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Experimental, Numerical and Analytical Analysis on Diaphragm Wall in Cohesive Soil

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Abstract The Diaphragm wall is a reinforced concrete wall that will isolate the structure from the adjacent structure and will also provide the basement for the accommodation of the residents. Unnecessary provision of anchors in diaphragm walls will increase the construction cost of diaphragm walls. In the research, one basement diaphragm of 0.5-meter thickness is taken into consideration along with 0.45-meter diameter pile. The pile was spaced at a distance of 3, 5, and 6 meters in cohesive soil. The numerical, analytical, and experimental methods were adopted to analyze and understand the behavior of the diaphragm wall. The embedment depth of 8.85 meters was obtained by analyzing using an analytical method. The numerical analysis was done using Plaxis 3D software. The experimental work was done for a model of a diaphragm wall and pile with a scale of 1:30. The bending moment available from numerical work and from analytical work was 51.11 kNm and 57.521 kNm. Experimental work found that the diaphragm wall had an average deflection of 25.41 millimeters and analytical analysis found an average deflection of 25.66 millimeters. All three methods concluded that the deflecting was within the permissible limit and that an 8.85-meter embedment depth was the most suitable embedment depth. It was also concluded that parameters like cohesion, density of soil, excavation depth, and angle of internal friction affect the stability of the Diaphragm wall. Research also found that excavation depth should be more than a ratio of 4 times cohesion to bulk density of soil. It was also concluded that the deflection of the diaphragm wall is independent of loading on the pile as deflection is only because of the soil pressure.

Keywords Diaphragm Wall, Cohesion, Angle of Internal Friction, Deflection, Bending Moment, Thickness, Embedment, Excavation

1. Introduction

In most of the developing countries, population plays a major role in its development. Particularly India, where land is scarce will have the major problem of accommodation of the large population. Major areas of the developed cities are already occupied by infrastructure. So much land from the outskirts is utilized in the construction. Under such conditions of rapid urbanization vertical development will be a better solution than horizontal development. Vertical development should be accommodated without compromising the facilities like parking, stability of surrounding soil, deep foundation, obstruction to the seepage, and obstruction of the entrance of moisture in the parking areas.

A diaphragm wall will be the perfect solution that can accommodate such services. A diaphragm wall is a reinforced concrete structure that will be constructed in the soil. It will provide support to the surrounding soil and prevent the collapse of the soil. The diaphragm wall also known as the bulkhead will isolate the existing structure from the surrounding structure. The diaphragm wall will prevent the effect of the construction of adjacent property on the existing structure.

In this urbanization, the areas have started developing in the outskirts. So the construction has started in the outskirts of cities on land which were previously used for agriculture and farming purposes. So diaphragm wall will be constructed in fertile and cohesive soil and there it will have to resist extra lateral pressure which was not acting in the core areas of the city.

So to work on this problem and to observe the behavior of the diaphragm wall in the research, a 0.5-meter-thick diaphragm wall is taken into consideration and it is supported and surrounded by cohesive soil which also has an angle of internal friction. In the research paper, numerical, experimental, and analytical analysis is done. Analytical work provided the suitable embedment depth for one basement diaphragm wall and the behavior of the diaphragm wall was observed using the experimental and numerical work.

In the analysis, pile foundation was considered on which the concentrated point load is acting. Bending moment and deflection were available using the numerical analysis. Numerical analysis results were compared with analytical and experimental work. Experimental work was performed to determine the actual site deflection of the diaphragm wall.

Here, the results of the experiment work are compared with experimental work and analytical work so that the impact of parameters like the thickness of the diaphragm wall, and properties of soil on the diaphragm wall will be observed.

1.1. Literature Review

G J W King [1] conducted research on the sheet pile wall in which he proposed a method for the analyses of sheet pile walls. The proposed method was based on two methods. G J W King [1] has adopted method A and method B for the analysis. Method A was the simplest method where the net pressure diagram wall was assumed. In method A, the wall is assumed to be rotating about point O. In method A it was observed that active earth pressure and passive earth pressure are very equivalent. Moment A method also provided the method to find the bending moment, for a moment a homogeneous and stratified soil. Method B was specified by Bowles as a very realistic method to find the pressure distribution diagram. Here no modification and simplification are supposed to be done. There is a method to do not provide any formula for the bending moment.

