Numerical analysis of expansive soil behaviour using the Swell Equilibrium Limit

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ABSTRACT
Soil deformation in swelling clay often cause excessive ground movements and swell pressures on adjacent structures. The excessive deformation could cause adverse impacts on the integrity of a structure. Siemens and Blatz (2008a) proposed a new method to describe swelling soil behaviour which is known as the Swelling Equilibrium Limit (SEL). The proposed method captures the behaviour of expansive soil under the boundary conditions ranging from constant stress to constant volume. In the field, soil expansion is subjected to a wide influence of the boundary conditions that may be captured by the SEL. In this paper, a numerical analysis is completed to show how the SEL can be used to analyze foundations constructed in swelling soil. The numerical model is first calibrated to laboratory swell tests on Bearpaw Formation. Following calibration with the experimental data, the model is used to investigate soil deformations and induced-stresses of a basement foundation during wetting conditions. Sensitivity analysis was performed to determine the influence of model parameters.

RÉSUMÉ
La déformation des sols dans les argiles gonflantes causent souvent des pressions et des déplacements excessifs. La déformation excessive peut avoir des effets néfastes sur une structure. Siemens et Blatz (2008a) ont proposé une nouvelle méthode pour décrire le comportement des sols gonflants, connue sous le nom de Limite de Gonflement à l'Équilibre (LGE). La méthode proposée capte le comportement d'un sol gonflant sous des conditions limites allant de "contraintes constantes" à "volume constant". Sur le terrain, le gonflement est assujettis à une vaste gamme de conditions limites qui peuvent être captées par la LGE. Dans cet article, une analyse numérique est effectuée pour montrer comment la LGE peut être utilisée pour l'étude des fondations construites dans les sols gonflants. La LGE est tout d'abord calibrée contre des essais de gonflements réalisés sur du Formation de Bearpaw. Par la suite, le modèle est utilisé pour étudier les déplacements d'une fondation durant des conditions de mouillage. Une analyse de sensibilité à été réalisée pour déterminer l'influence des paramètres du modèle.

1 INTRODUCTION

Structures constructed in expansive soil can be subjected to excessive swell-induced deformation or pressure which would adversely affect the structure's integrity. Engineered design should account for swell-induced impacts in order to avoid or minimize the cost of repairing the damage caused.

The evidence of damage caused by swelling to a residential basement is demonstrated in Figure 1. Cracking of floor slab is commonly seen as evidence of neglecting swelling considerations in expansive soil. If damage caused are not taken care of in a timely manner more serious structural defects can occur.

The objective of this paper is to present a practical design analysis that includes swell-induced effects. Recent insight gained from the research in expansive soil provides a different perspective from the conventional consideration. A new relationship termed the 'Swell Equilibrium Limit' (SEL) by Siemens and Blatz (2008a) is capable of describing general swelling soil behaviour in a broader perspective. Traditionally the conventional one-dimensional oedometer test measures the swell pressure and the amount of vertical heave (ASTM 4546). Swelling behaviour between the two extreme boundaries is not normally well defined in oedometer test. The SEL provides a general limit to swelling induced stresses and displacements. In this paper an example analysis using the Finite Element Method (FEM) is performed displaying use of the SEL in the foundation design. Oedometer results are converted into the SEL framework and then the SEL is used to predict equilibrium stresses and deformations on a foundation constructed in swelling soil.

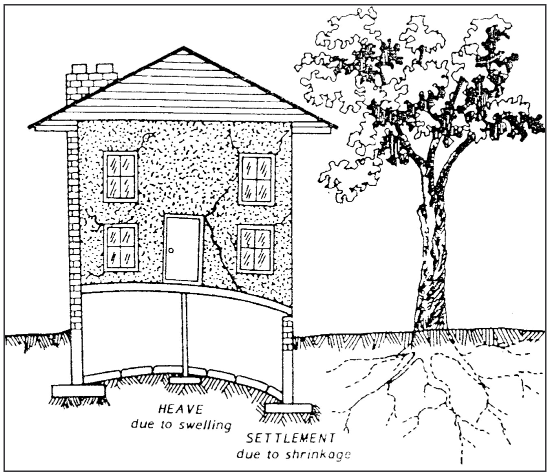

Figure 1. Damage to houses caused by ground movements of swelling soils (Domaschuk, 1986).

