

Evaluation of Unsaturated Layer Effect on Seismic Analysis of Unbraced Sheet Pile Wall

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Abstract

This paper is built upon the previous developments on lateral earth pressure by providing a series of analytical expressions that may be used to evaluate vertical profiles of the effective stress and the corresponding suction stress under steady-state flow conditions. Suction stress profile is modeled for one layer sand near the ground above the water level under hydrostatic conditions. By definition, the absolute magnitude of suction stress depends on both the magnitude of the effective stress parameter and matric suction itself. Thus, by developing the Rankine's relations in seismic state, the composing method of active and passive surfaces in sides of unbraced sheet pile is examined and the effects of soil parameter on those surfaces are evaluated by a similar process. The relations described the quantitative evaluation of lateral earth pressure on sheet pile and the effects of unsaturated layer on bending moment and embedded depth of sheet pile in soil.

Keywords

Unbraced Sheet Pile, Suction Stress, Effective Stress Parameter, Lateral Earth Pressure, Embedded Depth

1. Introduction

Computation of the lateral earth pressure is extremely important and it is the basic data required for the design of geotechnical structures like the retaining walls moving towards the backfill, the sheet piles, the anchors etc. The level of importance of the lateral earth pressure increases many folds under the earthquake conditions due to the devastating effects of the earthquake. Hence, to design the sheet pile both under the static and seismic conditions, the basic theory is very complex and several researchers have discussed on this topic. Initially Okabe [1] and Mononobe and Matsuo [2] had proposed the theory to compute

the static lateral earth pressure on the wall, which is commonly known as the Mononobe-Okabe method (see Kramer [3]).

Again, by using an approximate method based on a modified shear beam model Wu and Finn [4] developed charts for seismic thrusts against rigid walls. After a design method by considering the surcharge and using Mononobe-Okabe method, Caltabiano *et al.* [5] proposed a design method for retaining wall by considering the effect of seismic accelerations on both the soil and wall. Nadim and Whitman [6] had further proposed a new seismic design method for the gravity retaining wall, based on the earthquake induced permanent displacement of the wall considering the effects of ground motion amplification. In recent past, Morrison and Ebeling [7], Soubra [8], Kumar [9], Choudhury and Subba Rao [10], Choudhury *et al.* [11], Subba Rao and Choudhury [12] and few others had proposed the seismic design of a retaining wall under the lateral earth pressure condition. These theories consider the static method of analysis, *i.e.* without considering any time dependent behavior of the soil and the wall. In most of the design methods proposed by the previous researchers, the effects of seismic accelerations were considered only on the soil wedge but not on the wall. But under the earthquake condition, it is obvious that both the soil and the wall will experience the seismic accelerations in both horizontal and vertical directions and the analysis should deal with the effect of the earthquake on both the soil and wall while analyzing the earth pressure problems. Rectifying this drawback, initially Richards and Elms [13] had suggested a new design method for the gravity retaining wall by considering the effect of seismic accelerations on both the soil and the wall under the lateral condition of earth pressure. From this work, it was clear that both the soil and the wall inertia effect must be considered for seismic design of a retaining wall. But the similar consideration of both the soil and the wall inertia effects for seismic design of a retaining wall under the passive condition of earth pressure is still scarce. Recently, based on the dynamic method proposed by Steedman and Zeng [14], Zeng and Steedman [15], Choudhury and Nimbalkar [16] for the active earth pressure condition, Choudhury and Nimbalkar [17] [18] had proposed the theory to compute the seismic passive earth pressure by dynamic method by considering both the shear and the primary waves propagating through the soil with a time variation. But the analysis did not consider the effect of the amplification and the wall inertia in the seismic design of the wall, hence leading to an incomplete analysis for design purpose of the wall. Again the recent research by Choudhury and Nimbalkar [19] shows the need of seismic design of retaining wall under passive earth pressure condition by considering the rotational stability of the wall. However, another important displacement-based sliding stability analysis for the design of retaining wall is still scarce. Hence in this paper the rotational stability of a sheet pile wall under the seismic lateral earth pressure condition is studied by considering the dynamic effect of earthquake forces with the variation of the seismic accelerations in both horizontal and vertical directions propagating through the soil using the semi-static approach. The effects of variation of different param-

ters such as soil friction angle, effective suction parameter and matric suction stress on the design of a sheet pile wall against rotational stability under seismic conditions are considered in the present analysis.

Before determining of the related formulation for evaluation of unsaturated layer effect on seismic condition, it is necessary to gain the correct profile of active and passive stresses on the unbraced sheet pile wall. Profiles of stress in soil are often used as the theoretical basis for foundation design and analysis. Establishing relationships among different stress components such as horizontal and vertical earth pressures requires stress-strain constitutive laws. The most commonly used linear stress-strain equation in elasticity is Hooke's law. For unsaturated soil, an extended Hooke's law in light of the suction stress concept can be derived by substituting the effective stress components in those equations.

2. Active Earth Pressure

2.1. Rankine's Active State of Failure

For soil at a state of active failure, the vertical effective stress σ'_v is the maximum principal stress σ'_1 and the horizontal effective stress σ'_h is the minimum principal stress σ'_3 . Following the suction stress concept, each may be expressed for unsaturated soil as,

$$\sigma'_1 = (\sigma_v - u_a) - \chi(u_a - u_w) \quad (1)$$

$$\sigma'_3 = (\sigma_h - u_a) - \chi(u_a - u_w) \quad (2)$$

In seismic situation, the relationship between the minimum principal stress and maximum principal stress at failure can be written as,

$$\sigma'_3 = \sigma'_1 k_{ae} - 2c'\sqrt{k_{ae}} \quad (3)$$

where k_{ae} is the coefficient of Rankine's active earth pressure in seismic mode. Substituting Equations (1) and (2) into Equation (3) leads to,

$$\sigma_h - u_a = (\sigma_v - u_a)k_{ae} - 2c'\sqrt{k_{ae}} - \chi(u_a - u_w)(1 - k_{ae}) \quad (4)$$

It is evident that the first two terms on the right-hand side of Equation (4) are included in Rankine's original theory. The third term represents the contribution of suction stress that arises in unsaturated soil. The first term induces a compressive earth pressure in the soil mass or on adjacent retaining structures. The second and third terms are tensional stresses.

