EFFECT OF PLASTICITY INDEX ON LATERAL SWELLING PRESSURE

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Abstract

Retaining structures are used to hold earth and maintain a difference in the elevation between two levels. Soils behind a retaining system could be expansive materials, which may result in significant lateral swelling pressure in addition to the active earth pressure due to soil own weight. Swelling pressure is mainly correlated with soil plasticity index (PI) and change in moisture content. Retaining structures such as diaphragm walls that are constructedin front of such expansive soilsare subject to damage and cracks, as the swelling pressure is not usually considered in the design due to the complexity of its assessment. This study aimed to assess the effect of changing the PI on lateral swelling pressure for different retaining systems using the finite element program GeoStudio. After validating the model outcomes, a parametric study was carried out to determine the relation between swelling pressure and PI, and it was found that they are directly related to each other. In addition, the rate of change in the swelling pressure declines along the bottom third of retaining walls due to relative stabilization in the moisture levels.

Background

Soils that exhibit swell-shrink characteristic (volume change) when subjected to moisture fluctuations are termed as expansive or swelling soils. These expansive soils are found in abundance in semi-arid regions of tropical and temperate climatic zones, where annual evaporation is more than the precipitation (Jones and Holtz, 1973). Structures which are constructed on such soils are subjected to large heave forces due to swelling, which could result in severe damage and cracks in the super-structure.During the pastsixty years, several problems related to swelling soils were reported and studied in various research works. Damages to infrastructure constructed onor inside expansive soils have been mainly attributed to thesignificant change in the soil volume. For example, Krohn and Slosson (1980) estimated that $7 billion were spent each year only in the United States as a result of damages in structures due to expansive soils.

Expansive soils have diverse origins, mainly including lacustrine, alluvial, eluvial, and pluvial origins, in addition to soils found in two or more origins such as alluvial-pluvial, and eluvial-pluvial. In general, pluvial soil has lower swelling tendency compared with lacustrine soils, but eluvial and alluvial soils are diverse in shrinkage and swelling characteristics (Miao et al., 2007).Expansive soils swell upon wetting and shrink upon drying due to seasonal changes (Ng et al. 2003; Al-Homoud et al., 1995; Erzin and Erol, 2007; and Zhan et al., 2007). The volume change of expansive soils with respect to changes in water content (or suction) is due to the influence of clay minerals such as the montmorillonite, illite and kaolinite. Once the swelling potential of expansive soils is restrained by surrounding soils or prevented by the overburden pressure or other loads, a counterforce which is commonly referred to as swelling pressure would be generated. The swelling pressure will act on infrastructure such as foundation slabs, highway pavements, outer walls of basements, tunnels, and pipelines.Consequently, extensive damages occur in such infrastructures (Fredlund et al., 1995). Swell-shrink properties also contribute to instability of slopes that are formed of expansive soils (Ng et al., 2003).

Swelling Pressure Measurement

Swelling pressure can be defined as the pressure which the expansive soil exerts if it is not allowed to swell or the volume change of the soil is prevented. There are two types of pressure, vertical swelling pressure and lateral swelling pressure which affects the retaining structures. Both lateral and vertical swell pressures decrease with increasing initial moisture (Erol and Ergun, 1994) and swelling pressure increases with the increase of final moisture content (Fredlund and Rahardjo, 1993). Accordingly, the relationship between water content and soil suction governs the induced swelling pressure, whereas the soil-water characteristic curve (SWCC) describes the relationship between them (Fredlund and Rahardjo 1993). Another governing factor is the type of the soil itself, which can be practically correlated with the soil plasticity index (PI).

The assessment of the vertical swelling pressure can be conductedusing conventional laboratory tests such as the soil volume change meter that yields maximum possible volume change (PVC) values. Vertical swelling can also be measured by means of the oedometer testor using soil suction method.On the other hand, the prediction of lateral swelling pressure in these tests requires the use of a lateral swelling pressure ring (Ofer, 1980), or thin wall oedometer ring (Ertekin, 1991), or a modified hydraulic triaxial apparatus (Fourie, 1989). All these laboratory techniques do not necessarily provideaccurate values for the in-situ vertical and lateral swelling pressures. Research studies have shown that these laboratory tests tend to overestimate the actual earth pressures (Nelson and Miller, 1992).