Haiyang Zhuang [2] researched relieving method deformation and other inner forces that are acting on the sheet pile wall. For this, in his research, he provided the relieving platform at the intermediate location. In reality, the reference was taken for the real structure that was made in Shenzhen city. Adopting the relieving platform was very advantageous in comparison to the traditional type of Sheet pile. Haiyang Zhuang [2] analyzed through the numerical method and analytical method. For the numerical method, the analysis is done through the finite element analysis method. For the numerical analysis equations were provided and based on that analysis was done. Here Haiyang Zhuang [2] used the Elastic foundation method for the analysis of the sheet pile. He has divided the sheet pile into two segments so that the unknowns like deformation and inner force can be obtained from the derivation. Haiyang Zhuang [2] assumed that the boundary condition of the hinge condition, both the numerical method and analytical method were compared. It was concluded that the proposed numerical method was very feasible and could be adopted for the analysis of sheet pile diaphragm walls.

M. Das [3] researched the design optimization of sheet piles. The research was on both anchored and cantilever sheet piles. The condition of the diaphragm wall considered in the research was such that the wall penetrated the clayey soil. M. Das [3] performed the research using the practical centrifuge test and finite element analysis. The design of the diaphragm wall was based on the equilibrium condition. Here all moments were taken about the base point. The cost optimization was also the target of the author. The author has analyzed it in Microsoft Excel software. According to M. Das [3], the design of the diaphragm wall is based on the penetration depth and the thickness of the Diaphragm wall. The embedment depth of the diaphragm wall will provide the stability of the diaphragm wall and the thickness of the diaphragm wall will provide the capacity of the diaphragm wall to take bending moment and shear force.

Guharay [4] conducted research on cantilever sheet pile walls with different types of soil using the finite analysis method. Guharay [4] penetrated the diaphragm wall in cohesionless soil. In the research, the backfill supported by the sheet pile wall is both cohesive soil and cohesionless soil. According to the author, the main purpose of the research was to identify the failure probability. In the research of obtaining the failure probability, Guharay [4] varied the parameters. In the research, the sheet pile has a height above the dredge level of 6 meters. The sheet pile is penetrated in soil having a density of 19 kN/m^3 and cohesion of 40 kN/m. For the soil below the dredge level, Guharay [4] has considered two cases 1) the soil below the dredge level with a density of 19 kN/m^3 and $\phi=30°$, 2) soil below the dredge level with a density of 19 kN/m^3 and $c=40kN/m^2$. The factor of safety was obtained by the formula suggested by Guharay [4]. From the result and analysis, Guharay [4] observed that for cohesionless soil the value of the factor of safety was 1.52 and for cohesive soil, the factor of safety available was 1.59. Guharay [4] found that the embedment depth for cohesionless soil is greater in comparison to cohesive soil backfill. The probabilistic analysis of the sheet pile wall was done in Plaxis-2D software. The sheet pile wall had a thickness of 0.611 meters. In the modelling, the properties were assigned and for the concept of the factor of safety, the values of ϕ and Υ were varied. Guharay [4] also found that from the analysis cohesion is a very important parameter in the analysis of both types of conditions. As for cohesive soil backfill because value of cohesion is less, it resulted in more embedment depth. Finally, Guharay [5] concluded that the depth of embedment for cohesive soil is much lesser in comparison to the cohesionless soil.

Babu [5] conducted research on the design of a cantilever sheet pile wall in sand clay soil. The analysis was based on the reverse reliability approach method. The reliability method was adopted to determine the depth of penetration of the wall in the soil and also to determine the suitable section modulus of the diaphragm wall so that a safe diaphragm wall can be designed. In the analysis, Babu [5] has used the Gaussian and Lagrangian methods. Babu [5] concluded from his research that the reverse reliability approach was made against the point of rotation of the diaphragm wall and flexure failure of the diaphragm wall that satisfies the required stability check. Analyzing the diaphragm based on the reverse reliability approach received a much conservative result.

