Estimation of Lateral Earth Pressure on Cantilever Sheet Pile using Flat Dilatometer Test (DMT) Data: Numerical Study

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ABSTRACT: In the present paper, a numerical study has been conducted to estimate the lateral earth pressure acting on cantilever sheet pile using Flat Dilatometer Test (DMT) Data. The numerical analysis is done using computer program FLAC (Fast Lagrangian Analysis of Continua). The unit weight of soil, undrained cohesion, the coefficient of lateral earth pressure at rest, the stiffness of the soil layers are calculated by using the DMT data. The DMT data presented by Anderson et al. (2006) is used in the present study. The results of the present numerical analysis are compared with the measured filed data where Flat Dilatometer Test has been conducted to estimate the soil properties. Based on the numerical results, simplified earth pressure distribution is proposed for cantilever sheet pile.

1 INTRODUCTION

The estimation of lateral earth pressure on cantilever sheet pile below excavation depth is complex in nature as below the excavation depth both active and passive earth pressure act on the sheet pile. Thus, it is necessary to estimate the earth pressure acting on sheet pile (especially below the excavation depth) properly. Very limited studies are conducted to determine the lateral earth pressure on sheet piles. Anderson et al. (2006) conducted DMT testing for the estimation of lateral earth pressure on sheet piles in Piedmont residual soil. Two instrumented flexible retaining walls were used to measure the earth pressure. Ruffing et al. (2011) determined lateral earth pressure in a soil-bentonite slurry trench cutoff wall. Bilgin (2012) proposed new lateral earth pressure coefficients for anchored sheet pile walls considering the stress concentration around the anchor level. The proposed methodology can be used in the design of single-level anchored sheet pile walls to provide more realistic earth pressure distributions acting on the wall. Thus, more accurate wall designs can be made.

In the present paper, a numerical study has been conducted to estimate the lateral active and passive earth pressure acting on cantilever sheet pile using Flat Dilatometer Test data. The earth pressure below the excavation depth is also estimated. The present study is based on Anderson et al.'s (2006): (a) DMT results (b) cantilever behavior observed in the field and both Anderson et al. (2006) and present study have used DMT results to predict cantilever behavior. Based on the numerical results under various excavation depths, thickness of the wall and soil properties, earth pressure distribution is proposed for cantilever sheet pile.

2 NUMERICAL MODELING

The numerical analysis is done using computer program FLAC (Fast Lagrangian Analysis of Continua). The problem is analyzed as plane-strain problem (as shown in Fig. 1). In Fig. 1, D_e is the maximum excavation depth; H is the total length of the sheet pile. The Young's modulus (E_{wall}), cross-sectional area (A_{wall}) and moment of inertia (I_{wall}) are specified for the sheet pile. Due to symmetry, only half portion of the problem (as shown in Fig. 1) is modeled. Thus, the centre of the excavation is taken as one vertical boundary. The other vertical boundary is set at 30m from the wall. The mesh size is selected as 0.1 x 0.2m. The horizontal boundary of the analytical mesh is taken at 20m below ground level. Both horizontal and vertical movements are restrained along the bottom boundary and the vertical boundaries are restrained only against horizontal movements.

The Flat Dilatometer Test data presented by Anderson et al. (2006) has been used in the present study. The profiles of DMT data are shown in Fig. 2. From the DMT data, the soil is classified as silt to clayey silt. The average I_D is taken as 1.1 (<1.2) and undrained shear strength or cohesion (c_u), coefficient of earth pressure at rest (K_0), unit weight (γ), elastic modulus of the soil (E) are calculated based on DMT data. The friction angle of the soil is taken as zero. The average value of K_D and E_D are considered as 6 and 122 bar, respectively. The average c_u value is taken as 47.5 kPa. The average E value of the soil is calculated as 19.5 MPa. The unit weight of the soil (γ) is considered as 18 kN/m^3. The value of K_0 is limited to 1.

An elastic-perfect plastic "Mohr-Coulomb" model has been used to model the soil. Bulk modulus (K) and shear modulus (G) are calculated as:

$$K = \frac{E}{3(1-2\mu)} \tag{1}$$

$$G = \frac{E}{2(1+\mu)} \tag{2}$$

where, μ is the Poisson's ratio of soil. The Poisson's ratio of soil is varied from 0.3 to 0.45. The interface parameters, including the adhesion, normal and shear stiffness (K_n and K_s) are estimated from soil parameters *i.e.* cohesion, bulk modulus and shear modulus. The interface normal and shear stiffness are selected, such that the stiffness is approximately ten times the equivalent stiffness of the stiffest neighboring zone as suggested by FLAC manual (Itasca, 2005). The values of the equivalent stiffness of a zone normal to the interface is given by

$$\frac{(K + \frac{4}{3}G)}{\Delta z_{min.}} \tag{3}$$

where, $\Delta z_{min.}$ is the smallest width of an adjoining zone in the normal direction to the interface. The value of interface normal and shear stiffness *i.e.* K_n and K_s are taken as 2.6x10^9 N/m^2. The interface adhesion is taken as (2/3) of the soil cohesion. The value of Young's modulus (E_{wall}) of the steel pile is taken as 200 GPa. The wall is modeled as beam elements and with value of Young's modulus as E_{wall} /(1-μ_{wall}^2) in order to represent plane stress formulation for the structural elements in the plane-strain condition of a continuous wall as mentioned in the FLAC manual.

