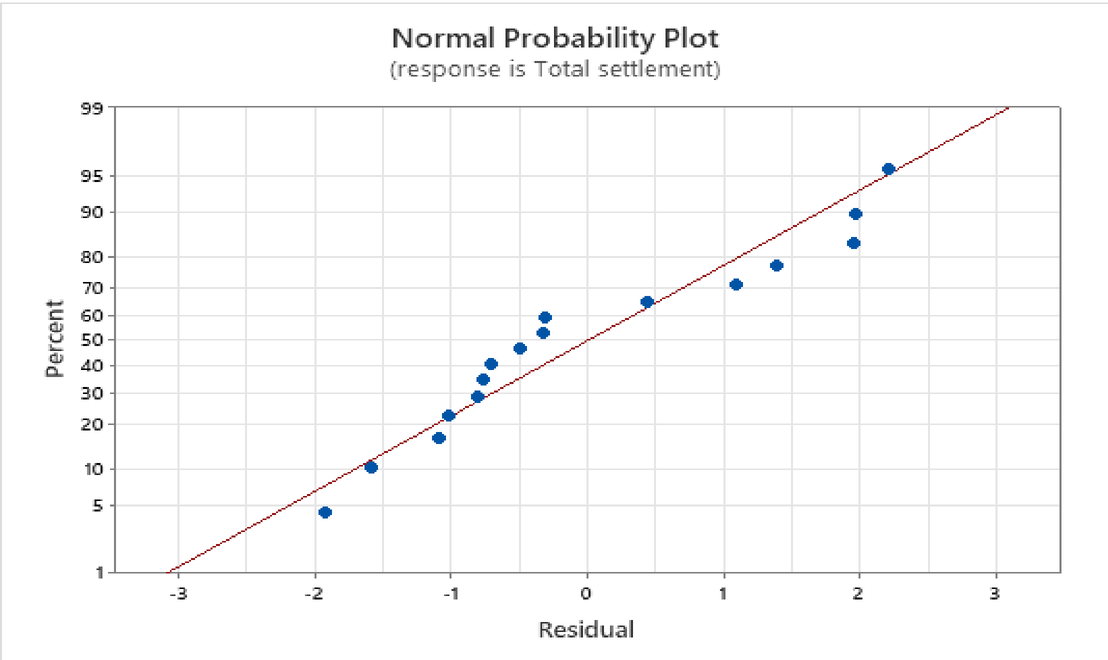


Fig. 20 Normal Probability Plot

Prediction

S/N Ratio	Mean
13.2986	4.33506

6 CONCLUSIONS

- Size of the piles developed were varying from 100 mm to 1000 mm with different height ranges varying from 500 mm to 2000 mm in order to analyse the performance of the structure with respect to geometrical parameters.
- Size of piles were subjected to different intensity of static loads varying from 195 N to 2095 N, in order to attain the variation or performance of the structure with respect to the varying load.
- Magnitude of displacement in piles of smaller size is lower with same thickness on action of same intensity blast loads.
- Magnitude of stresses in piles of smaller size is lower with same thickness on action of same intensity blast loads
- Intensity of displacement in each pile design combination showed an increase with the enhancement in the intensity of blast loads. The maximum displacement of 3.98 mm happens at 2495 N load while at 195 N load the maximum displacement was 1.238 mm.
- Intensity of stresses in each pile design combination showed an increase with the enhancement in the intensity of blast loads. The maximum displacement of 3.98 mm happens at 2495 N load with 2460 N/mm^2 while at 195 N load with 212 N/mm^2 the maximum displacement was 1.238 mm.
- ANOVA analysis is also carried to analyse the parametric performance of Pile design.
- Taguchi analysis is performed for analysis of the parameters of pile design
- Pareto analysis shows the blast load applied has more significant impact than the pressure applied over the area in performance of the structure with respect to the maximum deviation of the structure.

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