Muhammed [6] researched the effect of anchor depth on the behavior of the sheet pile. The overall research was done using Plasxis 2D software. Muhammed provided the sheet pile wall with a thickness of 1.265 meters with the embedment depth varying from 2, 4, 6 and 8 meters. The depth of excavation was 12 meters. Muhammed [6] has provided anchorage at different locations as the sheet piles. Anchors are modelled with the help of geotextiles. Geotextiles are grouted bodies and they have a free length of 10 meters and a fixed length of 5.5 meters. The anchors are provided at the inclination of 45 °. The sheet pile wall was modelled using the beam function. Muhammed [6] found the maximum bending moment, maximum displacement in both horizontal and vertical directions of the diaphragm wall, and shear force on the diaphragm wall. Muhammed [6] also found the factor of safety for the provided set of parameters. Muhammed [6] also concluded that anchors do increase the stability of the diaphragm wall. Muhammed [6] found that the 4-meter length of the anchor is the suitable length for the anchor and further the stability of the diaphragm wall will increase with the increase in length of the anchor. Muhammed [6] found the safe result of deflection by providing anchors at a depth of 25% of the total length of the wall and below the top of the wall.

Jesmani [7] researched a comparison between the 2D & 3D behavior of sheet pile walls. The soil considered in the research was loose sandy soil. For the comparison, Jesmani has used the finite element method. Jesmani [7] conducted a 3D analysis of sheet pile walls. Jesmani [7] in his research focused more on maximum bending moment and maximum displacement with the variation of L/H ratio. Jesmani [7] has varied L/H ratio from 0.1 to 6 and correspondingly he has found the bending moment and deflection. For maximum bending moment, Jesmani concluded that maximum bending moment was increasing linearly for L/H up to 1.6. The maximum bending moment remained constant from 1.6 to 3 and further, it started reducing till L/H up to 6. Jesmani [7] found the depth of the hinge point from the bottom. Jesmani [7] concerning the L/H ratio concluded that the depth of the hinge point reduced with an increase in the L/H ratio.

Choy [8] conducted research work on finding the effect of constructing the diaphragm wall adjacent to the pile foundation. For the research Choy [8] has constructed the centrifuge model so that the real aspect of constructing a diaphragm wall adjacent to the pile foundation. Choy [8] provided the model of 801 mm x 16 mm x 350mm. Choy [8] wanted to understand the effect of the reduction of slurry level in the diaphragm wall on the pile foundation. Choy [8] provided a diaphragm wall of 12 mm thickness that is similar to a 900 mm thick diaphragm wall. The total length of the pile was 270 mm and the diaphragm wall was inserted to the depth of 250 mm. The scale adopted by Choy was 1:75. In the model several strain gauges were provided by Choy [8] to determine the deflection of the diaphragm wall. On the periphery of the model, it was 0.5 mm thick. In the research work, Choy placed the pile at distances of 3.5D, 5.6D, 6D and 7.7D D where D is the diameter of the pile. Load on the pile head is provided using the brass weight and with the help of a laser distance sensor. The observation of vertical settlement and horizontal settlement was taken in the research with an increase in distance between the pile and diaphragm wall.

Mohamed [9] researched the interaction of the diaphragm wall and the adjacent pile foundation. He has considered the case study of Egypt concerning that he has modelled the diaphragm wall in Plaxis 2D. In the research, Mohamed [9] concluded that deep foundations perform stronger than shallow foundations in functioning with diagram walls.

2. Materials and Methods

2.1. Soil Properties

The soil was taken from Prantij village near Himmatnagar town in the Sabarkantha district in Gujarat. The soil was a C- Ø type of soil as it had both cohesion and angle of internal friction. The properties of soil determined after the laboratory test of soil are listed in Table 1. Soil is shown in below Figure 1.

Figure 1. Actual Soil

Table 1. Soil Properties

Sr. no.	Parameter	Value
1	Cohesion (C)	28kN/m ²
2	Angle of internal friction (Ø)	29 °
3	Bulk density of soil (ϒ)	18 kN/m ³
4	Dry density of soil(ϒdry)	16 kN/m ³
5	Type of soil	C- Ø

2.2. Diaphragm Wall Properties

The properties of the diaphragm wall taken into consideration are listed in Table 2.

Table 2. Diaphragm wall parameters

Sr. no.	Parameter	Value
1	Modulus of elasticity	25000000 kN/m ²
2	Grade of Concrete	25 MPa
3	Total number of basement	1
4	Normal stiffness	12500000 kN/m
5	Flexural stiffness	260000 kN/m

The diameter of the pile was fixed to 0.45 meters as per the soil report. The depth of the pile was fixed to 7 meters. The spacing between the diaphragm wall and pile foundation was finalized as 3 meters, 5 meters and 6 meters. The spacing was finalized on a practical basis and based on GDCR rules. The safe bearing capacity report was also available from the laboratory. According to the report, a 450-millimetre diameter pile is chosen for a depth of 7 meters. Corresponding to that safe bearing capacity available was 28 tons.

