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Anchored sheet pile wall design in expansive soils

Conception d'un mur de palplanches ancré dans les sols expansifs

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ABSTRACT: Expansive soils cause damage to civil engineering structures in various parts of the world, because they swell when absorb water and shrink when dry out. Due to swelling pressures, retaining walls can be subjected to additional lateral pressures causing increased wall deformations and bending moments. Anchor forces can also increase, if the walls are anchored. When expansive soils are present behind retaining walls, swell pressures should also be considered during design in addition to the traditional lateral earth pressures. This study proposes a method to predict potential swell pressures acting on retaining walls for use in design of these walls. A parametric study using the limit equilibrium approach was performed to investigate the effect of swell pressures on the design of anchored sheet pile walls in expansive soils. The results of the study show that the presence of expansive soils can significantly affect earth retaining structures and swell pressures should be considered in the design of retaining walls when the expansive soils are present at the site.

RÉSUMÉ : Les sols expansifs causent des dommages à des structures de génie civil dans diverses parties du monde, ils gonflent quand ils absorbent de l'eau et se contractent quand ils se dessèchent. En raison des pressions de gonflement, les murs de soutènement peuvent être soumis à des pressions latérales supplémentaires augmentant les déformations et les moments fléchissant. Les forces d'ancrage peuvent également augmenter, si les murs sont ancrés. Lorsque les sols expansifs sont présents derrière les murs de soutènement, les pressions de gonflement devraient également être envisagées, en plus des pressions latérales des terres traditionnelles. Dans cette étude, une méthode a été proposée pour prédire d'éventuelles pressions de gonflement agissant sur les murs de soutènement, à utiliser dans la conception de murs de soutènement. Une étude paramétrique en utilisant l'approche d'équilibre limite a été réalisée pour étudier l'effet des pressions de gonflement sur la conception de rideaux de palplanches ancrées dans les sols expansifs. Les résultats de l'étude montrent que la présence de sols expansifs, peut influencer considérablement la conception de structures de soutènement et doit être pris en compte dans la conception des murs lorsque les sols expansifs sont présents sur le site.

KEYWORDS: Retaining wall, anchored sheet pile wall, expansive soil, swell pressure, wall design.

1 INTRODUCTION AND OVERVIEW

The sidewalls of structures and retaining walls may experience additional lateral pressures when they are located within expansive soils. When the expansive soils absorb water the moisture content increases and the soil tends to expand. If the free swelling or expansion of the clay is restricted, then swell pressures develop and this cause an increase in the lateral pressures acting on the structures. The design of retaining walls usually specifies cohesionless soils as a backfill material behind the wall mainly to avoid hydrostatic pressures by providing easy drainage. These cohesionless materials also help to prevent swell pressures that may develop if cohesive soils are used.

Due to economical reasons, local soils which may be expansive are sometimes used as a backfill material (Thomas et al. 2009). However, use of these soils as backfill may result in wall failures (Marsh and Walsh 1996) not only because of the hydrostatic pressures but also due to the additional lateral earth pressures caused by the swelling of expansive soils.

The selection of soils behind the wall is not even optional for in-situ retaining walls, such as cantilever and anchored sheet pile walls, slurry walls, secant and tangent pile walls. These walls are installed in existing soils and front of the wall is usually excavated. When these walls are installed at locations where expansive soils are present, the walls would experience not only the traditional lateral earth pressures but also the swell pressures when soil's moisture content increases.

The objective of this study is to investigate the behavior of anchored sheet pile walls when they are installed in expansive soils and exposed to additional stresses due to the swelling of these soils.

1.1 *Expansive soils*

The best way to deal with the shrinkage and swelling of expansive soils is to maintain constant soil moisture. If the soil moisture content does not change, there can be no shrinkage or swelling. However, it is usually not possible to maintain constant soil moisture. Moisture content fluctuates due to several factors, such as precipitation and evaporation. The seasonal variation of soil moisture is much higher at shallower depths and it decreases as the depth below the ground surface increases (Figure 1).