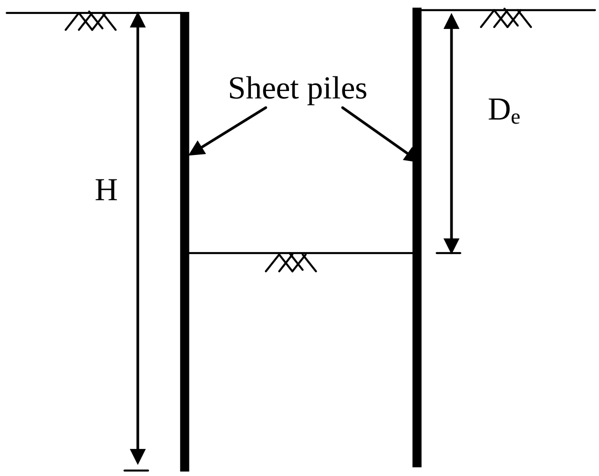


Fig.1 Cross sectional view of the chosen problem of cantilever sheet pile

3 RESULTS AND DISCUSSION

To validate the present numerical model, the results obtained from the present numerical study are compared with the field results of a cantilever sheet pile of length 10.4 m as presented by Anderson et al. (2006). The maximum excavation depth was 6.1 m. Thus, embedded depth was 4.3 m. The sheet pile section was chosen as PZ22. Inclinometers and strain gauges were used to measure wall defection, earth pressure acting on the wall.

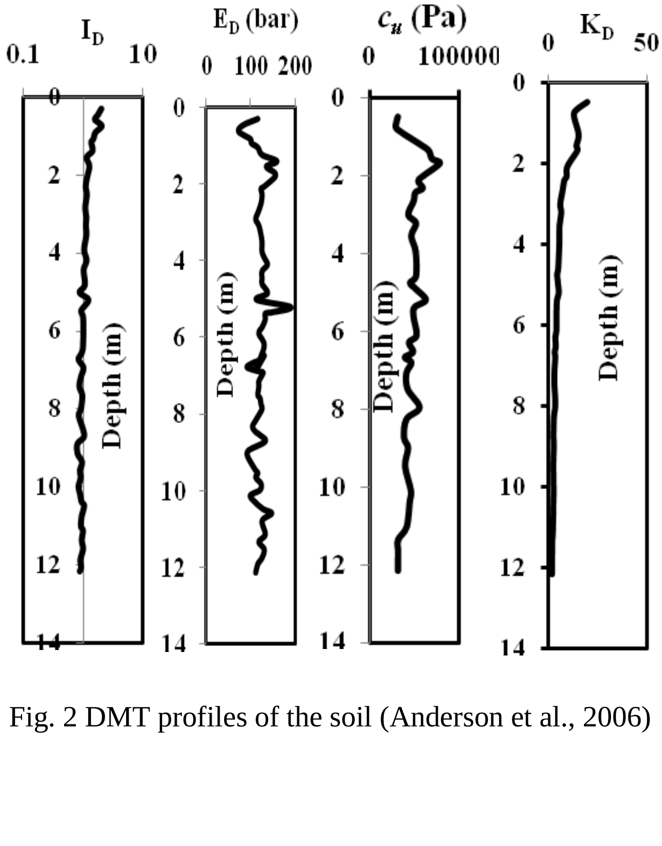


Fig. 2 DMT profiles of the soil (Anderson et al., 2006)

Fig. 3 and Fig. 4 show the lateral displacement and net earth pressure profile obtained from present study and from field data, respectively. Similar trend of results has been observed between both the studies. In the field, the separation between the wall and soil was observed at around 3m and deeper. From the present study also negative earth pressure is observed up to 4.4 m. In the field, the maximum wall deformation (at the top of the wall) at 6.1m excavation depth was observed around 24 mm and from the present study, the maximum defection value (at the top of the sheet pile) is obtained as 23mm. However, difference between the lateral displacement values obtained in the field and present study is slightly more at the base of the sheet pile.

Anderson et al. (2006) also conducted numerical analysis by using finite element tool PLAXIS to determine the earth pressure, bending moment and shear force in the sheet pile wall. However, the results predicted by the Anderson et al. (2006) and present study are different due to the fact that in the present study DMT based c_u value is considered whereas, the active earth pressure presented by Anderson et al. (2006) is based on DMT and CPT ϕ value. Thus, the active earth pressure based on DMT ϕ value increases with depth (Anderson et al., 2006), whereas negative earth pressure is observed up to 4.4 m from the present study based on DMT c_u value. In the field also the separation between the wall and soil (negative earth pressure) was observed at around 3m and deeper. Anderson et al. (2006) also presented earth pressure acting on sheet pile at rest condition based on DMT ϕ value and as expected at rest earth pressure is higher than the active earth pressure acting on sheet pile wall.

