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Parametric Study of Sheet Pile Wall using ABAQUS

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Abstract

In the present study two-dimensional finite element analysis has been carried out on cantilever sheet pile wall using ABAQUS/Standard software to study the effect of different friction angles and its related parameters such as dilation angle, the interfacial friction coefficient between soil-wall on earth pressure distribution, and wall deformation. From the results obtained, it is found that there is a significant decrease in wall deformation with an increase in the angle of internal friction and its related parameters. The earth pressure results obtained from the finite element analysis shared a unique relationship with that of a conventional method. Both the results showed similar linear behavior up to a certain percentage of wall height and then changed drastically in lower portions of the wall. This trend of behavior is seen in both active as well as in passive earth pressure distribution for all the frictional angle. Hence, after comparing the differences that exist in the results for both methods, from the analysis a new relationship between the earth pressure coefficients from a conventional method and the finite element method has been developed for both active and passive earth pressure on either side of the sheet pile wall. This relationship so derived can be used to compute more reasonable earth pressure distributions for a sheet pile wall without carrying out a numerical analysis with a minimal time of computation. And also the earth pressure coefficient calculated from this governing equation can serve as a quick reference for any decision regarding the design of the sheet pile wall.

Keywords: Sheet Pile Wall; ABAQUS; Lateral Earth Pressure; Earth Pressure Coefficient.

1. Introduction

Sheet pile wall has been used for both temporary as well as permanent structures in the earth and waterfront retaining structure. It can either be cantilever or anchored bulkhead type according to the height and design of sheet pile wall [1]. Earth retaining structure and its related earth pressure problem has been an important topic in the field of civil engineering and has attracted various researchers since time immemorial. Many commonly used earth pressure theories, such as Terzaghi (1943); Jumikis (1964); Bowles (1996); Coulomb and Rankine's earth pressure are the conventional design method available, yet they come with shortcomings due to various assumptions and considerations [2-4]. One of the major assumptions made in the conventional design method is the use of triangular earth pressure distribution but in real practice, the earth pressure distribution is not triangular but much more complicated. Another drawback of the conventional design method is the use of constant earth pressure coefficient throughout the wall height for the calculation of earth pressure [5, 6], which may result in the erroneous design of sheet pile wall using conventional design method.

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With the development of computers, analysis using numerical methods are gaining popularity in solving more complicated mathematical models of the soil-wall system. Complex boundary value problems can be solved in simpler manner without compromising on incorporating the realistic soil-profile and other important parameters affecting the earth pressure computation [7-9]. Various investigators studied the numerical models of the soil-wall system using different numerical tools like finite element method, finite difference method, etc. Chugh et al. (2011) reexamined the observed response of field data and found that the conventional method of earth pressure calculation using a coefficient of earth pressure is unsatisfactory whereas numerical analysis results are in good agreement with field data [4]. Hazarika and Matsuzawa (1996) proposed a new numerical method for analysis of active earth pressure of rigid retaining wall for different modes of wall displacement and they also exposed the shortcomings of the conventional method of analysis [2]. Tang et al. (2018) carried out a parametric study considering the effect of pile length, sheet's location, cross-section, and stiffness of pile using FEM. They compared the results with the traditional method and proposed a simplified earth pressure diagram [5]. Benmeddour et al. (2012) carried out a numerical study on a rigid retaining wall investigating the effect of various mechanical and geometrical properties of backfill. From the analysis, they found that the earth pressure coefficient was highly influenced by the crest of the slope and the wall [7]. Choudhury et al. (2006) developed a design method to calculate the penetration depth of the sheet pile wall, which takes into account wall friction and partial mobilization of passive pressure [10]. Day and Potts (1998) carried out series of finite element analyses on retaining walls and found that earth pressure distribution on the wall was affected by maximum wall friction angle and deformation was affected by the dilation properties of the interface element [11]. Bilgin (2012) carried out a numerical analysis on anchored sheet pile wall to investigate the behavior of lateral earth pressures, bending moments, and anchor forces of single-level anchor sheet pile walls and developed a new earth pressure coefficient which takes stress around anchor and wall into consideration [12].

From the literature study, it is observed that FEA results give a more reasonable earth pressure distribution in comparison to a conventional design method. It is also seen that earth pressure behavior and coefficients of earth pressure are largely affected by friction angle and its parameters [13, 14]. So to understand the realistic behavior of sheet pile walls, a present parametric study is carried out, considering its focus on friction angle and its related parameters. For the FEA analysis FEM software, ABAQUS/Standard is used, which is found to have a very good interface processing function for simulating the realistic soil-wall behavior. The results obtained from the analysis using ABAQUS/Standard are reliable and are well adapted for geotechnical problems [15-17]. The results for the present parametric study are obtained from FE analysis based on the lateral deflection and earth pressure distribution, which is later analyzed and compared with the results of a conventional method. Further, a new relationship between conventional earth pressure coefficient and that obtained from FEA is proposed, which can be used to calculate and present more reasonable earth pressure distribution for more accurate design of cantilever sheet pile wall without carrying out the FE analysis, for speedy analysis and accurate design.

2. Numerical Modelling Procedure

2.1. Method of approach

In the present paper, a parametric study is carried out to investigate the influences of various friction angle, $\phi = 26^0$, 30^0, 36^0, 40^0, 46^0 and its related parameters such as dilation angle, interfacial coefficient friction between soil-wall and further considering the effect of stress around pile wall on the performance of sheet pile wall using FEM as continuum mechanics numerical method. In this study sheet pile wall height of 7.5 m (H) and a width of 0.3 m (B) is taken and the wall dimension is kept unchanged throughout the study. Also, other parameters like material properties of sheet pile wall and soil properties are kept constant. Concrete sheet pile wall of M30 grade with density 2400 Kg/m^3; Youngs modulus 0.24×10^{11} N/m^2; Poisson's ratio 0.17 are adopted from Senthil et al. (2013) [17]. The soil used in the study is considered to be medium dense sand with an unsaturated density of 1700 Kg/m^3; Youngs modulus $0.35\text{x}10^8$ N/m^2; Poisson's ratio 0.35, which are adopted from Bilgin [12]. A nominal cohesion of 0.3 kPa is used for the sake of easy convergence [18]. Other parameters needed for the Mohr-Coulomb model such as the dilatancy angle is taken half of the frictional angle and the interfacial friction coefficient δ between wall-soil is taken 2/3 tan ϕ [5, 11, 14].