2.2. Active Earth Pressure Profiles for Constant Suction Stress

If suction stress is assumed constant (*i.e.*, the same at all depths from the ground surface) and the soil is homogeneous, the relative contribution of each term in Equation (4) can be conceptualized in **Figure 1**. The first term (shown as a stress increasing linearly with depth) is the classical Rankine's linear earth pressure due to the soil's self-weight. The second term reflects the mobilized cohesion at the failure state, a constant value with depth. The third term is the constant suction stress due to the existence of suction stress in unsaturated soil. The combined

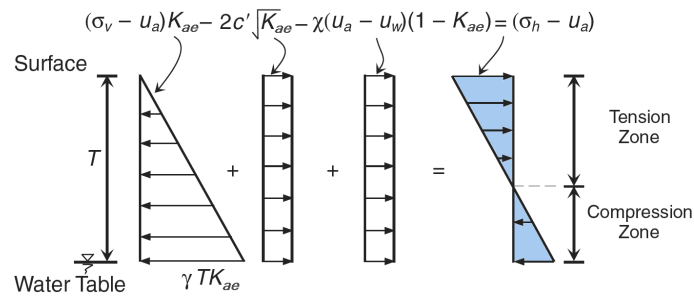


Figure 1. Decomposition of total active earth pressure components for condition of constant suction stress with depth.

effect of these three components of stress results in a linear lateral earth pressure profile that divides the unsaturated soil zone into zones of resultant tensional stress and compressional stress. Tensional stress will act to cause soil to crack, thus nullifying the lateral earth stress within the zone near the surface.

3. Passive Earth Pressure

3.1. Rankine's Passive State of Failure

In situations such as a soil mass located in front of a failing retaining wall or an expansive soil mass located behind a retaining wall, the horizontal earth pressure could be greater than the vertical stress induced by the overburden. Failure occurs when the horizontal stress develops to a magnitude such that the state of stress reaches the Coulombian failure stress. This general condition is referred to as the passive limit state. For soil at a state of passive failure, the vertical effective stress σ'_v is the minimum principal stress σ'_3 and the horizontal effective stress σ'_h is the maximum principal stress σ'_1 . According to the concept of suction stress, each can be expressed for unsaturated soil similar to Equations (1) and (2).

The relationship between the minimum principal stress and maximum principal stress at failure can be written as,

$$\sigma'_1 = \sigma'_3 k_{pe} + 2c' \sqrt{k_{pe}} \quad (5)$$

where k_{pe} is the coefficient of Rankine's passive seismic pressure. Substituting Equations (1) and (2) into Equation (5) leads to,

$$\sigma_h - u_a = (\sigma_v - u_a) k_{pe} + 2c' \sqrt{k_{pe}} + \chi(u_a - u_w)(k_{pe} - 1) \quad (6)$$

The first two terms on the right-hand side of Equation (6) fall from classical Rankine theory. The third term represents the suction stress component arising in unsaturated soil. All three terms induce compressive earth pressure.

3.2. Passive Earth Pressure Profiles for Constant Suction Stress

If suction stress is assumed constant with depth and the soil is homogeneous, the relative contribution of each term in Equation (6) can be conceptualized in **Figure 2**. The first term, shown as a linearly increasing stress with depth, is the limit state horizontal stress resulting from overburden. This contribution is usually 3

to 6 times the overburden stress. The second term reflects internal resistance arising from cohesion. The third term is the contribution from suction stress, equal to about 2 to 5 times the magnitude of the suction stress. In contrast with the active limit state described in previous section, both the cohesion and the suction stress contribute positively to the total lateral earth pressure. The combined effect of all three components leads to a linearly distributed earth pressure profile. Accordingly, there is no zone of tension.

4. Governing Equations

In following, the distribution of pure pressure on unbraced sheet pile in granular soil is calculated at different regions and afterwards by determining of passive lengths in soil, the embedded depth will gain too.

As shown in **Figure 3**, the active lateral pressure of soil on sheet pile at depth $z = L_1$ from top will be calculated with Equation (7) as below,

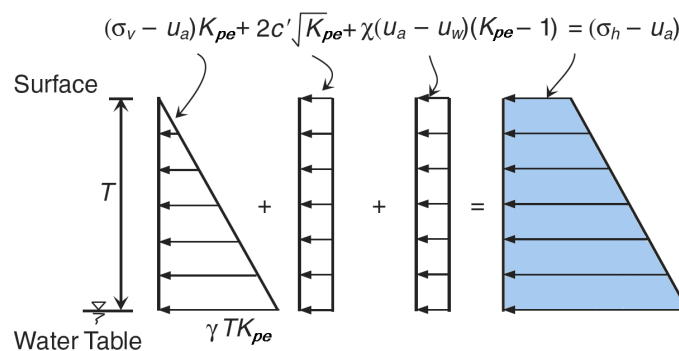


Figure 2. Decomposition of passive earth pressure for condition of constant suction stress with depth.