Soil Water Characteristic Curve (SWCC)

The soil-water characteristic curve (SWCC) describes the relationship between water content and soil suction for a single soil specimen (Fredlund and Rahardjo, 1993). The amount of water in the soil is generally quantified in terms of gravimetric water content, w, volumetric water content, θ, or degree of saturation,S. Many alternative terminologies are available in the literature and are widely used for representing the same meaning of soil-water characteristic curve. There include, water retention curve, soil moisture curve, soil-water retention curve, soil water characteristic, and numerous other terms (Fredlund et al. 2001).

Different graphical representations can be used for the SWCC data. The shape of the SWCC curve depends on the soil type, density, soil state, pore size distribution, presence of salt concentrations, and temperature. The total suction shown in Figure 1 includes two components, matric suction and solute suction (or osmotic suction). Matric suction is calculated in terms of difference in water and air pressures, and the radius of the curvature and the osmotic suction reflects the effect of dissolved salts in the pore fluid. The suction corresponding to the sudden drop in the curve is referred to as air entry value (ψ_a).

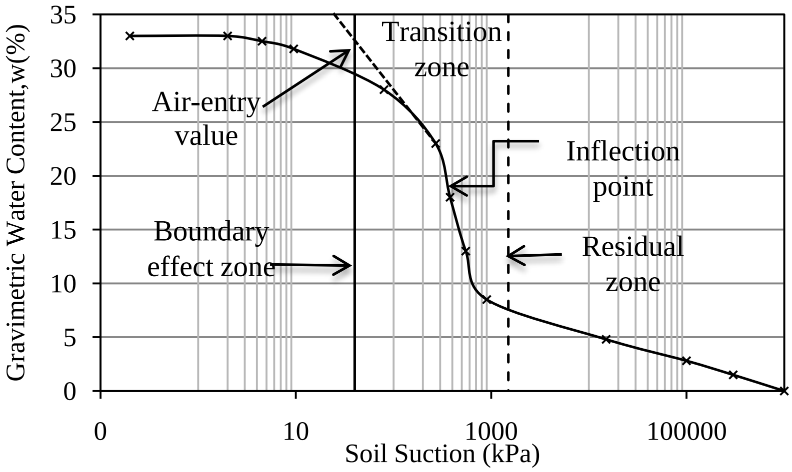

Figure 1: SWCC curve (after Fredlund and Houston, 2009)

One of the important best-fit formulations for the SWCC curve is the Fredlund-Xing equation (Fredlund et al., 1996) shown below.

$$\theta = \theta s\left(\frac{1}{\ln\left(e + \left(\frac{\Psi}{a}\right)\right)^{n}}\right)^{m}$$

Where a, n, and m are three fitting parameters, θ is the volumetric water content , θ_s is the saturated volumetric water content, and e is the irrational constant that is equal to 2.71828. There are several correlations to determine the three fitting parameters based on the plasticity index (PI). One of these correlations was developed by Zapata (1999) as shown below:

$a = 0.00364(WPI)^{3.35} + 4(WPI) + 11$; $m = 0.0514(WPI)^{0.465} + 0.5$;
$n = m(-2.313(WPI)^{0.14} + 5)$; and $h_r = a(32.44e^{0.0186(WPI)})$

Where the WPI is the percent passing the No. 200 sieve (i.e., W) multiplied by the plasticity index of the soil, e is a constant equal to 2.71828 based on natural logarithm. Due to the complexity of conducting sophisticated laboratory tests for calculating lateral swelling pressure, numerical modeling is adequate for simulating swelling soil. Numerical modeling can simulate the swelling soil in an acceptable manner and give the accessibility of simulating complex large-scale problems.