2 SWELL EQUILIBRIUM LIMIT (SEL)

The Swell Equilibrium Limit (SEL) forms a limit to expansion and swelling-induced stresses during wetting (Siemens and Blatz 2008a). It is a characteristic curve for each expansive soil depending on montmorillonite content and dry density. The SEL for bentonite-sand-buffer is plotted in Figure 2 in specific volume – mean stress space. It forms a limit to volume expansion and swelling-induced stress when the swell potential of the soil comes into equilibration with the imposed hydraulic and mechanical boundary conditions. The new relationship was discovered through the testing of highly expansive soil (bentonite-sand-buffer (BSB)) under the influence of controlled infiltration boundary conditions in an automated triaxial infiltration test (Siemens 2006, Siemens and Blatz 2008a). The SEL defines equilibrium swelling soil behaviour ranging from maximum expansion to maximum swelling induced stress.

2.1 Stress Paths to reach the Swell Equilibrium Limit

The conventional oedometer test captures the swell-induced response in either free swelling or constant volume conditions in the vertical direction (ASTM 4546). The soil behaviour in between these two extremes is not normally defined. The newly developed automated triaxial apparatus (Siemens and Blatz 2008a) is able to apply general boundary conditions to the tested specimen during infiltration.

A schematic plot of the stress paths in the automated triaxial test is shown in Figure 3. In the triaxial infiltration test free swell is referred to as 'constant mean stress' (CMS) where no constraint of volume change is imposed to the specimen. Fully constrained volume change in the triaxial test is termed as 'constant volume' (CV) where the specimen is subjected to high confining pressure in order to maintain the specimen's original volume. The interim condition, termed 'constant stiffness' (CS) boundary condition, acts as a flexible spring-type boundary condition under which both expansion and swelling-induced pressures are applied.

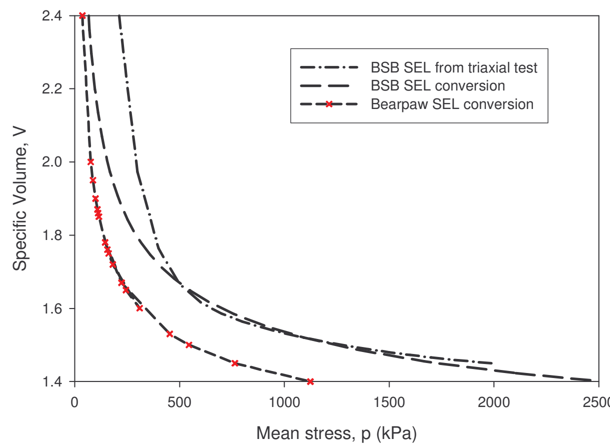

Figure 2. The Swell Equilibrium Limit (SEL) plotted in specific volume versus mean stress space.

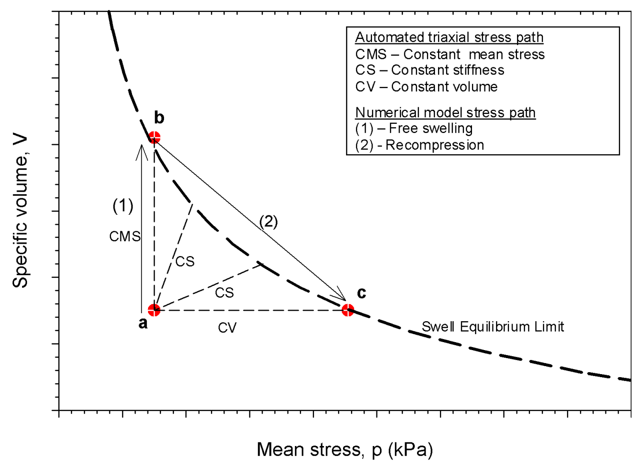

Figure 3. Boundary conditions applied in automated triaxial infiltration test and numerical model in specific volume versus mean stress space.

The SEL is directly defined by a curve fitting of all the 'end of test' experimental data points. The 'end of test' points indicate the final state of soil when the swelling potential comes into equilibrium under the imposed conditions. In addition, the SEL was shown to agree with one-dimensional swell pressure tests. Siemens and Blatz (2008a) successfully converted a swell pressure relationship given by Dixon et al. (2002) to compare with the SEL plot as shown in Figure 2. The relationship provided by Dixon et al. (2002) correlates one-dimensional swell pressures with the 'effective montmorillonite dry density' (EMDD). Siemens and Blatz (2008a) detail the process to convert the swell pressure – EMDD to an equivalent mean stress using an assumption of elasticity. The converted curve from Dixon et al. (2002) shows remarkable well comparison to the SEL curve.