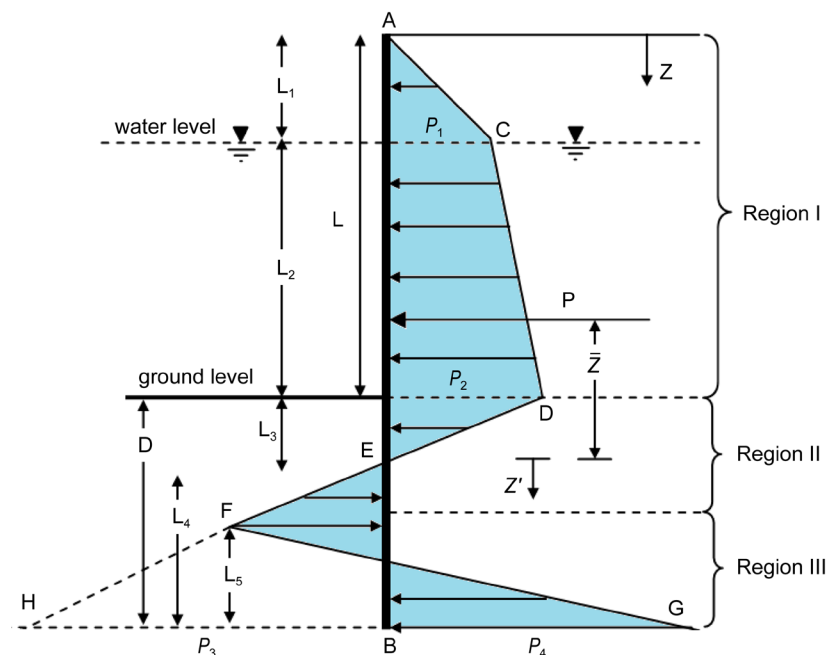


Figure 3. Distribution of pure pressure on burying unbraced sheet pile in granular soil.

$$p_1 = \gamma L_1 k_{ae} - \chi(u_a - u_w)(1 - k_{ae}) \quad (7)$$

where, γ is unit weight of soil around the sheet pile. Also, the quantity of $u_a - u_w$ is the suction stress in unsaturated soil above the water level and χ is the suction parameter of that too. Of course, k_{ae} is the coefficient of active earth pressure adopting to Rankine theory for calculation of seismic earth pressure which gains from Equation (8),

$$k_{ae} = \cos^2(\phi - \theta) / \cos \theta \cos(\delta + \theta) \left[1 + \sqrt{\frac{\sin(\phi + \delta) \sin(\phi - \theta - \alpha)}{\cos(\delta + \theta) \cos \alpha}} \right]^2 \quad (8)$$

where, ϕ and δ respectively are the friction angle of soil and the angle of wall friction, and θ is the inertial angle of earthquake which is defined as,

$$\theta = \tan^{-1}(k_h / 1 - k_v) \quad (9)$$

In this manner, the active earth pressure at $z = L_1 + L_2$ will be gained in form of Equation (10),

$$p_2 = (\gamma L_1 + \chi(u_a - u_w) + \gamma' L_2) k_{ae} \quad (10)$$

where, γ' is the effective unit weight of soil that equals to $\gamma' = \gamma_{sat} - \gamma_w$. The active earth pressure at turning point, E , placed in depth of z from top of sheet pile, can achieve be Equation (11),

$$p_a = (\gamma L_1 + \chi(u_a - u_w) + \gamma' L_2 + \gamma'(z - L_1 - L_2)) k_{ae} \quad (11)$$

The passive lateral earth pressure at depth $z > L_1 + L_2$ will be achieved from Equation (12),

$$p_p = \gamma'(z - L_1 - L_2) k_{pe} \quad (12)$$

where, k_{pe} is the coefficient of passive earth pressure by Rankine criterion which be calculated by Equation (13),

$$k_{pe} = \cos^2(\phi - \theta) / \cos \theta \cos(\delta + \theta) \left[1 - \sqrt{\frac{\sin(\phi - \delta) \sin(\phi - \theta + \alpha)}{\cos(\delta + \theta) \cos \alpha}} \right]^2 \quad (13)$$

with combining of Equations (11) and (12), the pure lateral earth pressure at ground level becomes,

$$p = p_a - p_p = p_2 - \gamma'(z - L)(k_{pe} - k_{ae}) \quad (14)$$

then, the location of point E under the ground level, may be expressed by L_3 for zero pressure on sheet pile in Equation (15) as,

$$L_3 = p_2 / \gamma'(k_{pe} - k_{ae}) \quad (15)$$

which the value of p_2 presents in Equation (9). With using Equation (6), it is considered that the gradient of pressure graph DEF is equal with 1 vertical to $\gamma'(k_{pe} - k_{ae})$ horizontal. Thus, in this graph, the value of p_3 may be written as,

$$\overline{HB} = p_3 = \gamma' L_4 (k_{pe} - k_{ae}) \quad (16)$$

then, the passive earth pressure p_p from right to left direction at $z = L + D$ and

the active pressure p_a with opposite direction corresponding to this level will be expressed as below forms,

$$p_p = (\gamma L_1 + \chi(u_a - u_w) + \gamma' L_2 + \gamma' D) k_{pe} \quad (17)$$

$$p_a = \gamma' D k_{ae} \quad (18)$$

At last, the pure lateral earth pressure on the end of the sheet pile will be equal to Equation (19),

$$p_p - p_a = p_4 = (\gamma L_1 + \chi(u_a - u_w) + \gamma' L_2) k_{pe} + \gamma' D (k_{pe} - k_{ae}) \quad (19)$$

which by considering of $D = L_3 + L_4$ in Equation (19), the value of p_5 may be written as Equation (20),

$$p_5 = (\gamma L_1 + \chi(u_a - u_w) + \gamma' L_2) k_{pe} + \gamma' L_3 (k_{pe} - k_{ae}) \quad (20)$$

with writing of horizontal forces equilibrium for unit of sheet pile length, Equation (21) may be gained as,

$$P - 0.5 P_3 L_4 + 0.5 L_5 (P_3 + P_4) = 0 \quad (21)$$

where P is the surface of under pressure graph ACDE. Also from Equation (22), the length of L_5 can expressed as following,

$$L_5 = P_3 L_4 - 2P / (P_3 + P_4) \quad (22)$$

Furthermore, by using of moment balance around the sheet pile leg, the Equation (23) will be achieved,

$$P(L_4 + \bar{z}) - 0.5 P_3 L_4 \times (L_4 / 3) + 0.5 L_5 (P_3 + P_4) \times (L_5 / 3) = 0 \quad (23)$$

where, the value of \bar{z} is the distance between horizontal P and turning point E. With combining of Equations (16), (19), (22) and (23) and with a few simplifying, the fourth order equation may be gained as Equation (24),

$$L_4^4 + A_1 L_4^3 - A_2 L_4^2 - A_3 L_4 - A_4 = 0 \quad (24)$$

where the coefficients of A_i will be expressed as below,

$$\begin{aligned} A_1 &= \frac{P_5}{\gamma' (k_{pe} - k_{ae})}, A_2 = \frac{8P}{\gamma' (k_{pe} - k_{ae})}, \\ A_3 &= \frac{6P [2\bar{z} \gamma' (k_{pe} - k_{ae}) + P_5]}{\gamma'^2 (k_{pe} - k_{ae})^2}, A_4 = \frac{P [6\bar{z} P_5 + 4P]}{\gamma'^2 (k_{pe} - k_{ae})^2} \end{aligned} \quad (25)$$