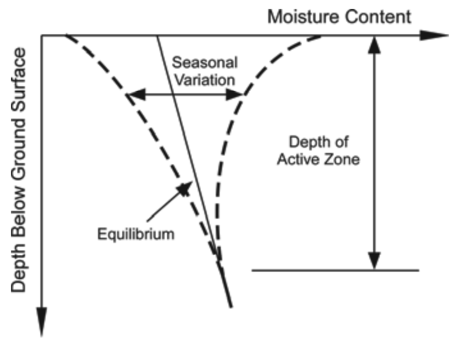

Figure 1. Moisture content fluctuations with depth.

Table 1. Classification of swell potential (after USACE 1983).

Classification of swell potential	Plasticity index, PI (%)
Low	< 25
Marginal	25 – 35
High	> 35

The depth where the seasonal soil moisture variations occur below the ground surface is called the active zone as shown in Figure 1. The depth of active zone is influenced by soil permeability, precipitation and evaporation amounts, seasonal temperature fluctuations, and presence of tree roots. Active zone depths in several U.S. cities were reported by O'Neill and Poormoayed (1980) as: 1.5 to 3.0 m in Houston, Texas; 2.1 to 4.2 m in Dallas, Texas; 3.0 to 4.6 m in Denver, Colorado; and 3.0 to 9.0 m in San Antonio, Texas.

The degree of swell potential of expansive soils can be classified by the soil's liquid limit, *LL*, or plasticity index, *PI*. As the liquid limit or plasticity index increases, the swell potential of the soil increases. The classification used by the U.S. Army Corps of Engineers (USACE) (1983) based on the plasticity index is given in Table 1.

1.2 *Conventional sheet pile wall design*

The design of sheet pile walls is based on active and passive earth pressures which are concerned with the failure condition using the Mohr-Coulomb failure criterion. For a typical wall section, the lateral earth pressures and the resulting forces acting on the wall are shown in Figure 2, where P'_A and P'_P are resultant effective active and passive earth forces, respectively; d_A and d_P are moment arms with respect to the anchor elevation; and *FS* is factor of safety. The factor of safety is applied to the passive loads during wall design (NAVFAC 1986; USACE 1994). The safety factors are used to take into account the uncertainties in soil conditions, method of stability analysis, loading conditions, as well as to restraint soil movements at an acceptable level (Potts and Fourie 1984).

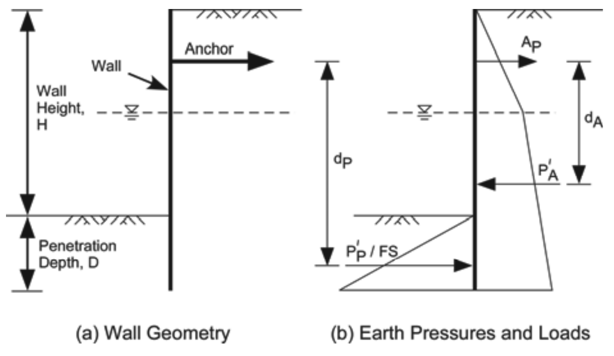

Figure 2. Typical sheet pile wall section and forces acting on the wall.

Wall penetration depth required below the bottom of the excavation is determined by considering the moment equilibrium about the anchor elevation. Because the water level is assumed to be at the same elevation behind and in front of the wall during this study, hydrostatic forces cancel each other. Once the wall penetration depth is determined, the anchor force, A_P, is calculated from horizontal force equilibrium. Based on the active and passive pressure distributions and the calculated anchor force, maximum wall bending moment is determined. The design moment is calculated by applying the moment reduction factor (Rowe 1952) to the calculated maximum bending moment. The steel sheet pile section is then selected based on the design moment, and the wall design is completed by selection and design of an anchorage system. This conventional design approach does not take into account any swell pressures that may affect walls when they are installed at locations where expansive soils are present.

2 METHOD OF APPROACH

The effect of swelling pressures on anchored sheet pile wall behavior has been investigated through a range of expansive soil activity. The swell pressures were calculated for a range of plasticity index values covering soils from low to high swell potential based on a study performed by Erzin and Erol (2007). Using these swell pressure potentials and moisture change profile in the ground within the active zone, the swell pressure distribution was developed. The swell pressure distribution developed was then applied on the anchored sheet pile wall as potential swell pressure, additional to the lateral earth pressures presented in Figure 2.