2.2. Finite Element Analysis

Figure 1 is a flowchart representing the research methodology followed in the present study. The soil-wall model (Figure 2) developed is analyzed using two-dimensional plane strain analysis in FEM software ABAQUS/Standard. The material of the concrete sheet pile wall is modelled as elastic using a linear isotropic elastic material model whereas soil is modelled using the Mohr-Coulomb model, which considers the soil to be linearly elastic perfectly plastic material. In this study depth of soil below the dredge, the line is taken 2 times wall height as per Bilgin [6]. It is observed that increasing the model boundary width beyond 8 times i.e. 4 times behind and 4 times in front of the wall almost does not have any effect on wall deformation and bending moment. Hence, the width of the soil model behind the wall as well as in front of the wall is taken as 4xH, i.e. 30 m, which makes a total width of the model as 60.3m, including the wall thickness [15, 12, 19]. The type of the element used for the finite element mesh used for the soil-wall system is CPE4 (4 node bilinear plane strain quadrilateral. This element has full integration with 2nd order integration. It has no convergence issue and no hour glassing. To take into account stress concentration near the wall, mesh density is adjusted judiciously from finer mesh near the wall to coarser mesh away from it (Figure 3). The boundary conditions are imposed in the soil-wall model as given in Figure 2 vertical edge boundaries of soil are restrained against horizontal movement ($u1= 0$) and the bottom edge boundary of soil is encastre ($u1= u2= u$R1$= u$R2 $= u$R3=0). A gravitational load of -9.81 m/s^2 is applied in the soil-wall model as a self-weight of soil and concrete sheet pile wall. For considering the influence of soil -wall interaction, a surface to surface contact is used. Where the soil is chosen as a slave surface and concrete wall as a master surface. A penalty tangential interaction and 'hard contact normal condition are specified for both surfaces.