Numerical Analysis

One of the commonly used finite element packages to simulate interaction between the retaining system and the expansive soils with high plasticity is the GeoStudioVer.2012 (GeoStudio Manual, 2012). SIGMA/W is a component of GeoStudio, which is a finite element code that can be used to analyze the stress and deformation of earth structures due to change in soil water content. The software can input the fitting parameters for SWCC models using models such as Fredlund-Xing orVan-Genuchten.SWCC combined with moisture change input allow SIGMA/W to estimate stresses and deformations. SEEP/W is another component of GeoStudio that can estimate the moisture content distribution by inputting the soil permeability properties and flux boundary conditions (i.e., precipitation). Coupling SEEP/W andSIGMA/W allows the estimation of the swelling soil pressure on retaining structures from precipitation input,hence allows a general study of the problem.

Model and Validation

Two numerical models were developed in this study to simulate the work conducted and published in the literature by Wang et al. (2015), and Bin-Shafique et al. (2010). The reason for selecting these models was to compare GeoStudio outcomes with comprehensive/verified field and laboratory results and validate the numerical outcomes to be used later in a parametric study.

The first model consisted of a steel box filled with swelling soil .The exact geometry of the actual laboratory box developed by Wang et al. (2015). In their research, they carried out an experimental study using awall prototype formed of a steel box with dimensions of 2 x 1 x 1 m as shown in Figure 2(a). Two vertical piles of soil bags were used to simulate the rigid retaining wall. A 30 mm PVC plastic tube was used to measure the water levels in the prototype. To measure the lateral swelling pressure of the expansive soils on the retaining walls, soil pressure transducers with a capacity of 0.2 MPa were mounted on the two vertical walls. Figure 2(b) shows a cross section of Wang et al., 2015, test configuration. Figure3 (a) represents the numerical model developed herein for the steel box using SIGMA/W (first validation). The boundary conditions for the numerical model were fixed in both X and Y directions at the bottom, fixed in X and Y directionsalong the vertical sides, and free at the top.

(a)

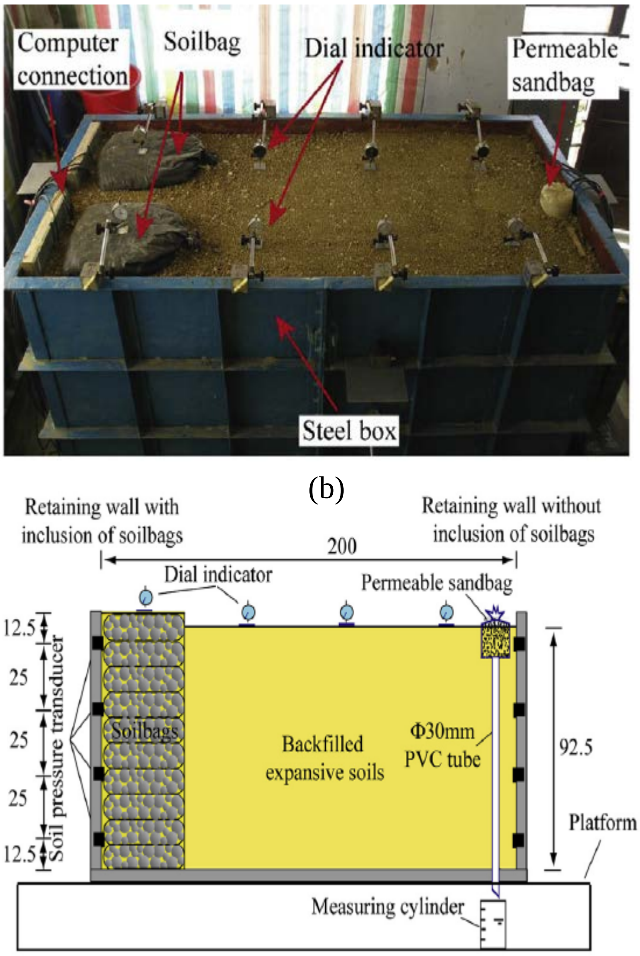

Figure 2: (a) lab model; and (b) test configuration (after Wang et al., 2015) (first validation)