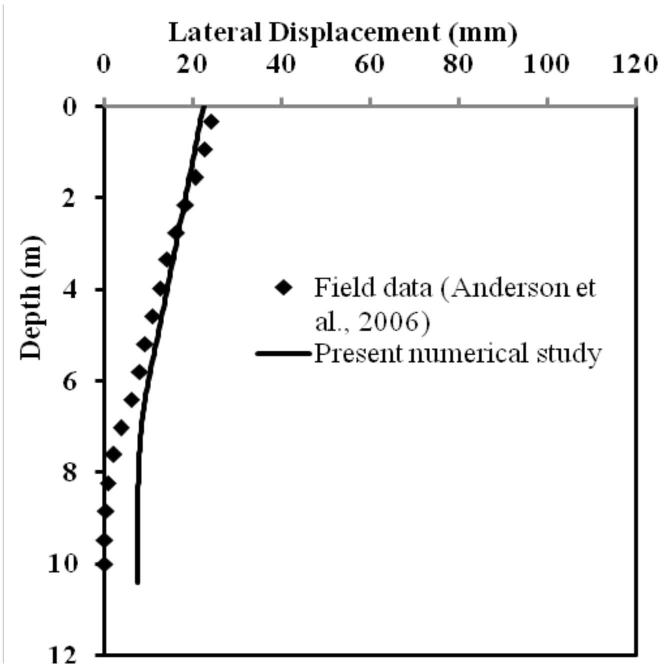


Fig. 3. Comparison of the lateral displacement profile obtained from present study and from field data

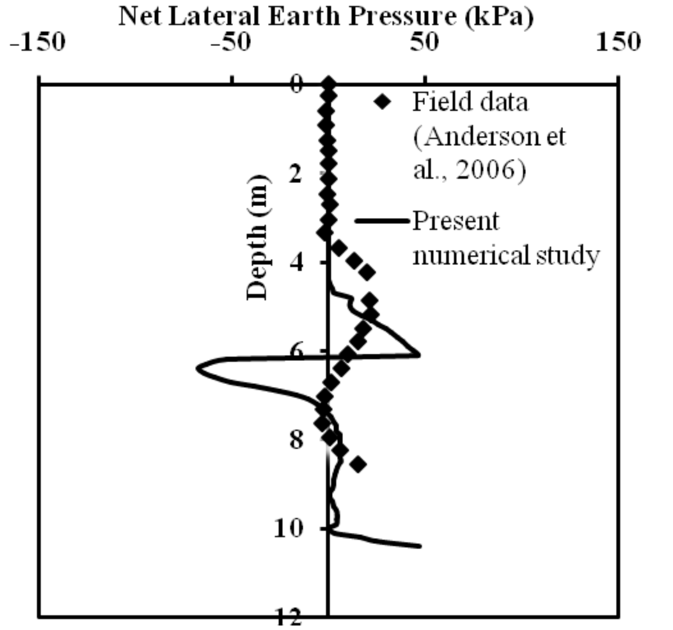


Fig. 4. Comparison of the net earth pressure profile obtained from present study and from field data

Fig. 5 shows the effect of sheet pile thickness on the earth pressure distribution. Different types of sheet pile sections are used in the study. As excepted sheet pile thickness is not affecting the earth pressure distribution significantly. Fig. 6 shows the effect of sheet pile length on earth pressure distribution. During this parametric study, depth of excavation is kept constant (6.1m). Similar trend is observed between the earth pressures distributions obtained with different sheet pile lengths. The maximum passive and active earth pressure values are almost same for different sheet piles with same soil profile.