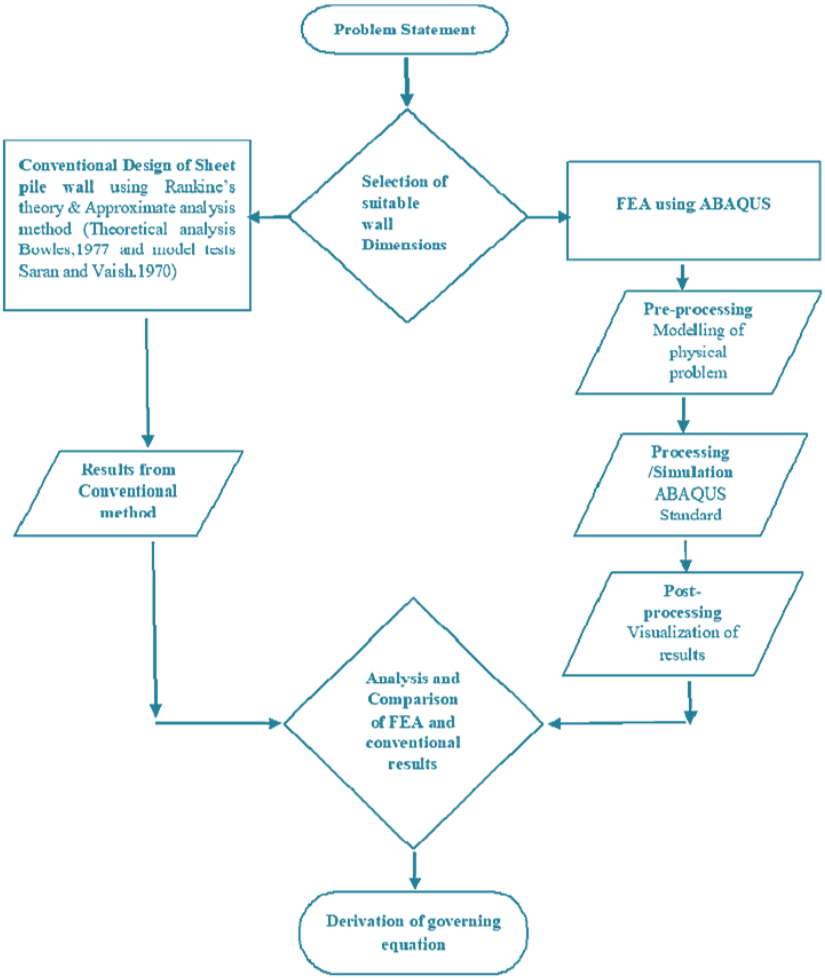


Figure 1. Flow chart of research methodology

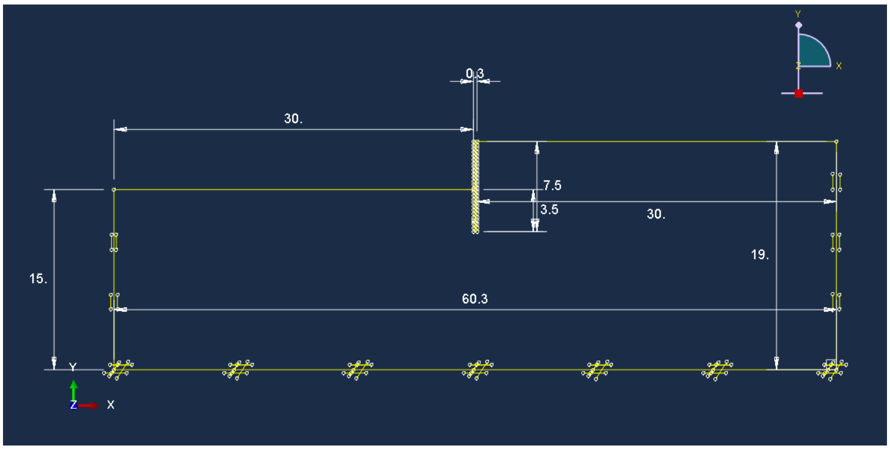


Figure 2. Finite element model of Soil-Wall system

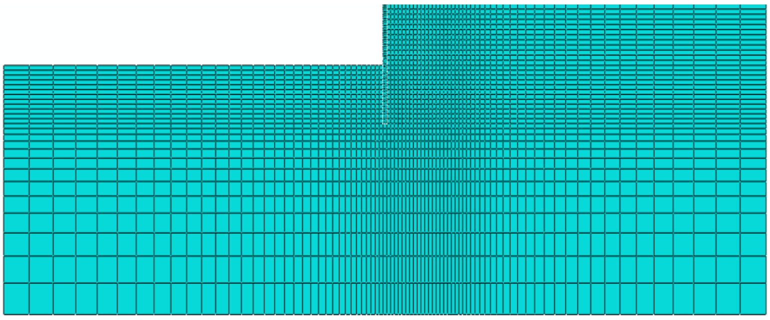


Figure 3. Finite element mesh of Soil-Wall system

3. Results and Analysis

The results from the parametric study carried out corresponding to all cases of the friction angle based on wall deflection and earth pressure distribution are given below. In the results and discussion, some designations are used for the representation of certain conditions and results. For example, in Figure 5 the curves representing the different angle of friction are designated with Pa and Pp where Pa is used for representing the active earth pressure condition whereas Pp is used for passive earth pressure. In Figures 6 to 11, curves representing the results of finite element analysis are designated with FEA and, results of the conventional analysis are designated with Conv. Likewise in Figures 8 to 11, curves representing the results of the proposed active earth pressure coefficient are designated as KaN, and results of the passive earth pressure coefficient are designated as KpN. Lateral wall deformations corresponding to a different angle of internal friction, $\phi = 26^0, 30^0, 36^0, 40^0, 46^0$ of soil are shown in Figure 4. The deflections of the wall away from the soil indicates the active earth conditions behind the wall. From the figure, it is seen that the maximum wall deformation is observed on top of the wall and minimum on the bottom of the wall. It is also seen that there is a decreasing trend of deformation as the angle of internal friction increases. This trend of the result is observed because, with an increase in the angle of internal friction, the interfacial frictional coefficient δ between soil-wall also increases which leads to a decreasing trend of deformation of the wall accordingly. Singh and Chatterjee also observed a similar result when studying the influence of varying soil-wall friction angle on wall deflection of sheet pile wall [20]. From the FEA results it is also observed that, for soil with the angle of internal friction, $\phi = 26^0, 30^0$ the amount of wall movement is larger in comparison to, soil with the angle of internal friction, $\phi = 36^0, 40^{0,} 46^0$. Hence it's quite clear that soil corresponding to an angle of friction $\phi = 26^0, 30^0$ shows a similar behavior likewise soil corresponding to an angle of friction, $\phi = 36^0, 40^0, 46^0$ showed the same similar behavior. So, for the sake of easy comparison, the analysis was carried out categorizing soil into two groups of soil ie, for an angle of friction $\phi = 26^0, 30^0$ and $\phi = 36^0, 40^0, 46^0$.