Now, with solving this achieved equation at Equation (23), the value of L_4 will be gotten in basis of geometric sheet pile conditions and resistant characteristics of soil. Thus, the embedded depth of unbraced sheet pile in soil can be expressed by the sum of $D = L_3 + L_4$. In following, the value of maximum bending moment on sheet pile beneath of turning point E, will be gotten. Thus, to this purpose, it must be found the zero shear point on pressure graph. As shown in **Figure 3**, by selecting of the z' -value from E origin, the zero shear point can get,

$$P = 0.5 (z')^2 (k_{pe} - k_{ae}) \gamma' \quad (26)$$

The place of zero shear point will be gained by setting of the value P equal to zero, leads to the following expression,

$$z' = \sqrt{\frac{2P}{(k_{pe} - k_{ae})\gamma'}} \quad (27)$$

with determining of zero shear point, the value of maximum bending moment on sheet pile becomes,

$$M_{\max} = P(z' + \bar{z}) - \left[0.5\gamma'z'^2(k_{pe} - k_{ae}) \right] \left[\frac{1}{3} \right] z' \quad (28)$$

Ultimately, for the better evaluation form lateral earth pressure of sheet pile and the embedded length in granular soil, basis of gained relations in above, in this section, several programs is prepared to parametric study more conveniently.

5. Numerical Example

A sandy unsaturated soil deposit backfilled the unbraced sheet pile near the sea water which the upper layer of it may be considered as a unsaturated soil above the water level. The soil has the following properties: internal friction angle $\phi = 30^\circ$, no cohesion, unit weight 16 kN/m^3 , and suction stress 20 kPa . Also, it is supposed that there is an earthquake with $0.2 g$ for kh horizontal seismic coefficient. These values are constant throughout the entire depth of the unsaturated zone.

Thus, with presenting of characteristics in **Table 1**, the classical Rankine's linear earth pressure due to the soil's self-weight is shown in **Figure 4**, by elongated line. If suction stress is assumed constant (*i.e.*, the same at all depths from the ground surface) and the soil is homogeneous, by suction stress parameter equal to 0.5 , the lateral earth pressure due to the existence of suction stress in unsaturated soil layer above water level is drawn with dotted line in **Figure 4**.

The effect of combining of suction stress results in a linear lateral earth pressure profile that divides the unsaturated soil zone into zones of resultant tensional stress and compressional stress. Tensional stress will act to cause soil to crack, thus nullifying the lateral earth stress within the zone near the surface.

Table 1. The mechanical backfilled soil properties.

Quantity	Value
unit weight of backfill soil (γ)	16 kN/m^3
saturated unit weight of soil (γ_{sat})	19 kN/m^3
internal soil friction angle (ϕ)	30°
cohesion constant (c)	0
angle of wall friction (δ)	0.67ϕ
suction stress parameter (χ)	0.5
suction stresses ($u_a - u_w$)	$10 - 50 \text{ kPa}$

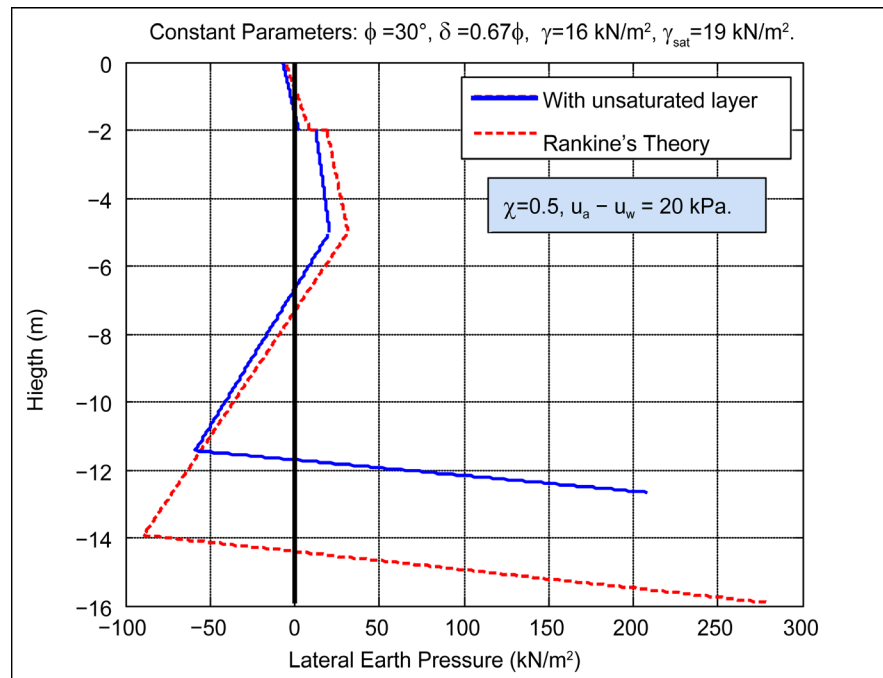


Figure 4. Distribution of lateral earth pressure on unbraced sheet pile in granular soil with unsaturated part.

According to **Figure 4**, as expected, with changing the situation of upper soil layer from dry to unsaturated supposing manner, the situation of pressure distribution does not change any more but the quantity of lateral earth pressure at the end of unbraced sheet pile will be more than the past form which the embedded length of this method may be a few decreased. Of course, in water level, a small jump in distribution of lateral earth pressure may be happened because of the difference in setting of the suction stress in lateral pressure relations that increases the active pressure at the first of the second saturated layer. Hence, a few increasing in active pressure and a few decreasing in passive pressure will be occurred. Thus in general, it is considered that supposing of unsaturating the upper soil layer may be necessary in correcting of calculated lateral earth pressure with real ones and determining of embedded length.