The current study shows how traditional one-dimensional swell tests can be used in design in the SEL context. Traditional swell pressure tests were completed and the results used to predict swelling induced stresses and deformations on foundation footings and walls. Test data is obtained from an on-going research project (Boyle 2007) in which a series of one-dimensional swell pressure measurements have been made on samples of the Bearpaw Formation, an extensive, Cretaceous-age, clayey silt bedrock unit in southern Saskatchewan. Although examples of foundations constructed in Bearpaw are limited, the purpose of the paper is to display a design procedure for expansive soils. Using a similar process as detailed in Siemens and Blatz (2008a) and Siemens (2006), a preliminary SEL for Bearpaw was found and plotted in Figure 2. Comparing the BSB and Bearpaw SEL curves, the clay and montmorillonite content of BSB is higher than Bearpaw and it has a greater dry density (lower specific volume), hence the SEL curve of BSB is reasonably located at a higher point in the volume-stress plot. Higher swelling potential results in greater equilibrium induced-pressures and volume change. Given initial stress and volume conditions, the SEL is used to predict the swell-induced soil behaviour given initial soil conditions and boundary conditions that are defined by the foundation application.

3 NUMERICAL MODEL USING THE SWELL EQUILIBRIUM LIMIT

The finite element programs used in this paper are SIGMA/W and SEEP/W from GeoStudio 2007. The stress distribution and volume change are analysed in SIGMA/W while the pore water pressure distribution is generated in SEEP/W. The numerical analysis begins with calibration of the experimental data (oedometer) using the concept of the SEL.

3.1 Insitu Analysis

The insitu analysis step builds in the initial stresses in the model. The initial condition is set-up by axis-symmetric (half-space model) ‘insitu’ analysis with the boundaries applied as per the oedometer test. As the soil specimen is constrained laterally in the oedometer ring both sides of the model boundaries are constrained horizontally but allowed to move vertically. A linear elastic model with Young’s Modulus, E=50 MPa (Hanna and Little, 1992) and Poisson’s ratio, ν = 0.2 was used for this step. The insitu stress field is used as the initial stress condition for the subsequent free swell analysis.

3.2 Free Swell Analysis

The free swelling process is modeled by the change in pore water pressure from unsaturated (with initial suction) to saturated (hydrostatic pressure) condition. Free swell in the numerical model is comparable to ‘constant mean stress’ in the SEL plot. The maximum volume change can be anticipated by the SEL curve where the soil will follow a vertical stress path from point ‘a’ to ‘b’ (Figure 3) until it reaches the SEL line.

In order to allow the soil to expand to the desired volume change, the soil stiffness is varied in the model until the amount of heave matches the prediction of the SEL curve. The free swell stiffness with respect to the predicted heave in numerical model is termed ‘$E_{free\ swell}$’.

For the laboratory study specimens were taken from a depth of 45 to 90m and had an unknown initial suction following removal from the insitu condition. The influence of the initial pore water pressure distribution was examined by varying three different suction levels (Δsuction), namely, 600kPa, 1000kPa and 1500kPa. Interestingly, the ratio of $E_{free\ swell}/\Delta$suction obtained from the numerical model is 5 for all the three different suction levels. A constant ratio was anticipated since the same displacement was modelled for each case.

There is inadequate test results on the material properties under the influence of different suctions in the current paper. Nevertheless, the study by Blatz et al. (2002) shows that increasing suction appears to have significant influence on the initial stiffness of the material. In future tests, initial suction will be measured and the final $E_{free\ swell}$ will be known.

3.3 Recompression Analysis

The ‘constant volume’ stress path (from point ‘a’ to point ‘c’ in Figure 3) can not be modeled directly in this type of numerical analysis since the swell pressure is generally less than the change in suction. Therefore, a recompression step is required to compress the swelled soil back to the original volume (from point ‘b to point ‘c’) to simulate the ‘constant volume’ stress path.

The objective of the recompression model is to reach the final state which is defined as point ‘c’ in the SEL plot. The known heave displacement from the previous free swell model is applied to the recompression model in a separate ‘load/deformation’ analysis. When the soil element is recompressed under hydrostatic conditions the swell-induced pressure can be related to effective vertical stress in the model. The material stiffness is varied until the effective vertical stress matches the measured swell pressure from the lab. The stiffness specified at this stage is termed as ‘$E_{recompression}$’.