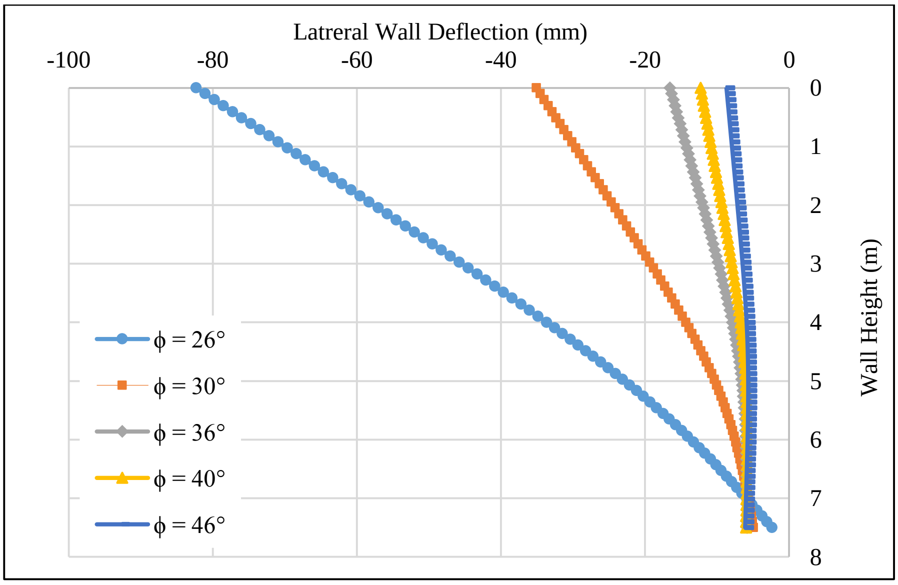


Figure 4. Lateral wall deformation

Figure 5 presents the results for active and passive earth pressure distributions from FEA analysis for all the cases of the angle of internal friction corresponding to $\phi = 26^0, 30^0, 36^0, 40^0$, and 46^0. From both the results of active as well as passive earth pressure distribution, it is visible that with increasing value of the angle of internal friction the lateral earth pressure decreases. This trend of the result is obtained, as the angle of internal friction increases, the wall friction angle δ also increases leading to a decreasing trend of lateral earth pressure. Another trend of result observed from the FEA results above is that the earth pressure distributions corresponding to the angle of internal friction $\phi=26^0$ and 30^0 have different behavioral trends as compared to the angle of internal friction, $\phi=36^0$, 40^0, and 46^0. And this can be seen both in the active as well as in the passive side of the wall. Curves representing the active earth pressure distribution corresponding to the angle of internal friction $\phi=26^0$ and 30^0 show more uniform and linear earth pressure distribution throughout the wall height. Whereas curves representing an angle of internal friction, $\phi=36^0$, 40^0, and 46^0 show more abrupt earth pressure distribution along the wall height. In the passive side of the wall, the curves representing the angle of friction $\phi=26^0$ and 30^0 show more sparsely distributed earth pressure distribution whereas curves representing the angle of internal friction, $\phi=36^0$, 40^0, and 46^0 are more closely packed along the wall height. Benmeddour et al. (2012) carried out a numerical study on the passive and active earth pressure for sand and observed similar behavior on the load-displacement curve. They also reported the effect of ψ on earth pressure coefficient to be more significant for higher internal friction angle, $\phi<30^0$ [7]. So these results from the previous and present study indicate that as the internal friction angle increase, nonlinearity increases, and their behavior changes. These show scope for future research on soil with higher internal friction angle, especially $\phi<30^0$ as their behavior is very unpredictable and unique in nature.

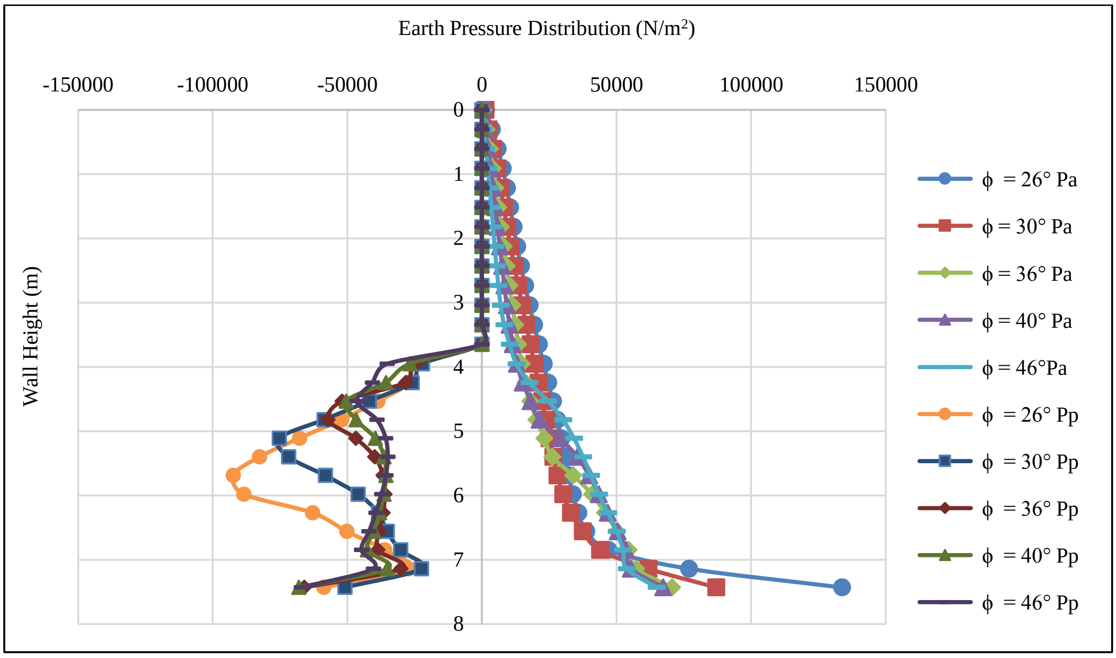
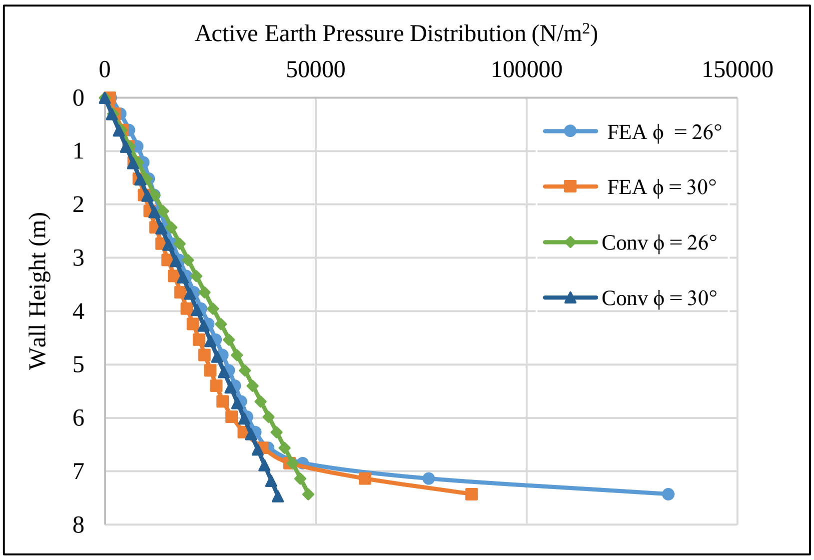


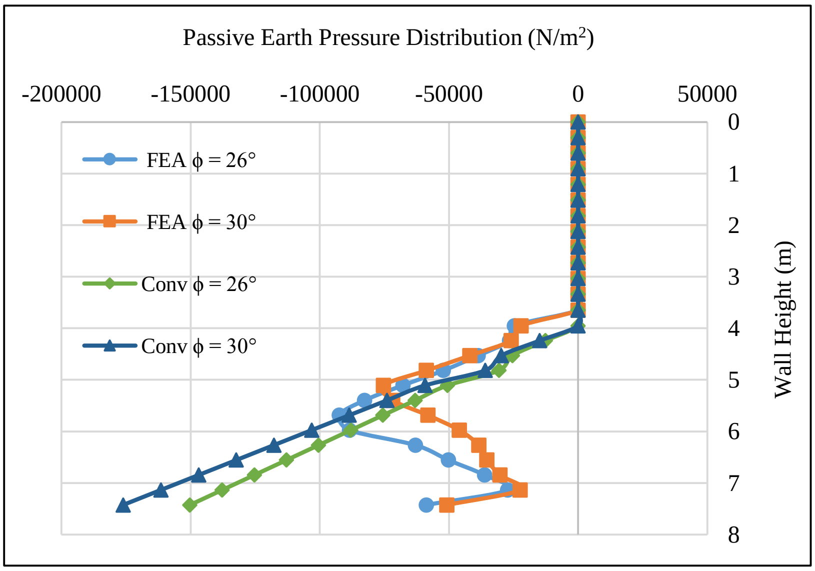
Figure 5. Earth pressure distribution from FEA method