6. Investigation of Lateral Earth Pressure on Unbraced Sheet Pile

Similar to the numerical example in previous section, by using of equations in previous part, the lateral earth pressure on unbraced sheet pile may be calculated at any depth conveniently and the distribution graph can be drawn too. Hence, in computing relations, the geomechanical characteristics present in **Table 1**, have been used. And also the seismic situation can be determined by seismic coefficient in active and passive manners. Thus, in following matter, for evaluation of any parameter changes on pressure distribution of unbraced sheet pile, the other parameters must be constant according to **Table 1**. So in this section, the effect of changes in internal soil friction angle, the matric suction stress and

the effective suction parameter may be investigated respectively on pressure distribution of unbraced sheet pile.

6.1. Effect of Internal Soil Friction Angle on Lateral Earth Pressure

According to inserted specifications in **Table 1**, it is supposed that the sheet pile is embedded in the granular soil with the unit weight of 16 kN/m^3 and the saturated unit weight of 19 kN/m^3 . So, for investigating of internal soil friction angle on lateral pressure distribution, the amount of it can be changed between 25 up to 45 degrees for rigid soil type. Thus, with considering to this object, that states the angle of wall friction is a function of internal soil friction angle ($\delta = 0.67\phi$), the value of δ will be changed in presented relations too. Of course, the unbraced sheet pile height is divided in two constant lengths $L1 = 2 \text{ m}$ and $L2 = 3 \text{ m}$ outside of soil, and two passive lengths $L3$ and $L4$ inside of granular soil. Furthermore, the seismic condition of problem may be applied by the horizontal seismic coefficient of k_h equal to $0.2 g$. Hence, the distribution of lateral earth pressure and the embedded depth of sheet pile in soil, corresponding to maximum influencing lateral pressure in seismic condition, may be drawn in **Figure 5**.

As shown in **Figure 5**, it is observed that with increasing in internal soil friction angle from loose to rigid soil type, the intensity of lateral earth pressure on unbraced sheet pile will be decreased and also the embedded length of it may be reduced. Of course, the more of these differences can be happened in regions I and II which are the locations of oppositeness of active and passive forming pressures at besides of sheet pile. Hence, increasing in internal soil friction angle will be decreasing in embedded depth from 22 m to 9 m , which is so considerable. In addition to, the value of embedded length less than 30 degrees of soil

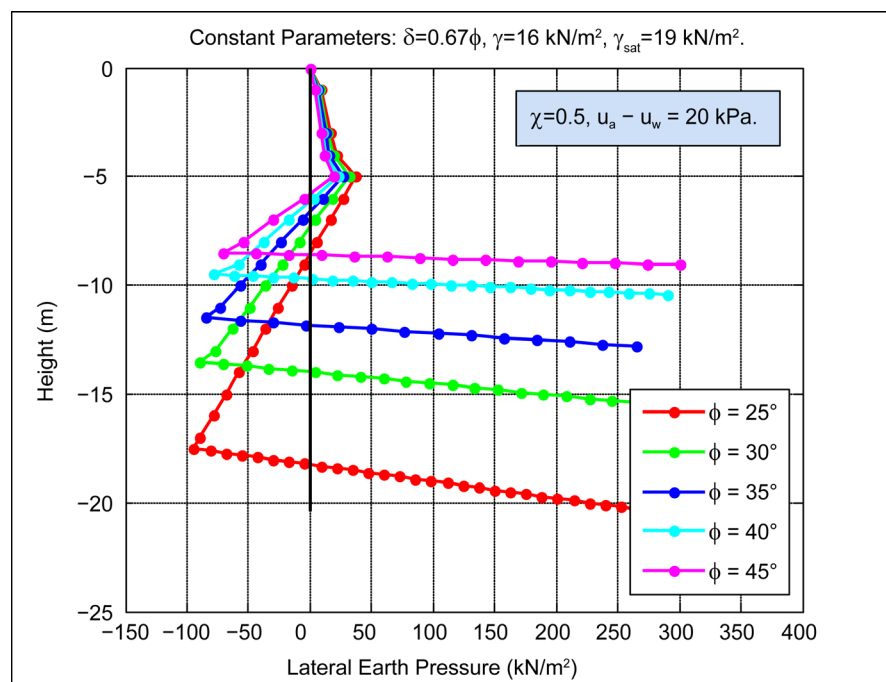


Figure 5. Distribution of lateral earth pressure against internal soil friction angle.

friction angle is so noneconomical and unaccomplishment. So, it is reasonable that for stabilizing of backfilled soil at seismic conditions, is used some cluster piles for sheet pile or changing the soil around it with the better resistant specifications. Also according to **Figure 5**, it is shown that the maximum of lateral earth pressure will be occurred at the end of the sheet pile which by decreasing in embedded depth of it, will be reduced on unbraced sheet pile that this case is so important for designing of them.

6.2. Effect of Effective Suction Parameter on Lateral Earth Pressure

The effect of variation in suction parameter on pressure distribution for unbraced sheet pile can be achieved by studying of **Figure 6**. As it is considered, the maximum of lateral earth pressure on unbraced sheet pile in granular soil will be decreased with increasing in effective suction parameter from 0.2 up to 1 for the saturated condition of upper soil layer. Of course, the variation of distribution pressure in this graph is so negligible that up to depth of 14 m, the whole of lateral pressure graphs are the same forms and values. But after depth of 14 m, the pressure graph will be distinguished besides that the value of maximum lateral pressure will be occurred at longer depth by decreasing in effective suction parameter.