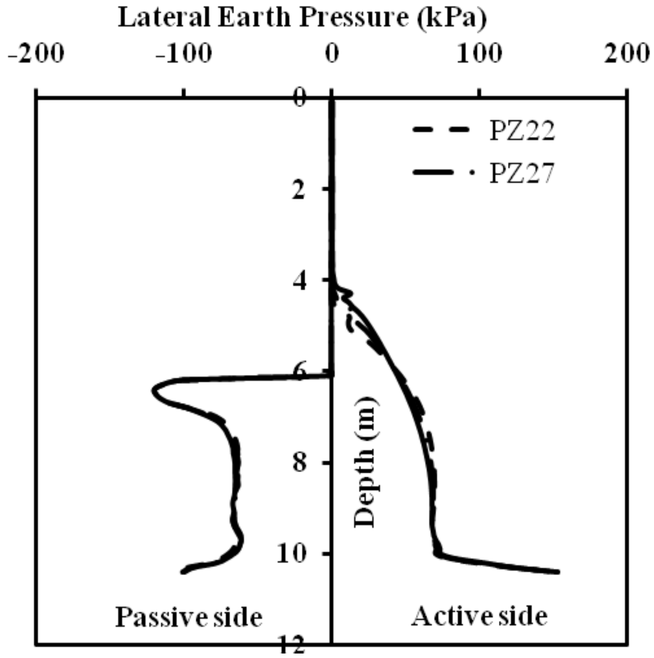


Fig. 5. Effect of sheet pile thickness on earth pressure

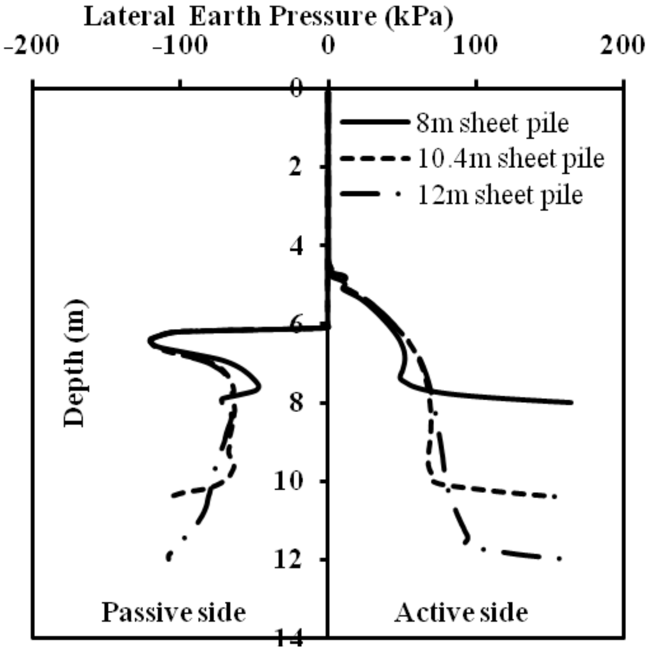


Fig. 6. Effect of sheet pile length on earth pressure

Fig. 7 shows the effect of excavation depth on earth pressure distribution keeping same sheet pile length (10.4m). Similar trend is observed between the earth pressures distributions obtained with different excavation depths. The maximum passive and active earth pressure values are almost same for different excavation depths with same soil profile. Fig. 8 shows the effect of Poisson's ratio of soil (μ) on earth pressure distribution. It is observed that Poisson's ratio of soil doesn't have significant effect on earth pressure distribution.

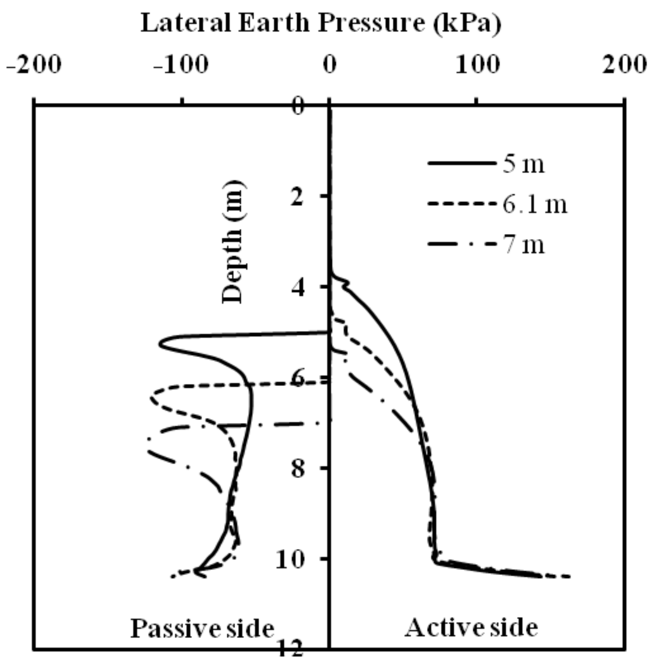


Fig. 7. Effect of excavation depth on earth pressure

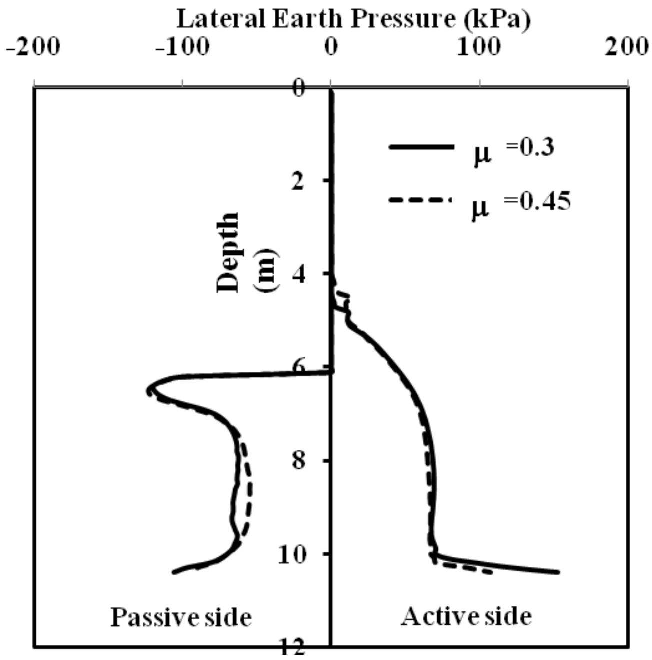


Fig. 8. Effect of μ on earth pressure

Fig. 9 shows the effect of soil consistency on earth pressure distribution. All the other studies are conducted with average K_D value of 6 and corresponding c_u value 47.5 kPa. During variation of soil cohesion value, two different c_u values (average) are selected (25 kPa and 100 kPa) and corresponding K_D values are determined. From the DMT profiles, other model parameters are determined based on the calculated K_D values. From the Fig. 9 it is observed that for c_u values 47.5 kPa and 100 kPa similar trend of earth pressure distribution is observed. However, for c_u value 25kPa different pressure distribution trend is observed.