$E_{recompression}$ from the analyses of the three different suction levels is constant ($E_{recompression}$ = 1164kPa). This is due to all recompression analyses compressing the same amount of heave under a hydrostatic pore water pressure distribution (eg, ponding).

For an initial suction value of 1500 kPa, the $E_{free\ swell}$ and $E_{recompression}$ of the expansive soil obtained from the numerical analysis is 7500kPa and 1164kPa, respectively. For the three initial suction levels applied, the ratio of $E_{free\ swell}/E_{recompression}$ is in the range of 2.6 to 6.4. A range is anticipated since the deformation amounts remain the same while the initial suction level is altered.

4 APPLICABILITY OF THE SWELL EQUILIBRIUM LIMIT IN PRACTICAL DESIGN

The applicability of the SEL in predicting the expansive soil response is shown in a basement foundation model. The soil below the basement would be under a ‘constant mean stress’ path because there is no significant constraint on the soil movement. Soil adjacent to the basement wall is likely to follow the ‘constant stiffness’ or ‘constant volume’ stress path. Soil movement is constrained by the stiff retaining system used in the basement wall.

Following a similar procedure as in the oedometer calibration, the SEL is used to predict vertical and horizontal deformation and swelling-induced stresses adjacent to the basement wall.

4.1 Modelling of a Basement Foundation

Swelling mechanisms induce volume change and stresses in the soil. The degree of change is observed as wall displacement and basement heave in the model. The magnitude of soil displacement indicates the amount of soil expansion when swelling occurs. The soil deformation result obtained from ‘volume change’ analysis assumed the pore water pressure distribution changed from unsaturated to saturated condition.

A foundation was analysed in a half space two-dimensional finite element mesh. The dimension of the basement was 2.5m in depth and 10m in total width. Initial groundwater table was assumed at 7.5m depth. Parameters including initial suction level, $E_{free\ swell}$ and $E_{recompression}$ used in the basement model were taken from the previous calibration exercise. A similar model process including insitu, free swell and recompression steps were followed.

A worst case scenario was simulated as ponding where the initial suction is lost due to the infiltration and inundation in the basement. The change in pore water pressure from dry condition (initial suction) to wet condition (saturation) simulates the swelling phenomenon in the expansive soil. This is an extreme event that could occur during an extended rainfall event or locally around the basement if proper drainage is not ensured.

Besides soil deformation, swell-induced stress on the adjacent structure (eg, basement wall) is another good indication on how much additional pressure has been exerted on the structure in addition to the mechanical loadings from the building and the retained soil. Stress and strain are the two fundamental variables in engineering design. Therefore, it is essential to look into the modelling result in these two particular aspects. The study of swelling soil behaviour in this paper is focused on the basement wall displacement, basement heave and swell-induced pressure on the wall.

4.2 Soil Deformation in Basement Foundation

When the soil in the basement swells, wall displacement and basement heave are the primary concerns in the engineered design. Structures should be checked for their deformation tolerance and serviceability limit during the functional design life.

Following definition of initial stresses and suction, a ‘free swell’ analysis was performed on an ‘open’ basement excavation. An initial suction of 1500, 1000 or 600kPa was applied at the surface and the bottom boundary condition (at the depth of 25m) was at the water table of 7.5m depth.

The unrestrained horizontal displacement due to ponding is shown in Figure 4. The highest horizontal wall displacement is estimated at 753mm at the top of the wall while the maximum basement heave is approximately 91mm at the centre of basement.

The influence of suction on soil deformation is investigated in Figure 5. A normalised plot of suction levels versus the swell-induced wall displacement is illustrated. At the lowest initial suction of 600kPa, the increase in wall displacement is close to 18% compared to the maximum wall deformation of 1500kPa initial suction. The slope of the linear relationship in the plot is 0.03. This shows the model is relatively insensitive to changes in the initial condition. This is anticipated since the $E_{free\ swell}$ value for each model was calibrated using the oedometer results.