6.3. Effect of Suction Stress on Lateral Earth Pressure

Further the researcher has also analyzed that the presence of water in the backfill may increase the seismic pressure. In about this case, for unsaturated earthfill, the saturated unit weight of the soil shall be adopted while calculating the seismic

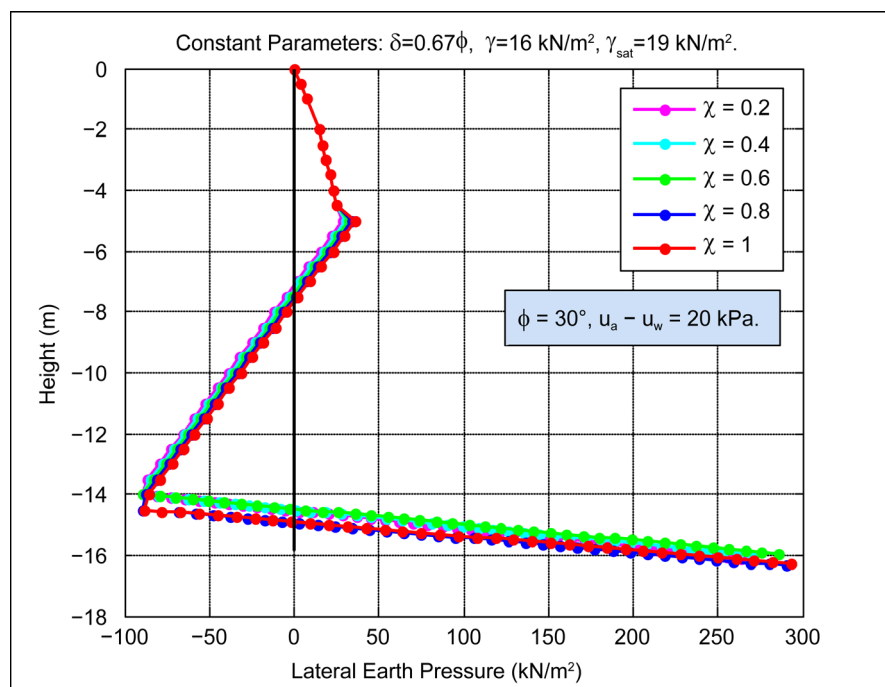


Figure 6. Distribution of lateral earth pressure against effective suction parameter.

active earth pressure increment or passive earth pressure decrement using the Equation (4) and (6) as discussed in preceding pages. Now in this section, the lateral earth pressure is shown by variation of the matric suction stress in unsaturated soil layer of backfilled soil in **Figure 7**. As shown in this figure, the pressure distribution will be changed in lower soil depth, with changing of the matric suction value. Hence, by increasing in suction stress value, the maximum lateral pressure on unbraced sheet pile will be increased in higher depth of its. Of course, it is supposed that the matric suction is the constant value in all over the length of unsaturated soil layer. In addition to, the effective suction parameter is equal to 0.5 in whole of unsaturated soil layer too.

7. Determination of Embedded Free Length Proportion

7.1. Evaluation of Embedded Depth Respect to Internal Friction Soil Angle

As you seen in the previous figures, the embedded depth of unbraced sheet pile in granular soil depends on the free length of it. Hence, with normalizing of the lengths, the variations of embedded depth will be more conveniently studied by changing in the other parameters values and also the effects of free length value can be omitted. Thus, as it shown in **Figure 8**, the normalized embedded depth is decreased by increasing of the internal soil friction angle which this matter is so accessible. Because, by increasing in soil resistant around the sheet pile with increasing in friction angle from 25 to 45 degrees, it is determined that the embedded length of sheet pile will be reduced. Of course, for a constant value of soil friction angle, by increasing in matric suction stress, the embedded length of unbraced sheet pile will be reduced.

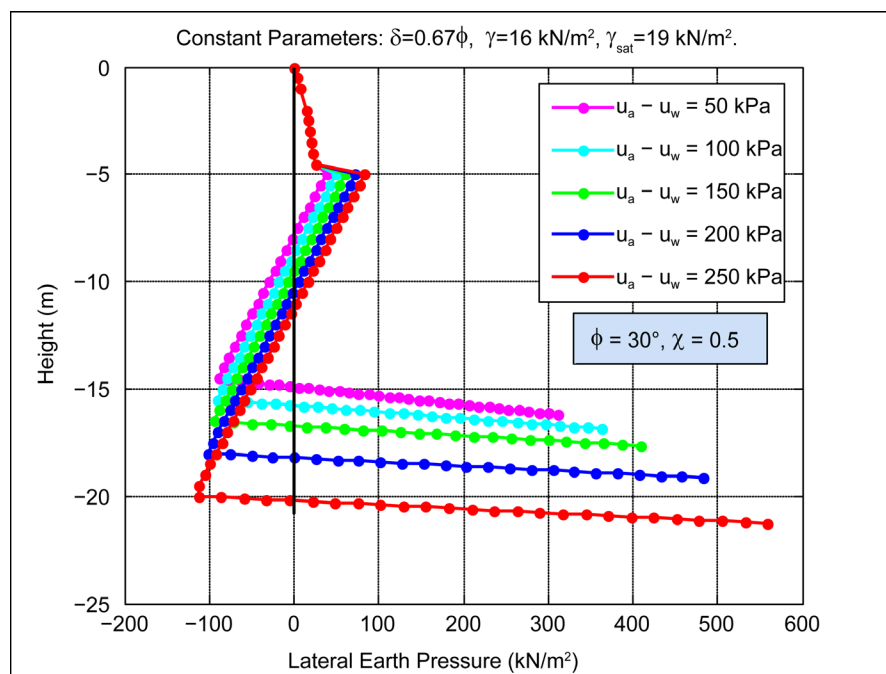


Figure 7. Distribution of lateral earth pressure against suction stress.