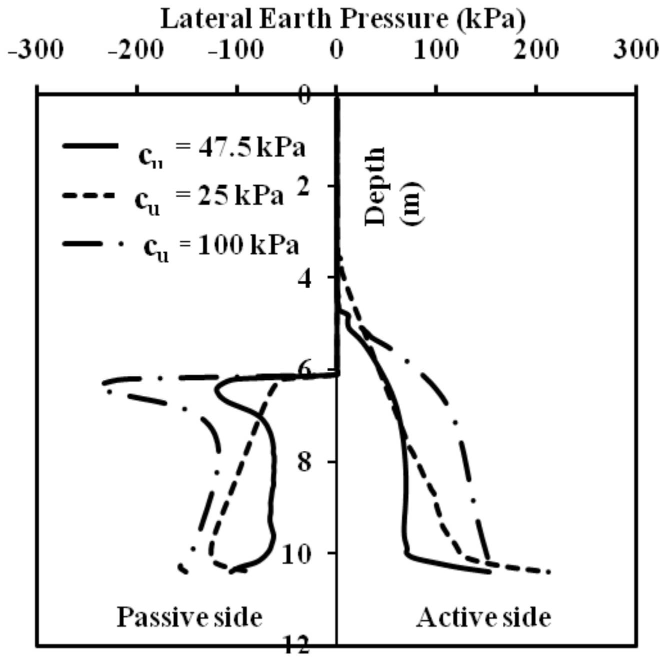


Fig. 9. Effect of soil consistency on earth pressure

Figs. 10, 12 and 14 show the effect of K_0 on active and passive earth pressure distribution of soil with stiff (c_u = 100 kPa), medium (c_u = 47.5 kPa) and soft (c_u = 25 kPa) consistency, respectively. Similarly, Figs. 11, 13 and 15 show the effect of K_0 on net earth pressure distribution of soil with stiff, medium and soft consistency, respectively. The value of K_0 is limited to 1 and varies from 0.54 to 1. It is observed that K_0 doesn't have any effect on active, passive as well as net earth pressure distribution in case of soft soil. In case of stiff soil, active and passive earth pressures significantly change with K_0. However, K_0 doesn't have any significant effect on net earth pressure distribution below excavation depth for stiff soil. Although, the net earth pressure above the excavation depth (basically the active earth pressure) changes with K_0. In case of medium soil, K_0 has significant effect on active, passive and net earth pressure distribution. For lower K_0 value, earth pressure distribution of medium soil follows the similar trend of the earth pressure distribution observed in case of stiff soil. However, for higher K_0 value, earth pressure distribution of medium soil follows the similar trend of the earth pressure distribution observed in case of soft soil. Thus, earth pressure distribution is transition in nature in case of medium soil. From the above discussion it can be said that K_0 value of the soil plays an important role on the earth pressure distribution of cantilever sheet pile especially above the depth of the excavation for sheet pile in medium and stiff nature of soil.

Fig. 10. Effect of K_0 on earth pressure (soil with stiff consistency, c_u = 100 kPa)

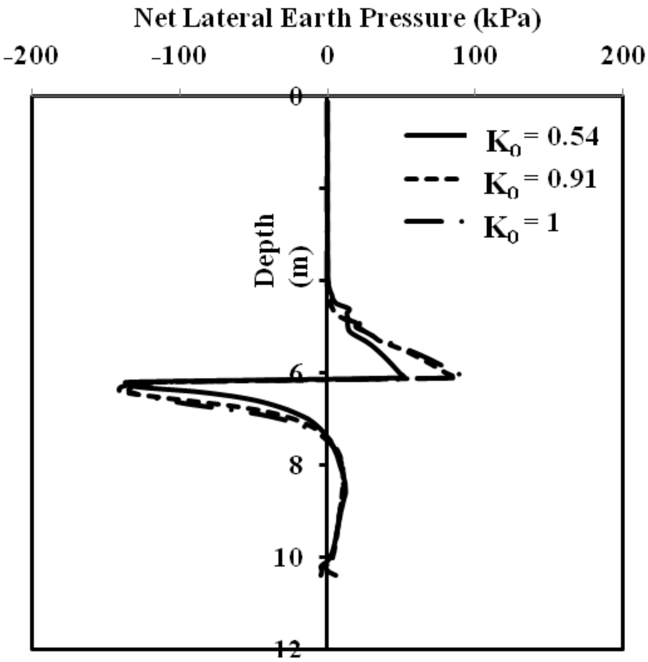
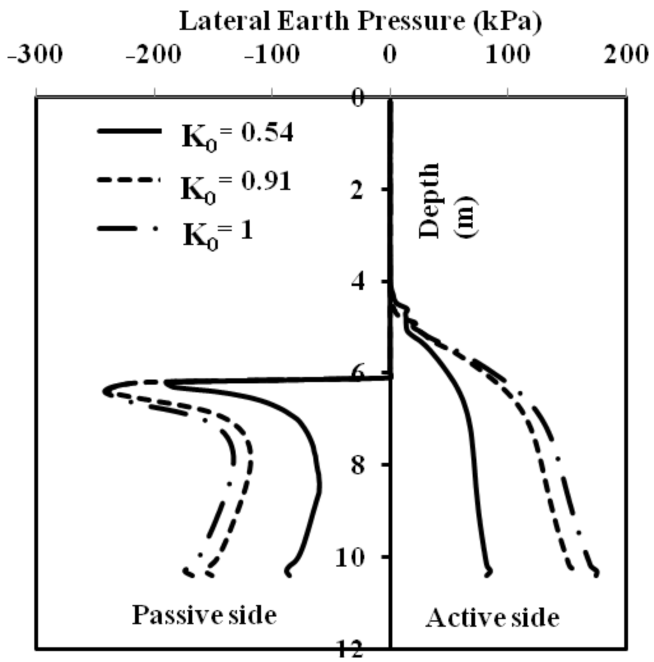


Fig. 11. Effect of K_0 on net earth pressure (soil with stiff consistency, c_u = 100 kPa)

Fig. 16 shows that even for soft soil also net pressure distribution can be similar to the net pressure distribution of stiff soil when deformation of the wall is small (or similar to stiff soil). Thus, deformation of the sheet pile is also a very important factor to choose proper earth pressure distribution along with the type of soil.