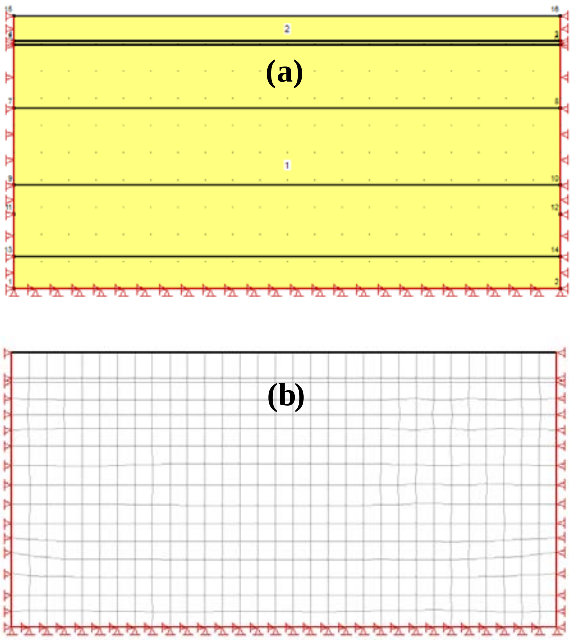

Figure 3: first validation (a)SIGMA/W model; and (b) structured mesh

The material properties of the soil are given in Table 1. A uniform mesh of 0.065 m x 0.065 m was finally used for the final analysis as shown in Figure 3(b).The water content profile properties for the side near the wall is given in Figure 4.

Table 1: Material properties used for swelling soil

Unit	**Value**	**Soil Properties**
Density	20	k N/m^3
Cohesion	10	kN/m^2
Angle of internal friction	20	degree
Poisson's ratio	0.35	-
Specific gravity	2.45	-
Plasticity index	23.3	%
Fredlund Parameters		
a (Air Entry Value)	170.6	kN/m^2
n (Steepness of SWCC)	1.01	-
m (Shape of SWCC)	0.71	-

Figure 5 shows the comparison between numerical result and experimental result. As one can see, numerical and experimental force curves show generally similar patterns. The second validation model is to simulate a drilled shaft wall inserted in swelling soil located in Texas City and conducted by Shafique et al. (2010). The drilled shaft wall was about 20.0m in length. The length of drilled shaft above ground surface is 6 m and the embedded length of drilled shaft is about 14.0 m. The diameter of the drilled shaft is 1.0 m. Figure 6 represents the numerical model outcomes for this wall from SIGMA/W. The drilled shaft is represented as a plate element and the swelling soil is simulated as elastic plastic. The boundary condition for the numerical model is fixed in both X and Y directions in the bottom of the geometry, fixed in X direction and free in Y direction for the vertical side of the geometry and free at the top.

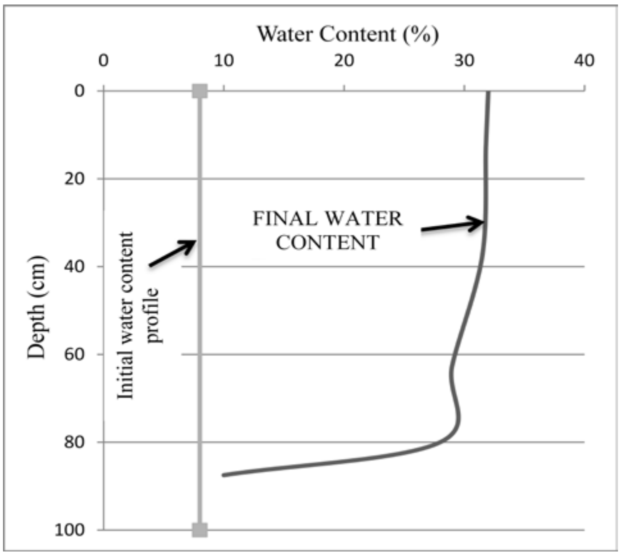

Figure 4: Water content variation through soil depth (after Wang et al., 2015) (first validation)