2.3. Analytical Analysis

Rankin's theory found that active earth pressure is acting up to the depth of excavation. According to Das [3], no cohesion that was considered in the analysis will be there up to the depth of excavation. Neglecting the cohesion will be beneficial as ultimately a critical condition was adopted in the analysis of the diaphragm wall. Till the depth of excavation, the angle of internal friction was 28 degrees. This was because, till the depth of excavation, critical non-cohesive soil was considered. Below the depth of excavation, there was embedment depth. The soil was consolidated and compacted in the embedment region. So the angle of internal friction in the region below the dredge level was zero degrees. The pressure diagram is shown in Figure 2. Here 'h' is the depth of excavation, 'd' is the embedment depth and 'm' is the depth of change in characteristics of pressure below the excavation depth.

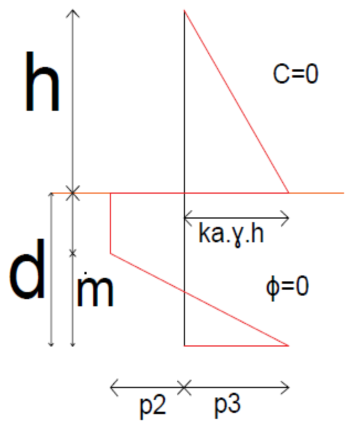

Figure 2. Pressure Diagram

The depth m is available from the equation made by the equivalent areas of the pressure diaphragm.

Pressure at the excavation was active earth pressure and it deflected the diaphragm wall away from the soil.

Intensity of pressure=ka x ϒ x h

Passive earth pressure was found below the dredge level. The intensity of pressure below the dredge level passive earth pressure started acting and the intensity of pressure of p2. Further below a point will come in the depth m and the characteristics of pressure will be changing from passive earth pressure to active earth pressure. The intensity of active earth pressure near the bottom of the pile was p3. Following are the equations of p2 and p3.

p2= [(kp.ɣ.z)+(2.c.kp^0.5)]-[(ka.ɣ.(z+h))-(2.c.ka^0.5)]

p3= [(kp.ɣ.(h+d)+(2.c.kp^0.5)]-[(ka.ɣ.(d))-(2.c.ka^0.5)]

The final equation after putting the value of the angle of internal friction as zero so that ka and kp will be equal will be

$$p1 = ka.\Upsilon.h$$

$$p2 = 4c-\Upsilon h$$

$$p3 = 4c+\Upsilon h$$

The equation has been simplified and the simplified pressure diagram is represented in Figure 3.

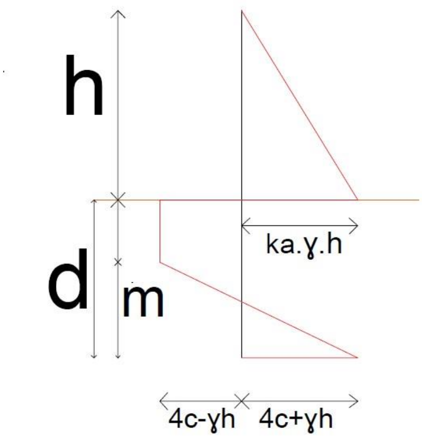

Figure 3. Simplified Soil Pressure Diagram

The depth m is available from the equation made by the equivalent areas of the pressure diaphragm.

$$m= ((4c-\Upsilon h)\ d-P1)/4c$$

To find the embedment depth an equation was determined. The equation was available taking all the moments coming from the top of the diaphragm wall to the bottom of the diaphragm wall. Pressure p1 was from the active earth pressure, p2 was the passive earth pressure coming from the soil just below the dredge level and finally, and p3 was the active earth pressure below the passive earth pressure. On equating all the moments at the toe of the diaphragm wall an equation was determined. Following is the available equation.

$$Ad^2+Bd+C=0$$

Where

$$A=(4c-\Upsilon h)$$

$$B=(-2P_1)$$

$$C= -1(P_1((12.c.z_1)+P_1)/(2c-\Upsilon h))$$

By putting the values of all parameters of soil and by solving the equation the depth of embedment was available. For the single basement overall depth of excavation level was 5 meters from the top of the diaphragm wall. About excavation depth the embedment depth available was depth 8.85 meters.