A parametric study for a range of plasticity index values, i.e. expansive soil activity and swell potentials, have been performed using the free earth support design method to investigate the effect of swell pressures on anchored sheet pile walls. Design of the wall was first performed for non-expansive soils, i.e. using only the traditional lateral earth pressure distributions, as a baseline case. Then the swell pressures, based on the varying plasticity index values, have been applied and the wall was re-analyzed.

3 SWELL PRESSURES

There are many factors that govern expansive behavior of soils. The primary factors are availability of moisture, amount and type of clay particles, and initial condition of soil in terms of dry density and moisture content (Day 1994). Several earlier studies (e.g., Snethen 1980, Erzin and Erol 2007) indicate that soil suction is the most relevant soil parameter for the characterization of swell behavior of expansive soils.

Multiple regression analyses carried out by Erzin and Erol (2007) revealed that the soil suction relates to the plasticity index and water content as

$$\log s = 2.02 + 0.00603\, PI - 0.0769\, w \tag{1}$$

where *s*=soil suction (in bar), *PI*=plasticity index (in percent), and *w*=water content (in percent). The study performed by Erzin and Erol (2007) also showed that the swell pressure, for pressures between 0 and 100 kPa, can be given as

$$\sigma_s = -3.72 + 0.0111\, PI + 2.077\, \rho_{dry} + 0.244 \log s \tag{2}$$

where σ_s=swell pressure (kg/cm^2), *PI*=plasticity index (in percent), ρ_{dry}=dry density (g/cm^3), and *s*=soil suction (in bar).

For this study, the plasticity index was used as the only variable to determine swell pressures. The plasticity index values considered ranged from 10% to 50%, which covers low to highly expansive soils as presented in Table 1. A constant value of 15% for the moisture content and a constant value of 1.65 g/cm^3 for the dry density were used. These selected values represent average values of the ranges considered by Erzin and Erol (2007) in their study. The swell pressures calculated using Eq. 2 for the range of plasticity index values studied, with the moisture content of 15% and dry density of 1.65 g/cm^3, are shown in Figure 3.

3.1 *Distribution of lateral swell pressures behind the wall*

As shown in Figure 1, seasonal variation of soil moisture content is the highest at the ground surface and it diminishes as the depth from the ground surface increases. The change in the moisture content with increasing depth is not linear. However, the variation is assumed to be linear in this study. This assumption is conservative, since the predicted swell pressures will be larger than the actual ones. The simplified linear model is shown in Figure 4.

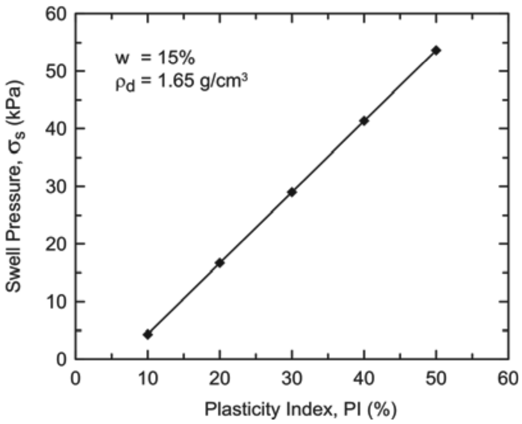

Figure 3. Swell pressure versus plasticity index.

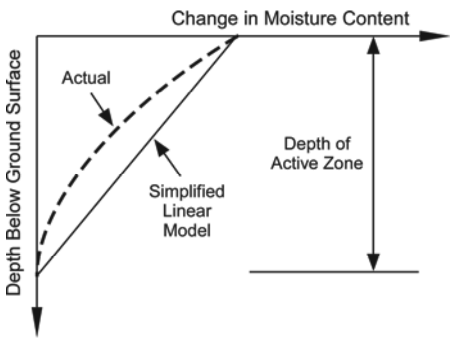

Figure 4. Change in moisture content with depth.

Because the change in moisture content causes the swelling of expansive soils, swell pressure will be maximum at the ground surface and will decrease as the depth increases. These maximum pressures, i.e. potential swell pressures, can be determined using Eq. 2. However, swell pressures close to the ground surface will not reach their potential due to shallow depths where soil confinement pressures are relatively lower. Soils closer to the ground surface will be able to expand, and full swell pressures determined by Eq. 2 will not be able to develop. When swelling occurs, passive lateral earth pressure conditions develop near the ground surface. Therefore, the passive earth pressures can be used as an upper limit for swell pressures near the ground surface. A schematic of the additional lateral pressure developed behind the wall due to the swelling of expansive soil is shown in Figure 5, where the potential swell pressure, σ_s, is determined by Eq. 2. When the swell pressures exceed the passive earth pressures near the ground surface (i.e., within the critical depth, z_c, shown in Figure 5), the additional lateral pressures due to the swelling of soil are capped by the passive earth pressures.