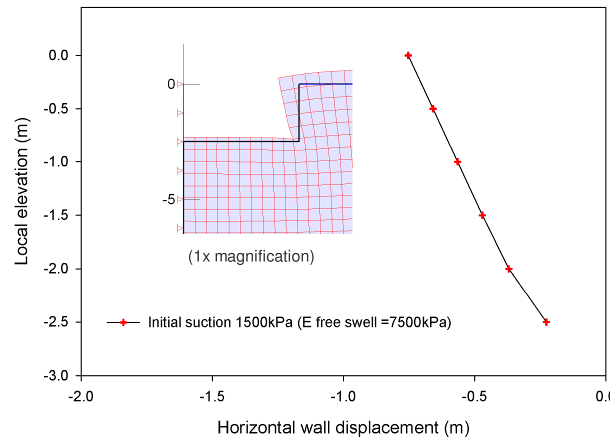

Figure 4. Horizontal wall displacement due to ponding at basement foundation.

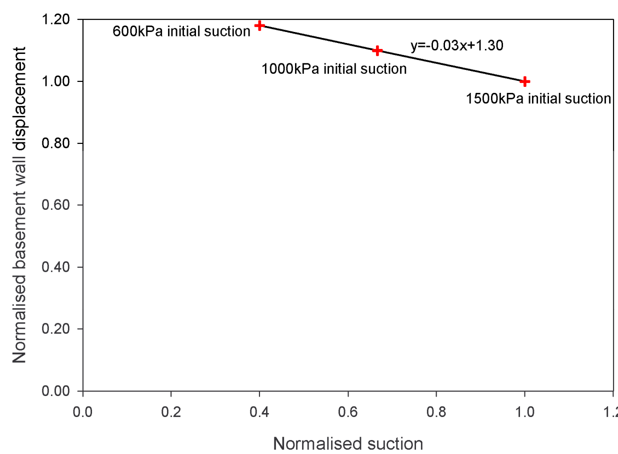

Figure 5. Normalised suction versus normalised wall displacement.

An analysis on the effects of varying depths of expansive soil layer on the amount of heave was also carried out. In Figure 6, the result of heave is normalised with respect to the heave in 25m full depth of expansive soil layer. The result shows that, as anticipated, as the depth of expansive soil layer increases the amount of heave increases. The heave of the 12.5m deep expansive layer

(50% of the full depth) is approximately 40% of the maximum heave.

Plotting the normalised depth of expansive layer versus normalised maximum vertical displacement (heave) at the basement foundation, Figure 7 shows the model behaves as expected. The positive slope of the fitted curve indicates greater deformations will occur in foundations constructed in thicker expansive layers.

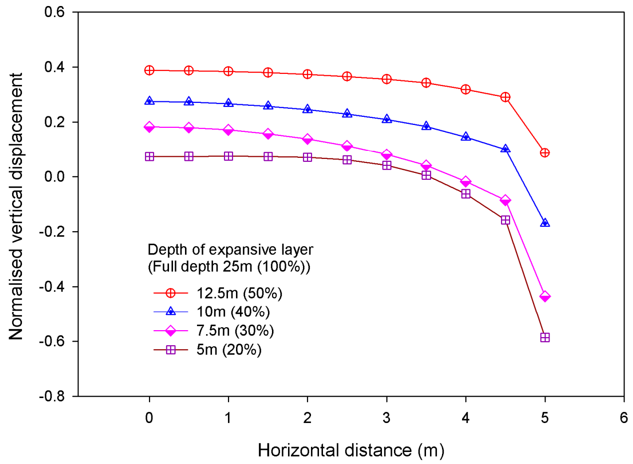

Figure 6. Normalised vertical displacement at basement foundation with respect to the vertical heave that occurs at 25m depth of expansive soil.

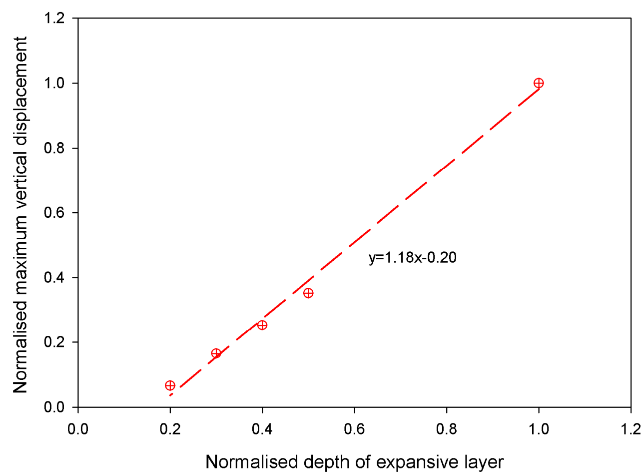

Figure 7. Normalised depth of expansive layer versus normalised maximum vertical displacement at the basement foundation.