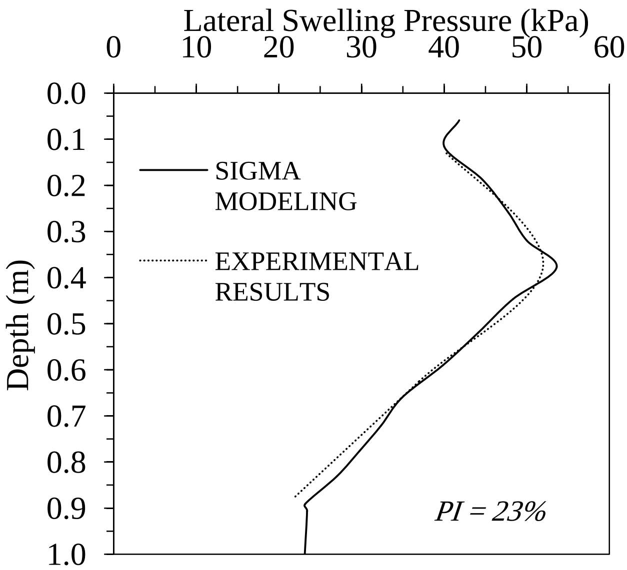

Figure 5: Experimental vs. Numerical Lateral Pressure Curve (after Wang et al., 2015) (first validation)

A uniform mesh of 0.6 m x 0.6 m was used for the final analysis as shown in Figure 6.The material properties of the soil and the wall are given in Table (2). The initial and final water content profile properties for the side near the wall are given in Figure7. The mesh for the model was generated automatically by the software.

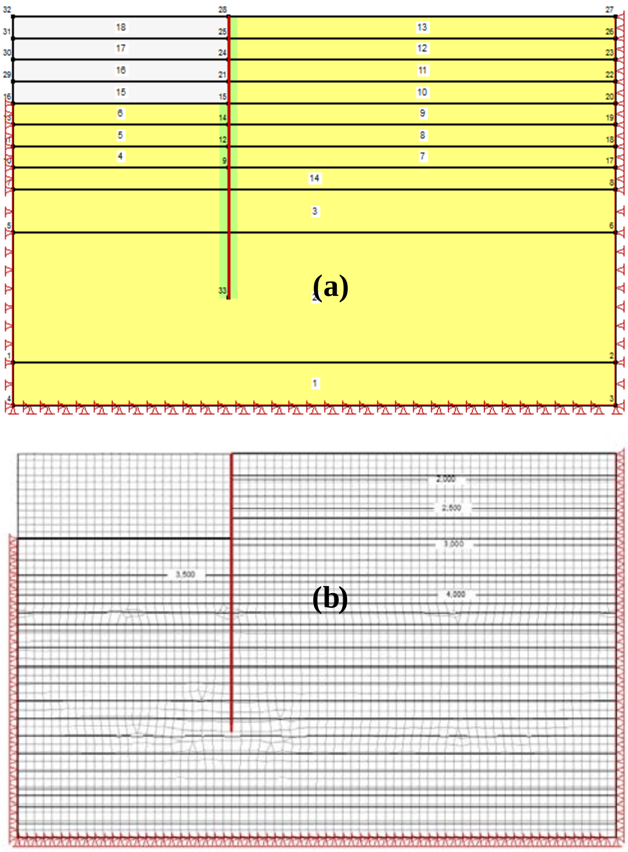

Figure 6: Shafique et al. (2010) (second validation)(a) Numerical model; and (b) structured mesh

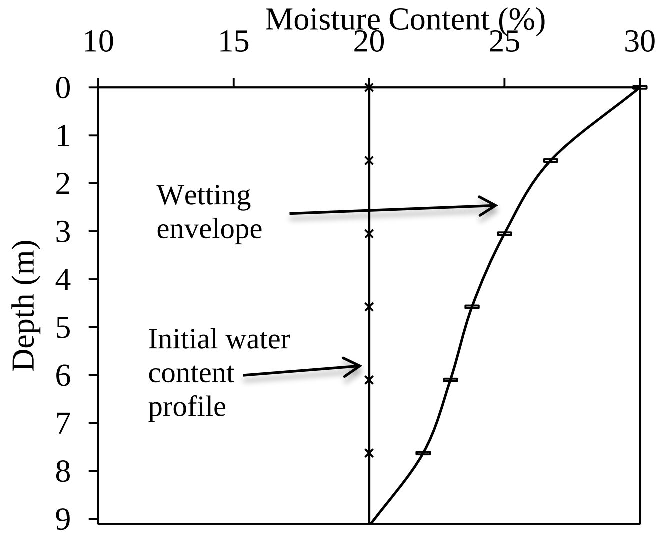

Figure 7: Change in initial and final water contents (after Shafique et al. 2010) (second validation)