Figures 6 and 7, present the comparative results of active and passive earth pressure of both conventional method as well as FEA analysis methods for an angle of internal friction, $\phi=26^0$, 30^0, and that of $\phi=36^0$, 40^0, and 46^0, Where Figure (a) in both Figures 6 and 7 represents the active earth pressure distribution and Figure (b) represents the passive earth pressure distribution. The results of the conventional method were obtained using the approximate analysis method for cantilever sheet pile wall derived from theoretical analysis and model tests [1]. This method was used as this is simple, easy, and very commonly used by engineers in the field. From results given in Figures 6 and 7 for active earth pressure distribution for both conventional and FEA method, it is observed that earth pressure results from FEA analysis are more or less similar in behavior to the earth pressure from conventional method up to a certain percentage of wall height from the top of the wall. After which the results of FEA in lower portions of the wall show much larger active earth pressure distribution as compared to a conventional method. For the frictional angle, $\phi = 26^0$ and 30^0, the average percentage of wall height up to which it shows a similar trend of behavior is 80% of wall height from the top. And for frictional angles, $\phi=36^0$, 40^0 and 46^0, the average percentage of wall height is 50% of wall height from the top. Also, from the comparative studies of passive earth pressure, it is observed that up to a certain percentage of wall penetration, there is a similar trend of behavior after which the results of FEA show smaller earth pressure values as compared to the conventional method. For the frictional angles, $\phi=26^0$ and 30^0, the average percentage of wall penetration up to which it shows a similar trend of behavior is 40% while for frictional angles, $\phi=36^0$, 40^0 and 46^0, the average percentage of wall penetration is 15%. This unique difference in behavior between results of conventional and FEA, in the lower portion of sheet pile wall, is more prominent in soil with higher friction angle, $\phi<30^0$. This may be due to high stress included due to restrained movement of the wall. And also increasing internal friction may increase the stress concentration that may lead to a change in the relation between different parameters of soil. Hence, this opens up scope for future research and that may unfold many unknown in this area. It is also observed that, for all the cases of an angle of friction corresponding to ϕ=26^0, 30^0, 36^0, 40^0 and 46^0 both the active and passive earth pressure distribution result shows maximum value, at the base of the wall. A Similar trend of results was reported previously in the literature [21, 23, 24]. Many researchers have associated the reason for this behavior as large wall deflection in the higher elevation of the wall and restrained or a very smaller wall deflection in the bottom of the wall.

These differences in results of the earth pressure for conventional and FEA method conforms to the triangular design method used for the earth pressure distribution in the conventional method of analysis in the active as well as the passive side of the wall. However, according to the literature available, it is very well known that actual pressure distribution is quite complicated and not a triangle [5, 6]. Many conventional methods (Terzaghi, Bowles and Rankine, etc.) assume a smooth wall considering wall friction angle δ = 0, [10] which is again not true for real case scenarios. Also, the conventional method of analysis devoid the presence of stress in and around the sheet pile wall which becomes an add on for FEA analysis [12]. Another drawback of the conventional design method is the use of constant lateral earth pressure coefficient throughout the wall height for the computation of earth pressure both in the active and passive side of the wall. From the above results and discussions, it is quite clear that earth pressure calculations using conventional methods may lead to the inaccurate design of sheet pile walls. So for the particular case of the parametric study carried out above, by comparing conventional and FEA results, a relation for earth pressure coefficient from conventional method and earth pressure coefficient from FEA was developed which may be used for more accurate computation of earth pressure distribution and this will lead to the more reasonable design of cantilever sheet pile wall without further carrying out the FEA analysis for the same case.