4 ANALYSIS AND RESULTS

The analyses were performed for a fixed wall height of 10 m with anchor level located at 2.5 m below the top of the wall. The anchor level was selected based on a study performed by Bilgin and Erten (2009) which showed that the best anchor location to have minimum wall deformations was 0.25×*H* below from the top of wall, where *H* is the wall height. The active zone depth used in the study was 5.0 m, selected based on the values given by O'Neill and Poormoayed (1980) as mentioned previously. The groundwater table is also assumed to be 5.0 m below the top of wall and at the same elevation on both sides of the wall. A schematic of the pressure diagrams used to perform parametric study are shown in Figure 6.

The analysis results are shown in Figure 7 through Figure 9, as a percent increase in the wall penetration depth, maximum wall bending moment, and anchor force versus soil plasticity index. The percent increase is given with respect to the baseline case in which the anchored sheet pile wall was installed in non-expansive soil. The results show that as the plasticity index increases the wall penetration depth, maximum wall bending moment, and anchor force can increase significantly.

4.1 *Wall penetration depth*

The effect of expansive soils and potential swell pressure, calculated based on the soil plasticity index, on anchored sheet pile wall penetration depth is presented in Figure 7. As shown in Figure 7, an increase in the plasticity index, i.e. increase in the activity of expansive soils, can result in significant increase in wall penetration depth. Compared with the wall installed in non-expansive soil, the wall penetration depth can increase more than 85% and 125% for low and marginally expansive soils, respectively. Within the plasticity index range considered during this study, the wall penetration depth can increase as much as 190% which is for the plasticity index of 50%.

4.2 *Wall bending moment*

The effect of expansive soils and potential swell pressures on wall maximum bending moment is shown in Figure 8. The results show that wall bending moment increases as the plasticity index of soil increases. While the presence of marginally expansive soils with fully reached swell potential can result in approximately 105% increase in wall bending moment, an increase of up to 170% can occur for soils with plastic index values of 50%, i.e. highly expansive soils.

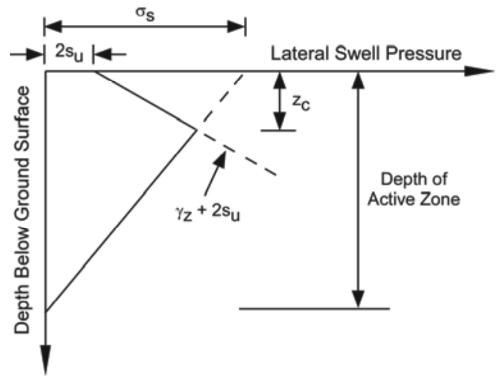

Figure 5. Lateral pressure distribution due to swelling of expansive soil.

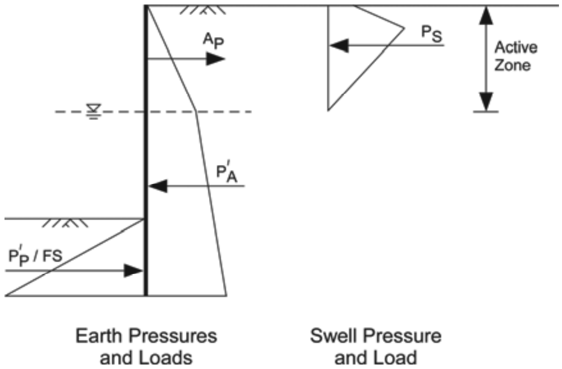

Figure 6. Soil and swell pressures acting on the wall.