Table 2: Material properties for swelling soil

Property	**Value**	**Unit**
Soil Properties		
Poisson ratio	0.34	-
Unit Weight	19	kN/m^3
Angle of Internal Friction	27.5	degrees
Dilation Angle	27.5	degrees
Effective Cohesion (c')	10	kN/m^2
Volumetric Water Content	37.7	%
K-Function Method	Fredlund-Xing Function	-
Volumetric Water Content Function (SWCC)		
Method Used	Fredlund-Xing Function	-
a (Air Entry Value)	732	
n (Steepness of SWCC)	0.77	-
m (Shape of SWCC)	0.89	-

Figure 8 shows the comparison between numerical result and actual result. As one can see, numerical and experimental force curves show generally similar patterns. From both curves there is a slight difference in the pressure through the wall depth.

Parametric Analysis

As previously mentioned, the first validation against the experimental work conducted by Wang et al. (2014) where the plasticity index for swelling soil was about 23% and the maximum lateral swelling pressure was about 53 kPa. A parametric analysis was performed on that first model by changing the soil plasticity index PI as follows: 30, 40, 50, 60, 70, and 80 %, which the initial water content was kept constant. For each model, the Fredlund input parameters a, m,n, and hr were changed according to the soil PI. Results of this parametric study are presented in Figure 9, where the lateral swelling pressure on the wall was found directly corelated with the PI and may vary by ± 50% at the lower third of the wall depth (the peak pressure point for this cantilever wall).

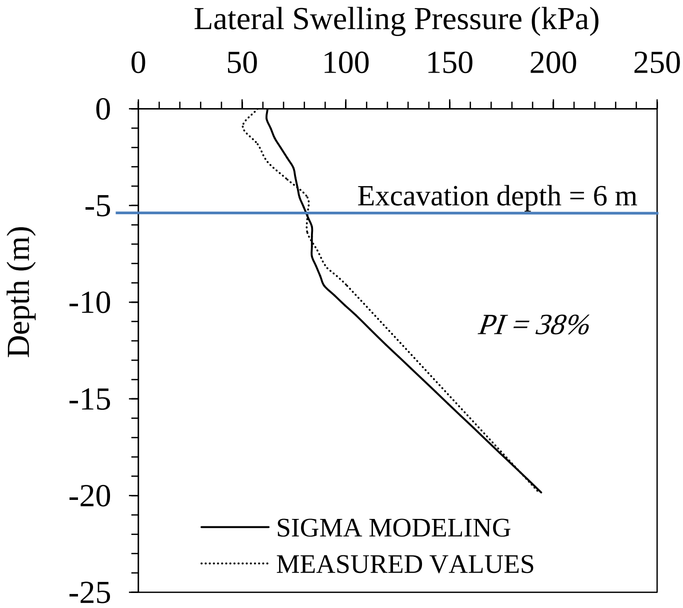

Figure 8: Experimental vs. Numerical Lateral Pressure Curve (Shafique et al. 2010) (second validation)