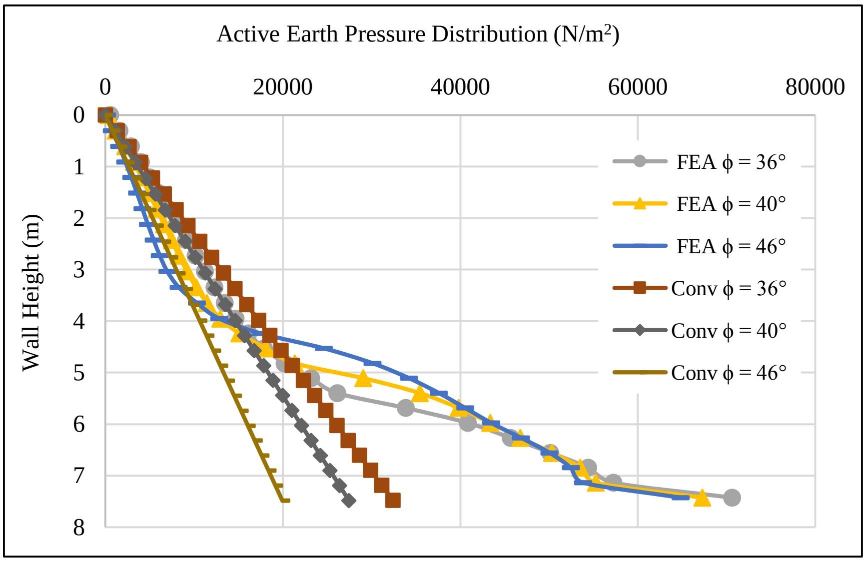


(a) Active earth pressure distribution

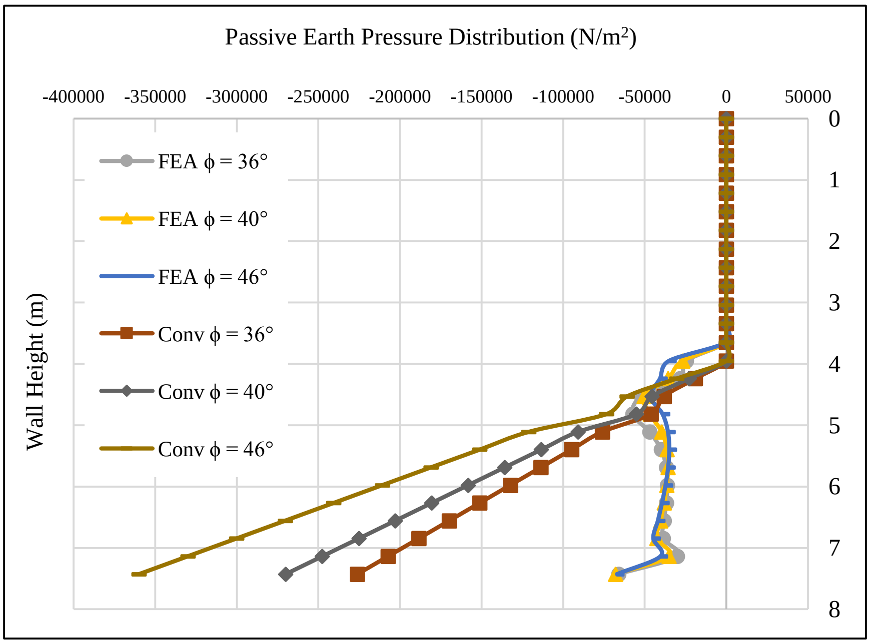


(b) Passive earth pressure distribution

Figure 6. Comparison of active and passive earth pressure: conventional and FEA method (ϕ = 26^0, 30^0)



(a) Active earth pressure distribution



(b) Passive earth pressure distribution

Figure 7. Comparisons of active and passive earth pressure: conventional and FEA method (ϕ = 36^0- 46^0)

Figures 8 and 9 presents the comparative study of earth pressure coefficients for FEA analysis and the conventional method along with the proposed new earth pressure coefficient for a frictional angle, ϕ=26^0, 30^0. Figures 10 and 11 present the same for a frictional angle, ϕ=36^0, 40^0, 46^0. In these Figures, 'Ka Conv' and 'Kp conv' represent the active and passive earth pressure coefficient obtained using Rankine's theory of earth pressure. From the above study, it can be depicted that the coefficient of earth pressure obtained from the conventional method in active side of the wall overestimates the lateral earth pressure in the tip of the wall and slowly comes to constant value till dredge level and then below dredge level earth pressure is underestimated in the conventional method in comparison to FEA analysis. This trend of results can be seen in both categories of soil for a frictional angle, ϕ=26^0, 30^0 and frictional angle, ϕ = 36^0, 40^0, 46^0. But this behavior is more prominent and drastic when it comes to frictional angle, ϕ = 36^0, 40^0, 46^0.

On the passive side of the wall, another trend of behavior has been seen. In this case, at the dredge level, coefficient of lateral earth pressure both from conventional and FEA are quite similar for a frictional angle, ϕ=26^0, 30^0 but for a frictional angle, ϕ=36^0, 40^0, 46^0 conventional value seems to be overestimated especially when it comes to higher friction angle value. It is also observed that the passive earth pressure coefficient starts to decrease from the dredge level till the bottom of the wall and then there is a sudden jump in value for FEA analysis. The reason for this sudden jump in passive earth pressure coefficient value can again be related to stress concentration developed in the base of the wall due to restrained wall movement.

From the results and discussion above it is well understood that there are differences in results from the conventional method and FEA method. So considering these differences in results of wall deformation and earth pressure distribution, and also taking into account the various effects of internal frictional angle, an effort is made to develop a new relationship between earth pressure coefficient from FEA and earth pressure coefficient from conventional. The earth pressure coefficient for FEA is obtained by taking the ratio of horizontal stress (S11) to vertical stress (S22). The stresses S11 and S22 are simulation based results extracted from numerical analysis. And the earth pressure coefficient for conventional is derived from Rankine's earth pressure theory. Using the curve fitting method both coefficients are fitted and the linear equation is generated. In order to avoid the complicated nonlinear equations and for the sake of simplicity in the calculation, two separate linear equations are generated throughout the wall height. The equations are developed for both the active as well as the passive side of the wall. These equations will serve as a link between results from FEA and the conventional method. The earth pressure coefficient calculated from this governing equation may act as a ready reference for any decision regarding earth pressure for sheet pile wall.

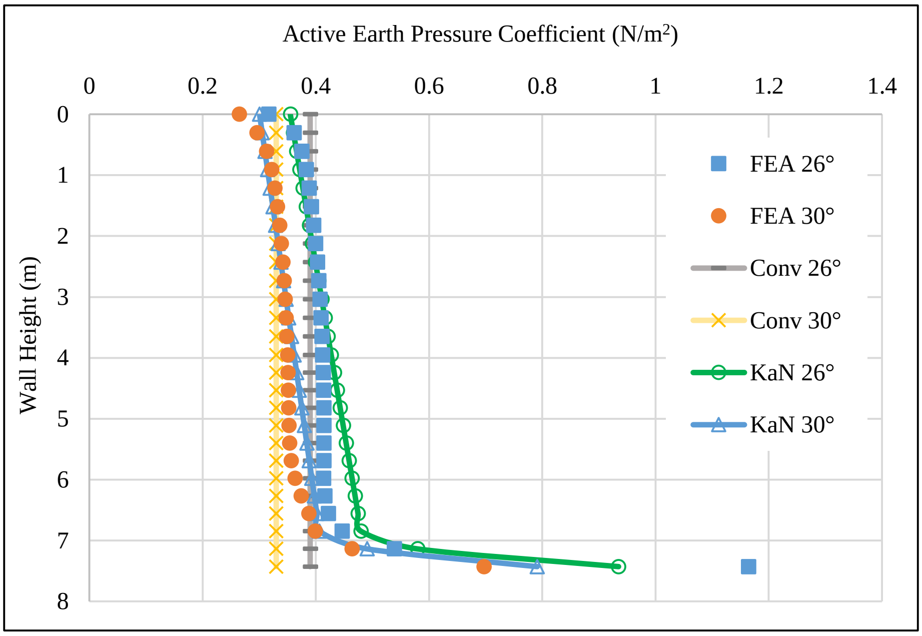


Figure 8. Active earth pressure coefficient Ka (ϕ = 26⁰, 30⁰)