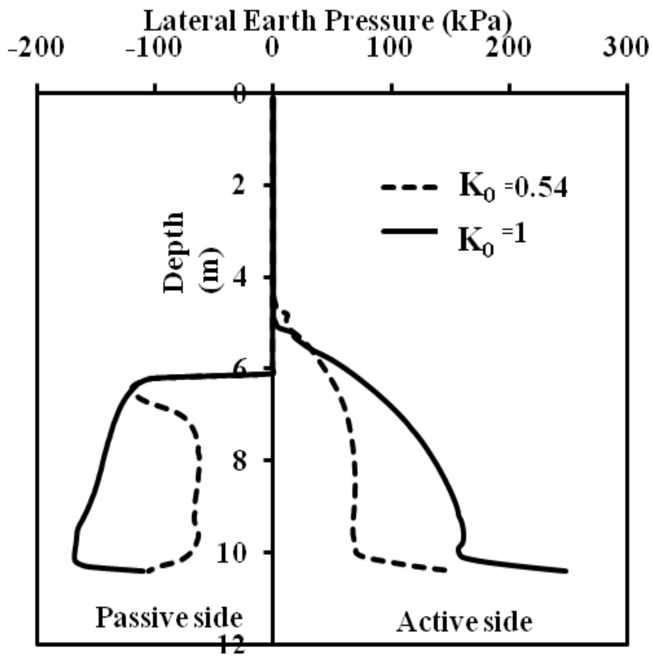


Fig. 12. Effect of K_0 on earth pressure (soil with medium consistency, c_u = 47.5 kPa)

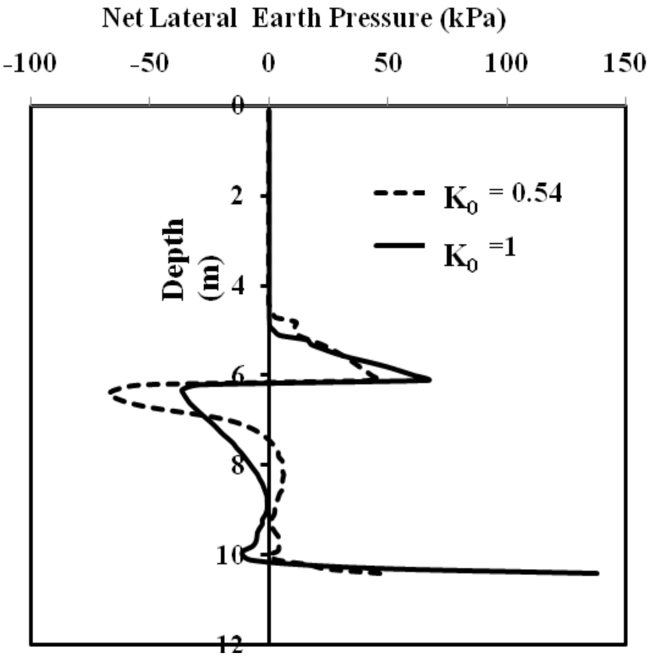


Fig. 13. Effect of K_0 on net earth pressure (soil with medium consistency, c_u = 47.5 kPa)

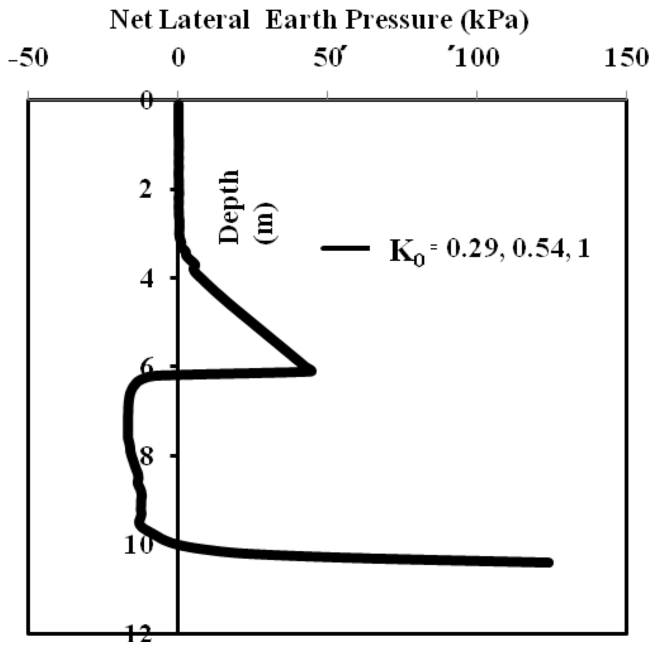


Fig. 15. Effect of K_0 on net earth pressure (soil with soft consistency, c_u = 25 kPa)