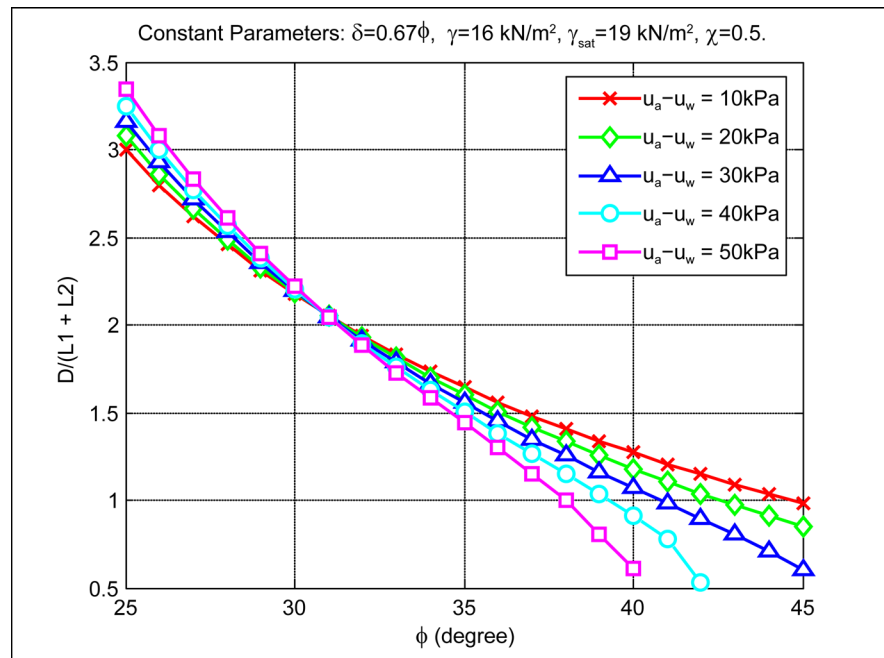


Figure 8. Normalized embedded depth to free length for different suction stresses against internal soil friction angle.

Now, we can consider to a numerical example of determination of embedded depth by using of **Figure 8**. Hence, for a relatively rigid backfilled soil with 45 degrees friction angle, it is required to embedding the sheet pile with the same free length value in soil, when the matric suction stress is 10 kPa. Of course, for the smaller value of matric suction of unsaturated soil layer, the value of embedded length will be greater reduced.

7.2. Evaluation of Embedded Depth Respect to Effective Suction Parameter

According to past relations, the embedded depth of unbraced sheet pile in granular soil depends on the matric suction, the effective suction parameter and the internal soil friction. Thus, as it shown in **Figure 9**, the normalized embedded depth is decreased by increasing of the effective suction parameter which this subject is so clear. That, by increasing in saturating situation of soil around the sheet pile with increasing in the effective suction parameter from 0 to 1 value, it is obvious that the embedded length of sheet pile will be reduced. Of course, for a constant value of the effective suction parameter, by increasing the resistant specification of soil, the embedded length of unbraced sheet pile will be decreased. In following, we can study a numerical example of determination of embedded depth by using of **Figure 9**. Hence, for a medium resistant backfilled soil with 40 degrees friction angle, it is required to embedding the sheet pile with the same free length value in soil, when the effective suction parameter is 0.45 respect to saturated condition. Of course, for the smaller value of the effective suction parameter of unsaturated soil layer, the value of embedded length will be greater.

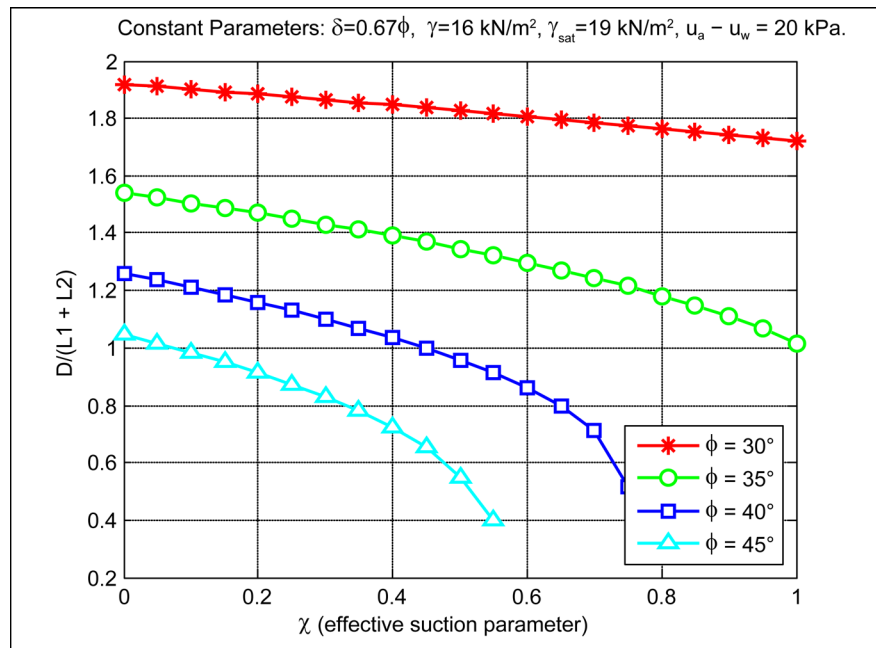


Figure 9. Normalized embedded depth to free length for different internal soil friction angles against effective suction parameter.

7.3. Evaluation of Embedded Depth Respect to Effective Suction Parameter

According to **Figure 10**, the normalized embedded depth to free length of unbraced sheet pile in granular soil is drawn for different suction stresses against effective suction parameter by some diagrams. Thus, as it shown in **Figure 10**, for a constant value of the effective suction parameter, the embedded depth is increased by increasing of the suction stress in any graph. That is, by increasing in saturating situation of soil around the sheet pile with increasing in the suction stress from 0 to 200 kPa, it is evident that the embedded length of sheet pile will be increased. And also, by increasing the effective suction parameter, the embedded length of unbraced sheet pile will be enlarged for a constant value of matric suction. In next, we may study a numerical example of determination of embedded depth by using of **Figure 10**. Thus, for a constant resistant backfilled saturated soil with 30 degrees friction angle, it is required to embedding the sheet pile with the three times of the free length value in soil, when the suction stress is equal to 108 kPa. Of course, for the smaller value of the suction stress of unsaturated soil layer, the value of embedded length will be shorter.

In general, by generating and using the above figures such as **Figures 8-10**, the embedded depth of sheet piles in granular soils with unsaturated situation can get without any calculations, which will be used profitably for designer engineers.