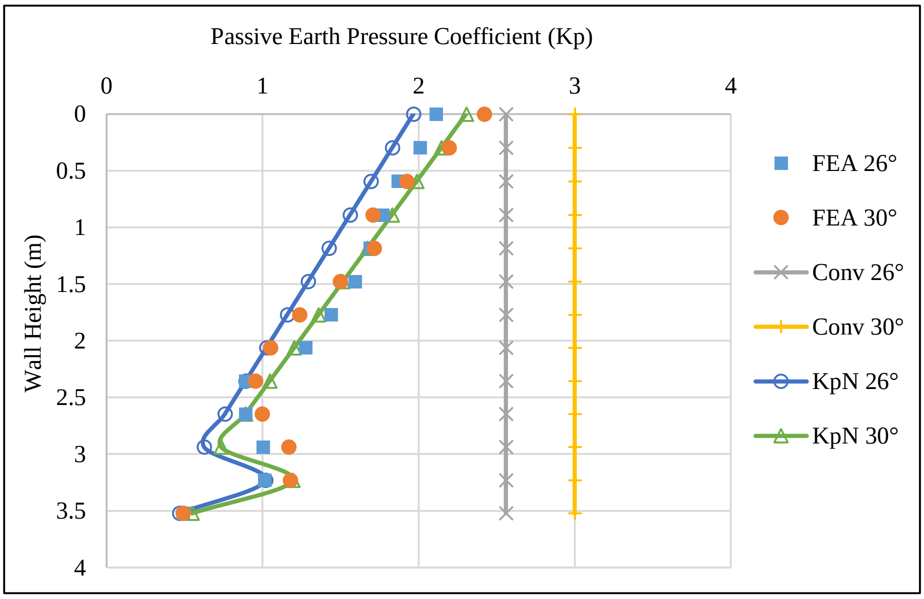


Figure 9. Passive earth pressure coefficient Kp (ϕ = 26⁰, 30⁰)

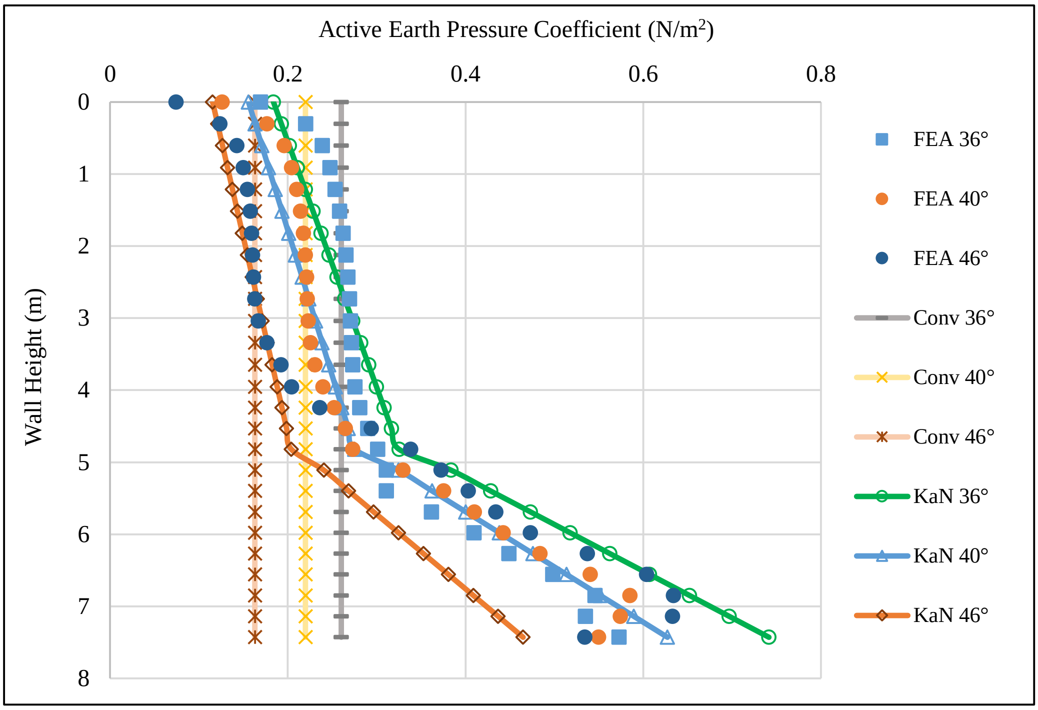


Figure 10. Active earth pressure coefficient Ka (ϕ = 36^0, 40^0, 46^0)