2.3.1. Analytical Work Observations

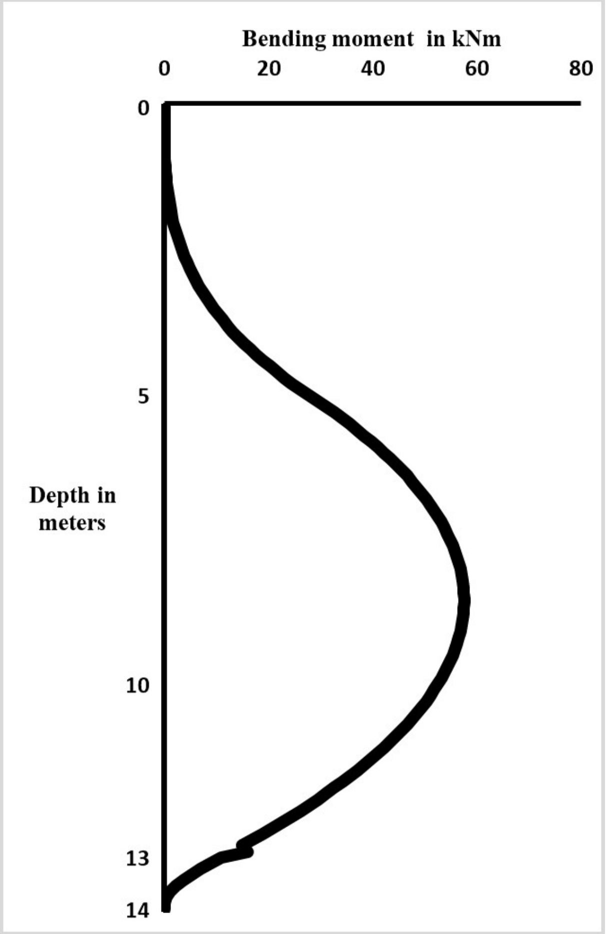

Figure 4. Bending moment diagram

From Figure 4 the maximum moment available was 57.721 kNm at 8.85 meters from the top.

2.4. Numerical Work

Numerical analysis was performed in Plaxis 3D software. The diaphragm wall is modelled as having a thickness of 0.5 meters. The spacing between the pile and diaphragm wall is based on the rules provided by GDCR (General Development Control Regulations). According to GDCR, the margin is provided at a distance ranging from 3 meters to 6 meters. So the spacing between the pile and diaphragm wall was 3 meters, 5 meters and 6 meters. A concentrated load of 280 kN was applied on the pile as represented in Figure 5 and Figure 6. The loading was based on the safe bearing capacity of the foundation. The maximum load that was applied on the foundation was 280 kN and the same was applied on the pile in the Plaxis 3D modelling also. Figure 7 represents the precise orientation of the pile and diaphragm wall. In similar conditions, the pile was spaced at 3 meters, 5 meters and 6 meters.