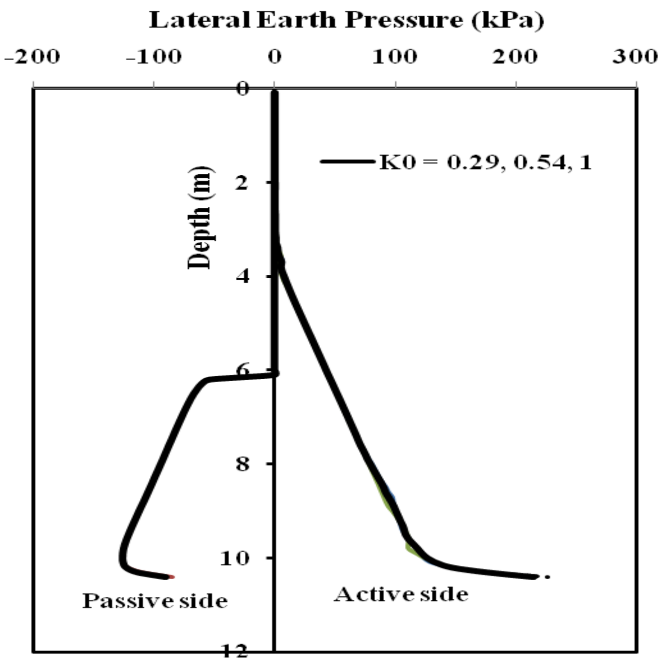


Fig. 14. Effect of K_0 on earth pressure (soil with soft consistency, c_u = 25 kPa)

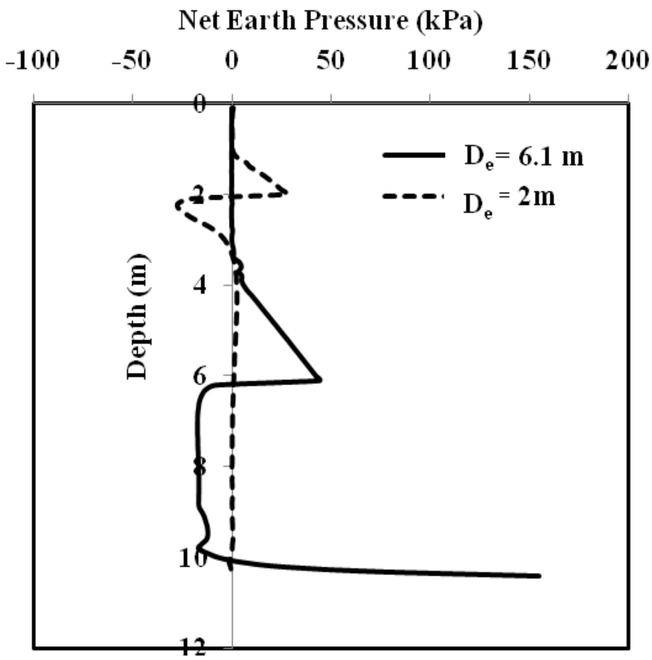


Fig. 16. Effect of deflection of sheet piles on earth pressure (c_u = 25 kPa, K_0 =1) [2m excavation depth has

smaller sheet pile deformation as compared to the 6.1 m excavation depth]

The results show mainly two types of definite pressure distribution one for soil with stiff consistency (or lower amount of sheet pile deformation) and other for soil with soft consistency (or higher amount of the sheet pile deformation). In case of medium soil (or medium deformation of the sheet pile), trend of pressure distribution is in between the trends observed for soft and stiff soil. Based on the observed pressure distribution diagrams, simplified earth pressure distributions are proposed for soil with soft and stiff consistency or sheet piles with higher and lower amount of deformation. Fig. 17 shows the simplified net earth pressure distribution for sheet pile with lower amount of deformation. Fig. 18 and Fig. 19 show the simplified active-passive and net earth pressure distribution, respectively for sheet pile with higher amount of deformation. The correlations or values are also suggested in the graphs in terms of soil properties obtained from DMT data. However, proposed distribution is based on the observed results from numerical analysis and from the numerical study it is noticed that for all the cases sheet pile rotates about its base and pile deflects totally towards the same direction (Fig. 3). More studies have to be conducted for various wall or pile rotation condition (*i.e* if pile rotates about a point above base) to get generalized pressure distribution trends under various wall rotation conditions. In the diagram (Fig. 17), the value of $0.25D_e$ (or $0.2D_e$) is an average value. Actually, the value increases with the increase in depth of excavation. The range of sheet pile deformation has to be studied to use the proper earth pressure distribution.

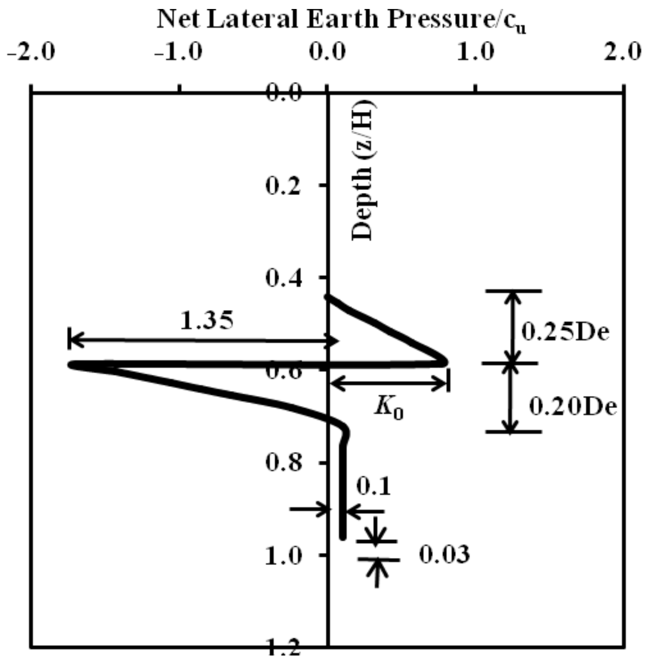


Fig.17. Simplified proposed net earth pressure distribution (for lower sheet pile deformation)