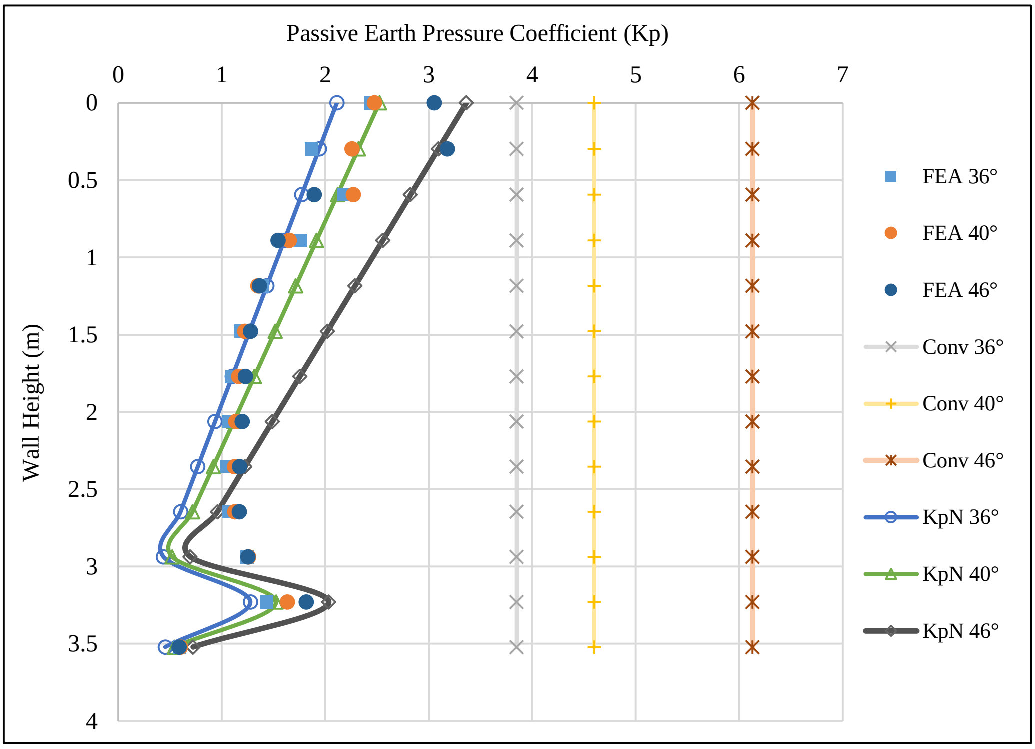


Figure 11. Passive earth pressure coefficient Kp (ϕ = 36^0, 40^0, 46^0)

Based on the results of this parametric study the proposed lateral earth pressure coefficient given below is categorized into two groups of the angle of frictions (ϕ=26^0 to 35^0), (ϕ=36^0 to 46^0) and it is given for both active and passive earth pressure.

The proposed lateral earth pressure coefficient for the angle of frictional (ϕ=26^0 to 35^0) is given as follows.

For active earth pressure:

$$KaN = (\text{h}/21.5587 + 0.9102)\ \text{KaConv.} \quad \text{For}\ \ 0 =< \text{H} =< 6.9043\ \text{m} \tag{1}$$

KaN = (h/0.32 -21) KaConv.

For 7.1956=<H=< 7.5 m (2)

For passive earth pressure:

KpN = (0.7684 - d/5.6088) KpConv.

For 0=<D =< 2.9370 m (3)

KpN = (2.7778 - d/1.3572) KpConv.

For 3.2295m=<D =< 3.5 m (4)

The proposed lateral earth pressure coefficient for the angle of frictional ($\phi = 36^0$ to 46^0) is given as follows.

For active earth pressure:

KaN = (h/8.9516+0.7069) KaConv.

For 0=<H=< 4.8660 m (5)

KaN = (h/1.6928 -1.5715) KaConv.

For 5.1571=<H=< 7.5 m (6)

For passive earth pressure:

KpN = (0.5487 - d/6.7434) KpConv.

For 0=<D=< 2.9370 m (7)

KpN = (2.6927 - d/1.3677) KpConv.

For 3.2295m=<D =< 3.5 m (8)

Where:

KaN = Proposed active earth pressure coefficient;

KpN = Proposed passive earth pressure coefficient;

$Ka\ Conv.$ = Conventional active earth pressure coefficient;

$Kp\ Conv.$ = Conventional passive earth pressure coefficient;

h = wall height from top, at which coefficient is to be found;

d = wall height from dredge line, at which coefficient is to be found;

H = Total wall height from the top;

D = Total depth of penetration.

4. Conclusion

From the present parametric study of sheet pile wall, it is observed that frictional angle, dilation angle, and interfacial friction coefficient between wall and soil has a significant influence on wall behavior. The wall deformation decreases as the frictional angle increases. And it is also seen that soil with frictional angle (ϕ=26^0, 30^0) has a different trend of behavior compared to soil with frictional angle (ϕ=36^0, 40^0, 46^0). These differential group behavior can be seen in results of both wall deflection as well as earth pressure distribution. The increase in frictional angle, dilation angle, and interfacial friction coefficient between wall and soil leads to the unique behavior of earth pressure results for FEA analysis of sheet pile wall. Especially, soil with a higher internal friction angle (ϕ<30^0) has a very unique and unpredictable nature. Further research may unfold many unknowns in this area. The earth pressure distribution results for FEA analysis show similar behavior to conventional methods up to a certain percentage of wall height in active side and up to a certain percentage of wall penetration in passive side as well. For active earth pressure, the percentage of wall height up to which it shows similar behavior is 80% for frictional angle (ϕ=26^0, 30^0) and 50% for frictional angle (ϕ=36^0, 40^0, 46^0). After which the active earth pressure from FEA analysis shows a much larger earth pressure distribution compared to the conventional method. For passive earth pressure distribution, the percentage of wall penetration up to which it shows a similar linear trend of behavior is 40% for frictional angle (ϕ= 26^0, 30^0) and 15% frictional angle (ϕ=36^0, 40^0, 46^0). After which the passive earth pressure from FEA analysis shows smaller earth pressure values compared to the conventional method. After analysis and comparison of results for both FEA analysis and conventional method, a new relationship between earth pressure coefficient from FEA and earth pressure coefficient from conventional is developed. The relation so developed can be used to compute more reasonable earth pressure distribution without carrying out the FEA analysis. Overall this developed earth pressure coefficient will serve as a link between a conventional method and the FEA method.

3. Declarations

3.1. Data Availability Statement

The data presented in this study are available in article.

3.2. Conflicts of Interest

The authors declare no conflict of interest.

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