8. Determination of Maximum Bending Moment on Unbraced Sheet Pile

According to the past equations, the value of maximum bending moment on

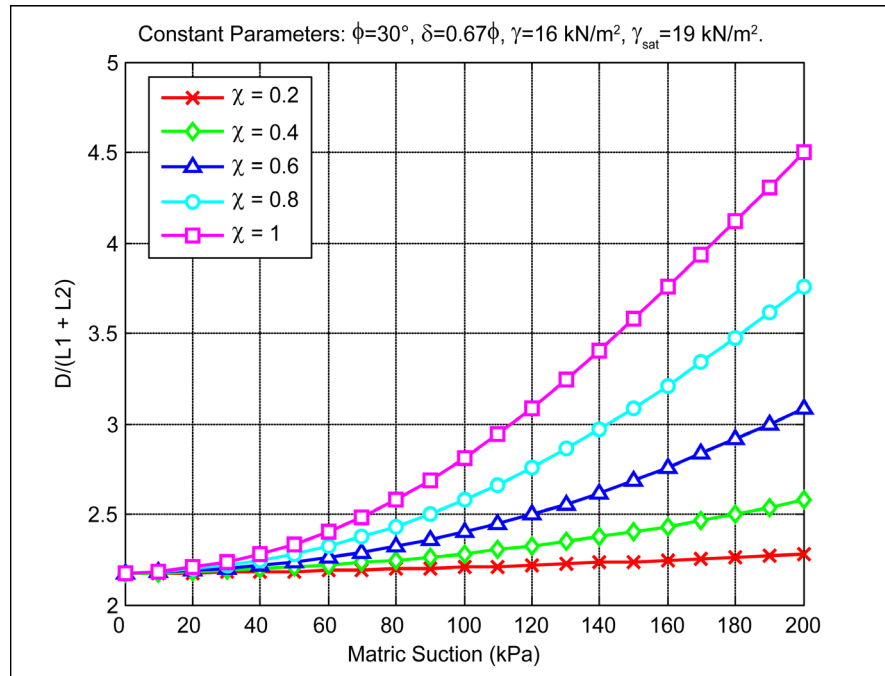


Figure 10. Normalized embedded depth to free length for different suction stresses against effective suction parameter.

sheet pile will be gotten beneath of the turning point *E*. Thus, with determining of zero shear point, the value of maximum bending moment on sheet pile will be found. Thus, by considering to the depending of maximum bending moment on active and passive lateral coefficients, it is founded that the varying in internal soil friction can be important. And also, the changing in some other parameters such as suction stress and effective suction parameter will be affects on the maximum bending moment value with depending of the place of zero shear point to them. Hence, as shown in **Figure 11**, by using of the inserted values of the soil parameters in **Table 1**, the maximum bending moment on unbraced sheet pile for different internal soil friction angles is drawn by a clear curve.

Now, by increasing in soil resistant specification, the maximum moment may be decreased. Thus, for a constant situation for unsaturated upper soil layer that is shown in **Figure 11**, by increasing in internal soil friction value from 25 to 45 degrees, the calculated maximum bending moment will be reduced about 6.3 times.

9. Conclusion

In present paper, the unbraced sheet pile behavior of lateral earth pressure and embedded depth is studied by changing in saturation condition. Thus, by varying the matric suction stress and the effective suction parameter, the distribution of lateral earth pressure is investigated by some graphs which explained the effects of any variation on them. And also in several graphs, the effects of soil mechanical parameters are obvious on the embedded depth of unbraced sheet pile in granular around soil. Of course, this matter is presented by normalizing

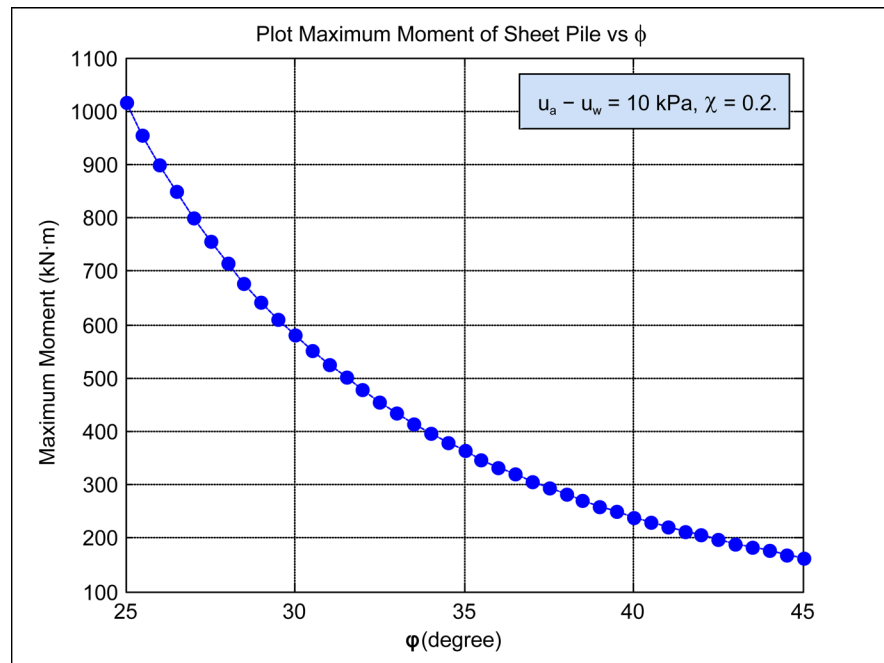


Figure 11. The maximum bending moment on unbraced sheet pile for different internal soil friction angles.

of the embedded depth with the free length of sheet pile. And in following, the maximum lateral earth pressure on sheet pile is considered in each graph from the first of paper and justified the reasons of variations of it by changing of embedded length. At last, the maximum bending moment of soil on unbraced sheet pile is considered with different internal soil friction angles in a normal curve. Thus, at a general state, it is cleared that the variations of saturating conditions in seismic manner are affected on lateral earth pressure and the embedded depth of unbraced sheet pile in different forms. Hence, it is so important that the designers may consider the effects of unsaturated soil layer on unbraced sheet pile behavior.

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