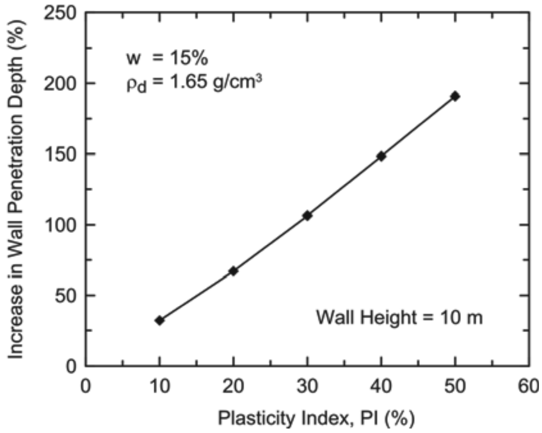

Figure 7. Effect of expansive soils on wall penetration depth.

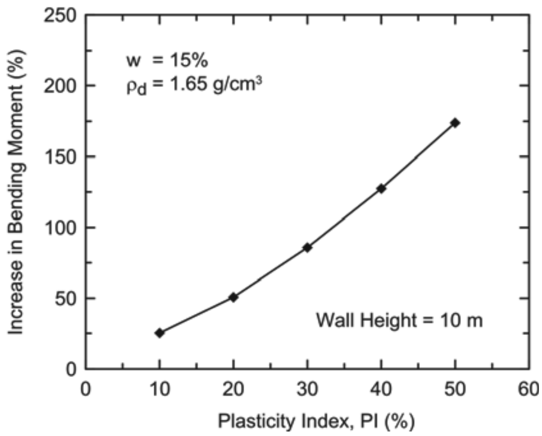

Figure 8. Effect of expansive soils on wall bending moment.

4.3 *Anchor force*

The effect of expansive soils and potential swell pressure on anchor force is presented in Figure 9. The results show that the anchor force increases as the plasticity index of soil increases, similar to the wall penetration depth and bending moments. However, the presence of expansive soils has the most significant effect on the anchor forces. This is because of the fact that the anchor is located closer to the top of sheet pile wall and the swell pressures are higher closer to the ground surface due to more fluctuations in soil moisture content in this zone. Within the range of parameters considered, an increase in the anchor force can be as much as 240% (when plasticity index is 50%) compared to the condition where the wall is installed in non-expansive soil.

5 SUMMARY AND CONCLUSIONS

The design of retaining walls usually specifies cohesionless soils as a backfill material behind the wall, however, in-situ retaining walls, such as anchored sheet pile walls, are installed in existing soils. Expansive soils exist in many locations around the world, and the design of anchored sheet pile walls needs to consider the effect of soil swell pressures when these walls are installed in these soils.

In this paper the effect of expansive soils and swell pressures on anchored sheet pile walls, in terms of wall penetration depth, wall bending moment, and anchor force were investigated. The swell pressures were determined using the soil plasticity index, based on earlier studies. For the cases studied and range of soil properties considered, the analysis results show that the effect of expansive soils on anchored sheet pile walls can be significant, even if the soils at the site are low to marginally expansive. For soils with the plasticity index of 50%, indicative of highly expansive soils, and for wall geometry and soil conditions considered during this study, the analysis results show that the wall penetration depth increased 190%, wall bending moments increased 170%, and anchor force increased 240%, compared with the wall design when soils at the site are non-expansive. The maximum increase was observed in the anchor force, because higher swell pressures develop closer to the ground surface due to the seasonal changes in moisture content. It should be noted that the swell pressures determined using the plasticity index values represent the maximum potential swell pressures, i.e. upper limit, and these pressures may not develop during each seasonal changes.

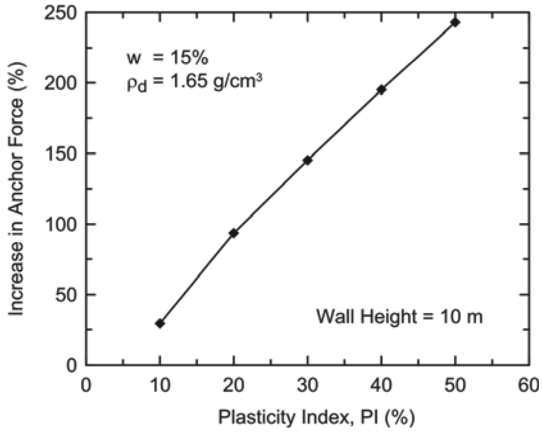

Figure 9. Effect of expansive soils on anchor force.

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