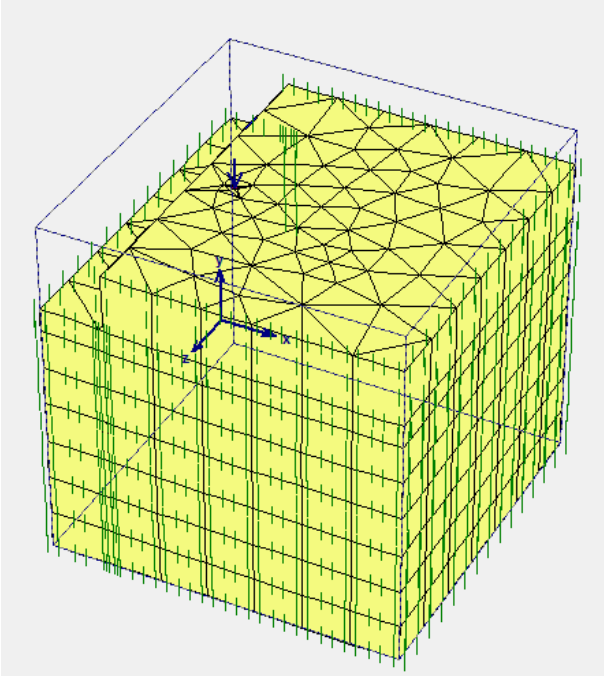

Figure 5. Soil and excavation

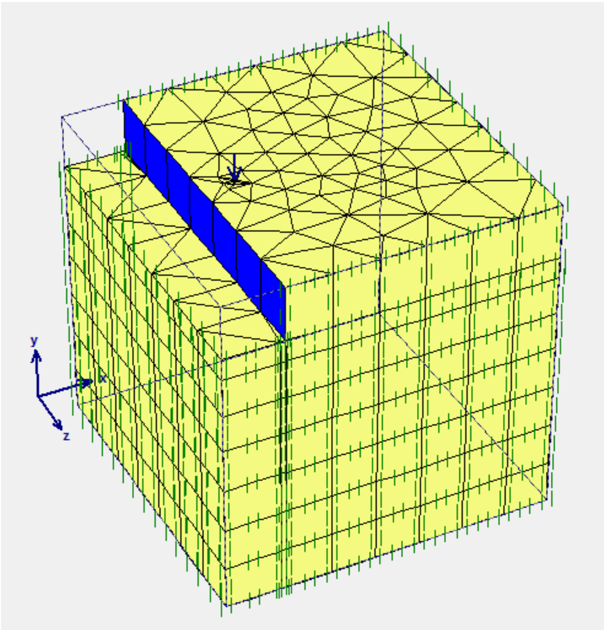

Figure 6. Diaphragm wall and pile with point load

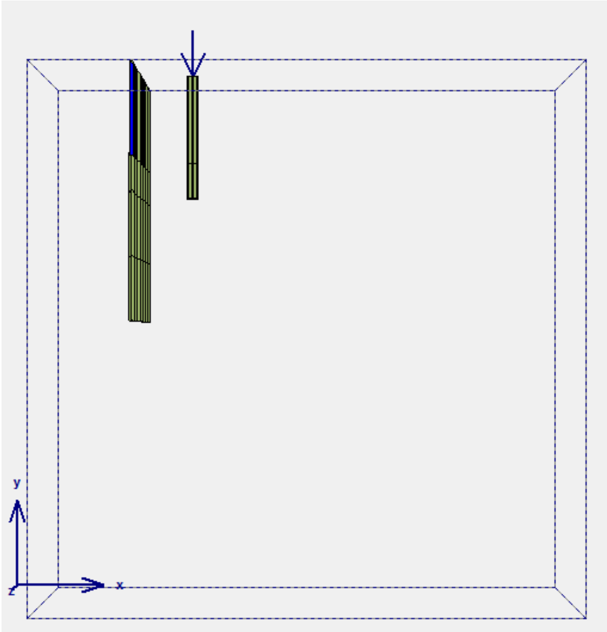

Figure 7. Elevation view

2.4.1. Observations of Numerical Work

The behavior of the diaphragm wall was observed when a concentrated load of 280kN was applied to the pile. The bending moment and deflection of the diaphragm wall were observed. Here Table 3 shows the available bending moment and Table 4 shows the deflection of the diaphragm wall with variation of pile spacing of pile from it.

Table 3. Bending moment

Sr.No.	Pile Diameter	Spacing	Load on Pile	Bending Moment (kNm)
1	0.45	3	280 kN	51.11
2	0.45	5	280 kN	31.76
3	0.45	6	280 kN	31.74

Table 4. Deflection

Sr.No.	Pile Diameter	Spacing	Load on Pile	Total Displacement (mm)
1	0.45	3	280 kN	28.16
2	0.45	5	280 kN	24.29
3	0.45	6	280 kN	24.54

2.5. Experimental Work

The model was prepared for an actual area of 30 meters x 30 meters in the experimental work. The actual depth was 30 meters. The scaled model was prepared for the experimental work. A 1:30 scale was adopted for the experimental work.

2.5.1. Experimental Setup

The model was prepared of 12 mm thickness plywood. A total of four plywood was erected. Four angles were used to provide support. First, all four angles were inserted in the ground at a 1-meter distance and after that plywood was inserted within that angle. The loading frame had a height of 1.83 meters and a width of 1.25 meters. The loading frame is represented in Figure 8.