4.3 Swell-induced Pressure and the Constant Stiffness Stress Path

The swell-induced pressure on the basement wall was investigated through the recompression model in the analysis. Commonly the basement wall would be designed with either timber or concrete materials depending on the suitability and the estimated lateral pressure on the wall. The stiffer material such as reinforced concrete will tend to have reduced displacements but corresponding increased horizontal pressures.

According to the SEL concept, the ‘constant stiffness’ stress path (Figure 3) represents different degrees of volume confinement in the soil. Recompressing the swelling soil back to the original volume is regarded as ‘full recompression’. To simulate varying confinement conditions the soil was recompressed partially back to 40% or 70% of the full displacement. As shown in Figure 3 the SEL is non-linear. Partially recompresion using a constant stiffness will therefore provide a conservative over estimation of the swelling induced stresses.

Swelling-induced stresses occur due to restrained boundary conditions. The results of swell pressure on the basement wall are presented in Figure 8. The maximum swell-induced pressure of full recompression is approximately 209kPa which is very close to the measured swell pressure obtained from the lab test.

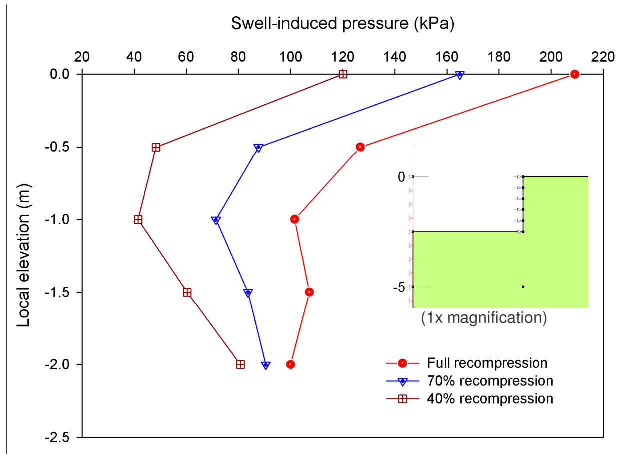

Figure 8. Swell-induced pressure on the basement wall with varying degree of recompression.

Figure 8 shows that as the degree of recompression decreases (more movement is allowed), the corresponding pressure of the wall decreases. It is a reasonable soil response since less pressure is induced when the soil deformations increase (less recompression).

The swell pressure of the basement wall was normalized to the maximum swell pressure and plotted versus varying degree of recompression. Figure 9 exhibits a linear relationship with a positive slope indicating a direct relationship between swelling induced pressure and recompression.

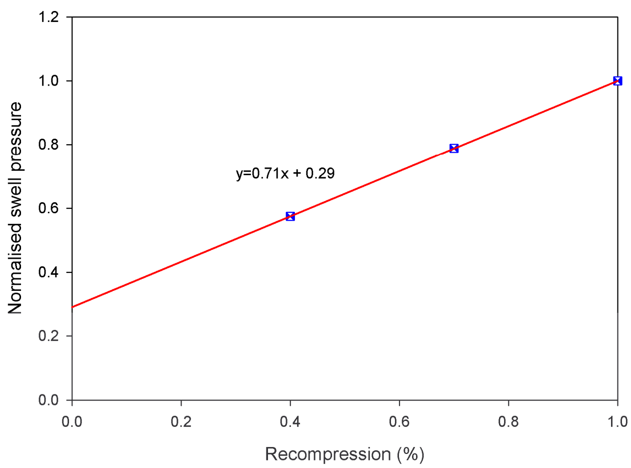

Figure 9. Normalised swell pressure versus varying degree of recompression.

With the predicted soil deformations and swell-induced pressures a better engineered structure can now be designed if the worst case condition (eg, ponding) would ever occur to the structure constructed in expansive soil.

5 CONCLUSIONS

Neglecting swelling effects in highly swelling soil will inevitably cause unforeseen maintenance costs in the future. This paper developed a method for using the Swell Equilibrium Limit for design of a foundation in swelling soil. It should be noted that this is a preliminary study and that the predicted pressures and displacements must be verified with field data.

The parameters used in this model provide realistic insight to the soil behaviour. The excessive soil deformation and swell pressure predicted by the SEL should be taken as a design consideration for structures constructed in high swelling potential ground.

Precautionary measures could include either reinforcing the structures with the anticipated deformation and stress or properly managing the drainage system in order to avoid excessive water ingress into the soil.

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