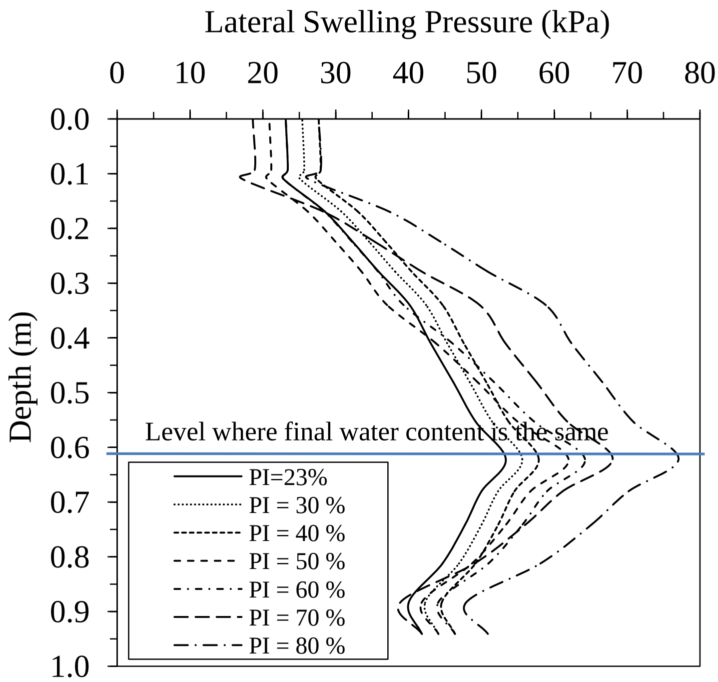

Figure 9: Effect of changing the PI on lateral swelling pressure (Applied Wang et al., 2015) (first validation)

The second validation model was against the study conducted by Shafique et al. (2010), which was based on changing the plasticity index to 20% and 60% to show the effect of changing plasticity index on swelling pressure.A parametric analysis was also considered herein, where the PI was changed as represented in Figure 10. From the figure, the plasticity index affected the lateral pressure within the top third zone of the wall depth. However, the differences were limited to around ± 15% by changing the PI from 38% to 60%. Along the remaining depth of the wall, the PI did not have a significant effect on the swelling pressure since the wall is embedded in the ground.

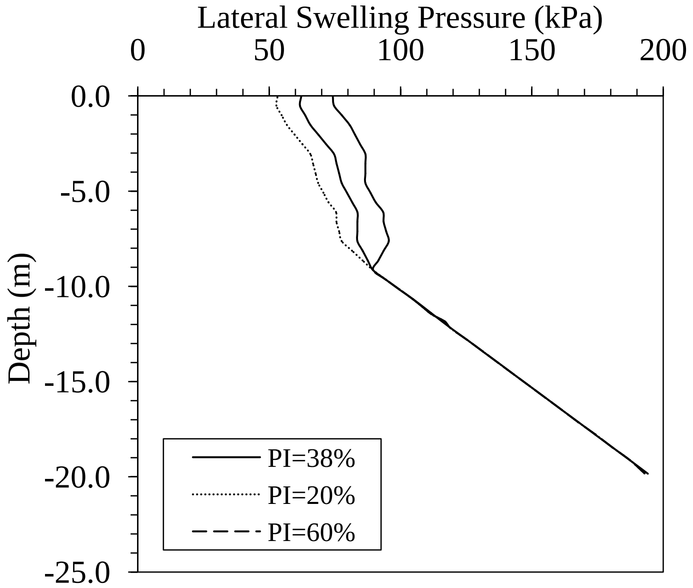

Figure 10: Effect of Changing PI on Lateral Swelling Pressure- (Applied Shafique et al. 2010) (second validation)

Conclusions

This study focused on estimating the lateral swelling pressure applied on retaining systems using finite element modeling based on Fredlund-Xing fitting equation for the SWCC. Two types of retaining systems were considered, first for cantilever walls, and second for embedded walls. A summary of the major findings is as follows:

- Lateral swelling pressure is highly affected by the soil water content.
- Lateral swelling pressure is directly proportional with the soil plasticity index.
- The application of correlation equation by (Zapata) to estimate SWCC fitting parameters is adequate for estimating the swelling pressure in the validation model.
- For cantilever walls, swelling pressure varies by ±50% by changing the PI, where peak stress occurs at bottom third of the wall and diminish at the wall base.
- For embedded walls, changes in swelling pressure with plasticity index are limited to ±15%.

- Charts are provided to summarize change in lateral swelling pressure versus soil PI.

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