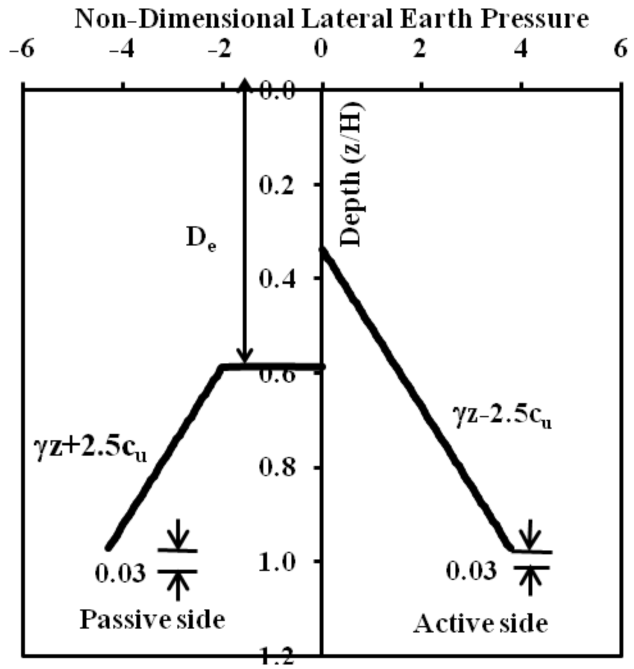


Fig. 18. Simplified proposed active and passive earth pressure distribution (for higher sheet pile deformation)

This is to be noted that the proposed simplified earth pressure distributions in the present paper are obtained based on the DMT data. However, the distributions are general in nature. The proposed distributions can be used for similar type of soil condition and sheet pile deformation.

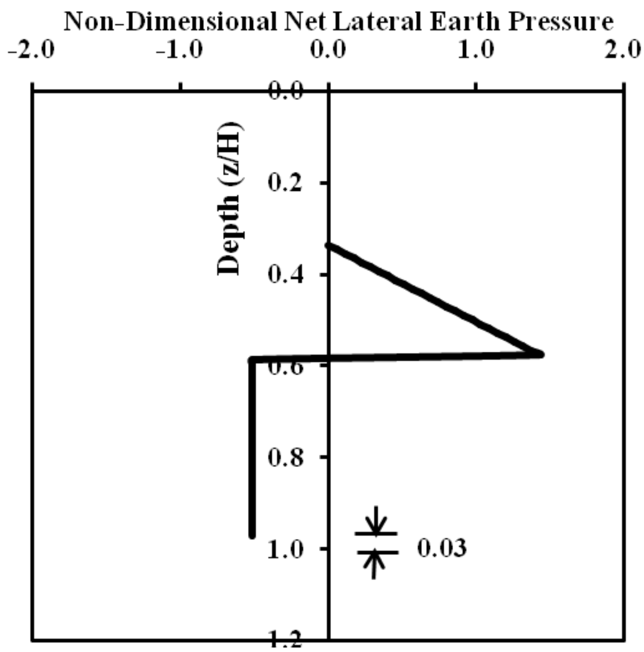


Fig.19. Simplified proposed net earth pressure distribution (for higher sheet pile deformation)

4 CONCLUSIONS

From the present study, the following conclusions can be made.

- The results of the present study show mainly two types of definite pressure distribution one for stiff soil (or sheet pile with lower amount of deformation) and other for soft soil (or sheet pile with higher amount of deformation). In case of medium soil or medium sheet pile deformation, trend of pressure distribution is in between the trends observed for soft and stiff soil.
- Sheet pile thickness is not affecting the earth pressure distribution significantly.
- Similar trend is observed between the earth pressures distributions obtained with different excavation depths. The maximum passive and active earth pressure values are almost same for different excavation depths with same soil profile.
- Poisson's ratio of soil doesn't have significant effect on earth pressure distribution.
- K_0 plays an important role on the earth pressure distribution of cantilever sheet pile especially above the depth of the excavation for sheet pile in medium and stiff nature of soil. Deformation of the sheet pile is also a very important factor to choose proper earth pressure distribution along with the type of soil.
- Based on the observed pressure distribution diagrams, simplified earth pressure distributions are proposed for soil with soft and stiff consistency or sheet piles with higher and lower amount of deformation. The correlations or values for the pressure distribution are also suggested based on the soil properties obtained from DMT data. However, the proposed approximate correlations or values are to be verified with further studies. The proposed simplified earth pressure distributions are obtained based on the DMT data, but the distributions are general in nature. The proposed distributions can be used for similar type of soil condition and sheet pile deformation.

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