Following Table 5 are the dimensions of all members of the scale model

Table 5. Model Dimensions

Sr. No.	Member	Dimension
1	Diaphragm wall	17 mm
2	Pile depth	25 cm
3	Pile cap	10 cm x 10 cm
4	Diameter of pile	15 mm

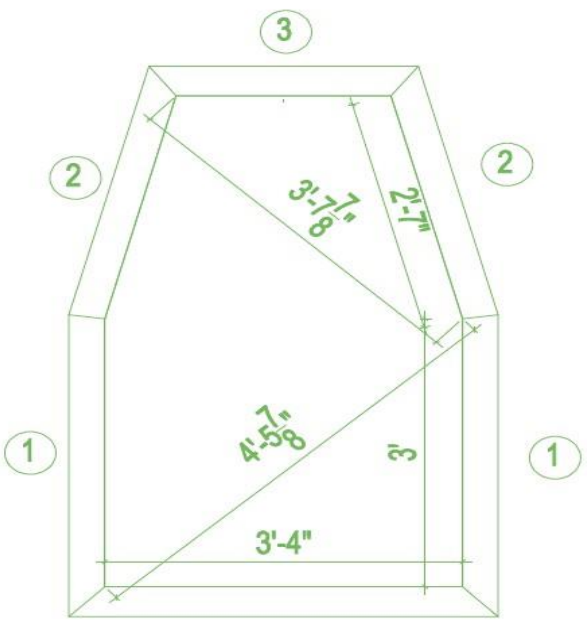

Figure 8. Frame Dimensions

The arrangement of the experimental set-up was such that a frame was prepared of a box section of 12.5 cm x 12.5 cm. The load on the pile was applied through a Hydraulic jack. The hydraulic jack was located at the top of the loading frame. The hydraulic jack was connected with a proving ring for noting down the peak load provided to the jack. The arrangement is shown in Figure 9. The proving ring was then connected to the pile cap. The load is applied till a 2 mm depth of pile is inserted in the soil. The whole procedure was done for the pile at a spacing of 10 cm, 16 cm and 19 cm and the corresponding deflection of the pile and peak load on the pile were noted. In the overall setup, a total of 2 dial gauges were used. One out of two was used in finding the vertical deflection of the pile and another will be used for the horizontal deflection of the diaphragm wall.

Figure 9. Actual Model

2.5.2. Experimental Observation

Table 6. Experimental Observation

Sr. No	Distance between D wall and pile foundation	Peak Load [kg]	Horizontal deflection of D wall
1	10 cm	7.86 kg	0.93 mm
2	16 cm	8 kg	0.808 mm
3	20 cm	10 kg	0.8 mm

Table 7. Scaled Observations

Sr. No	Distance between D wall and pile foundation	Peak Load [kg]	Horizontal deflection of D wall
1	3 m	234 kg	27.9 mm
2	5 m	240 kg	24.4 mm
3	6 m	300 kg	24 mm

It was observed that when the diaphragm wall was at 10-centimetre spacing, it required 7.86 kg to penetrate 2 millimetres in the ground. Similarly, when the spacing increased to 16 centimetres and 20 centimetres, the pile required 8kg and 10 kg to reach the penetration of 2 millimetres. Also, the diaphragm wall showed a maximum deflection of 0.93 millimetres for 10 centimetres spacing which was further reduced to 0.808 millimetres and 0.8 millimetres for 16 centimetre and 20 centimeters spacing (Table 6).

3. Conclusions

The results available from numerical, analytical and experimental work are deflection, bending moment and Peak load.

The embedment depth was finalized from analytical work. The same embedment depth was taken in analytical work, experimental work and numerical work. A bending moment from analytical work was 57.721 kNm and from numerical work was 51.11 kNm. The nearly same bending moment was available from both methods. The deflection of the diaphragm wall at a 3-meter spacing from the pile was 28.16 millimetres and 27.9 millimetres (Table 7) from the numerical method and experimental method. With the increase in spacing between the diaphragm wall and pile, the deflection starts reducing. The embedment depth available from the analytical method was the most efficient, economical and precise one.

The deflection and bending moment increases with the increase in embedment depth with the increase in embedment depth. The passive pressure on the diaphragm wall increases for fixity and along with it active pressure will also increase result in overstress on the Diaphragm wall.

Experimental results show that analytically the diaphragm wall can be made much stable.

The diaphragm wall will be stable if the excavation depth value is less than the ratio of four times the cohesion to the density of soil. Also, the following conditions should be satisfied,

$$C > (h\Upsilon/4)$$

The deflection of the diaphragm wall is not affected by the spacing between the diaphragm wall and pile as deflection was only because of soil pressure.

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