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A Appendix A - Symbols
THE SOFT-SOIL MODEL

For understanding the significance of the Soft-Soil model, we have to point out that Version 7 provides a change in the soil modelling policy of PLAXIS. Up to Version 6 we had the Mohr-Coulomb model, the Soft-Soil model and the Hard-Soil model. For Version 7, however, we dropped the idea of using separate models for soft soil and hard soil respectively. Instead, the previous Hard-Soil model was further developed to become an advanced model both for soft soil and hard soil. This has resulted into the present Hardening-Soil model. At the same time the Soft-Soil-Creep model was implemented to capture some of the very special features of soft soil. As a consequence, the old Soft-Soil model was superseded both by the new Hardening-Soil model and the Soft-Soil-Creep model. Hence, the old Soft-Soil model might have been dropped out of the set of models that is provided by the PLAXIS code. However, in order not to rob users from models that they have got to know well, it was decided to retain the Soft-Soil model in PLAXIS Version 7. Some characteristics of the Soft-Soil model are:

- Stress dependent stiffness (logarithmic compression behaviour).
- Distinction between primary loading and unloading-reloading.
- Memory for pre-consolidation stress.
- Failure behaviour according to the Mohr-Coulomb criterion.

6.1 ISOTROPIC STATES OF STRESS AND STRAIN \((\sigma_1' = \sigma_2' = \sigma_3')\)

In the Soft-Soil model, it is assumed that there is a logarithmic relation between the volumetric strain, \(\varepsilon_v\), and the mean effective stress, \(p'\), which can be formulated as:

\[
\varepsilon_v - \varepsilon_v^0 = - \lambda^* \ln \left( \frac{p'}{p_0'} \right) \quad \text{(virgin compression)}
\]  

(6.1)

In order to maintain the validity of Expression (6.1) a minimum value of \(p'\) is incorporated equal to 1 stress unit. The parameter \(\lambda^*\) is the modified compression index, which determines the compressibility of the material in primary loading. Note that \(\lambda^*\) differs from the index \(\lambda\) as used by Burland (1965). This is because Eq. (6.1) involves the volumetric strain instead of the void ratio. When plotting Eq. (6.1) one obtains a straight line as shown in Fig. 6.1. During isotropic unloading and reloading a different line is followed, which can be formulated as:

\[
\varepsilon_v - \varepsilon_v^{e0} = - \kappa^* \ln \left( \frac{p'}{p_0} \right) \quad \text{(unloading and reloading)}
\]  

(6.2)
Again, a minimum value of \( p' \) is incorporated in Eq. (6.2) equal to 1 stress unit. The parameter \( \kappa' \) is the modified swelling index, which determines the compressibility of the material in unloading and subsequent reloading. Note that \( \kappa' \) differs from the index \( \kappa \) as used by Burland. The ratio \( \lambda' / \kappa' \) is, however, equal to Burland's ratio \( \lambda / \kappa \). The soil response during unloading and reloading is assumed to be elastic, which explains the superscript \( e \) in Eq. (6.2). The elastic behaviour is described by Hooke's law of elasticity (see Section 2.2) and Eq. (6.2) implies the following linear stress dependency of the tangent bulk modulus:

\[
K_{ur} = \frac{E_{ur}}{3 \left(1 - 2v_{ur}\right)} = \frac{p'}{\kappa'}
\]  

(6.3)

The subscripts \( ur \) are used to denote that the parameters relate to unloading and reloading. Note that effective parameters are considered rather than undrained soil properties, as might be suggested by the subscripts \( ur \). Neither the elastic bulk modulus, \( K_{ur} \), nor the elastic Young's modulus, \( E_{ur} \), is used as an input parameter. Instead, \( v_{ur} \) and \( \kappa' \) are used as input constants for the part of the model that computes the elastic strains.

An infinite number of unloading / reloading lines exist in Fig. 6.1, each corresponding to a particular value of the isotropic pre-consolidation stress \( p_p \). The pre-consolidation stress represents the largest stress level experienced by the soil. During unloading and reloading, this pre-consolidation stress remains constant. In primary loading, however, the preconsolidation stress increases with the stress level, causing irreversible (plastic) volumetric strains.
6.2 YIELD FUNCTION FOR TRIAXIAL STRESS STATE \((\sigma_2' = \sigma_3')\)

For the sake of convenience, restriction is made here to triaxial loading conditions with \(\sigma_2' = \sigma_3'\). For such a state of stress the yield function of the Soft-Soil model is defined as:

\[
f = \frac{f}{p} - \frac{p_p}{p}
\]  

(6.4)

where \(f\) is a function of the stress state \((p', q)\) and the pre-consolidation stress \(p_p\) is a function of plastic strain:

\[
f = \frac{q^2}{M^2 (p' + c \cot \varphi)} + p'
\]  

(6.5)

\[
p_p = p_p^0 \exp \left[ \frac{-\psi'' \rho}{\lambda^* - \kappa^*} \right]
\]  

(6.6)

The yield function \(f\) describes an ellipse in \(p'-q\)-plane, as illustrated in Fig. 6.2. The parameter \(M\) in Eq. (6.5) determines the height of the ellipse. The height of the ellipse is responsible for the ratio of horizontal and vertical stress in primary one-dimensional compression. As a result, the parameter \(M\) determines largely the coefficient of lateral earth pressure, \(K_0^{nc}\). In view of this, the value of \(M\) can be chosen such that a known value of \(K_0^{nc}\) is matched in primary one-dimensional compression. Such an interpretation and use of \(M\) differs from the original critical state line idea, but it ensures a proper matching of \(K_0^{nc}\).

The tops of all ellipses are located on a line with inclination \(M\) in the \(p'-q\)-plane. In the Modified Cam-Clay model (Burland 1965, 1967) the \(M\)-line is referred to as the critical state line and represents stress states at post peak failure. The parameter \(M\) is then based on the critical state friction angle. In the Soft-Soil model, however, failure is not necessarily connected to critical state. The Mohr-Coulomb failure criterion is used with strength parameters \(\varphi\) and \(c\), which need not correspond to the \(M\)-line.

The isotropic pre-consolidation stress, \(p_p\), determines the magnitude of the ellipse. An infinite number of ellipses therefore exist (see Fig. 6.2), each one corresponding to a particular value of \(p_p\). The left hand side of the ellipse is extended into the 'tension' zone of the principal stress space \((p' < 0)\) by means of the term \(c \cot \varphi\) in Eq. (6.5). In order to make sure that the right hand side of the ellipse (i.e. the 'cap') will remain in the 'compression' zone \((p' > 0)\) a minimum value of \(c \cot \varphi\) is adopted for \(p_p\). For \(c = 0\), a minimum value of \(p_p\) equal to 1 stress unit is adopted. Hence, there is a 'threshold' ellipse as illustrated in Fig. 6.2.
Figure 6.2  Yield surface of the Soft-Soil model in $p'$-$q$-plane

The value of $p_p$ is affected by volumetric plastic straining and follows from the hardening relation as formulated in Eq. (6.6). This equation reflects the principle that the pre-consolidation stress increases exponentially with decreasing volumetric plastic strain (compaction). The value $p_p^0$ can be regarded as the initial value of the pre-consolidation stress. The determination of $p_p^0$ is treated in Section 2.5. According to Eq. (6.6) the initial volumetric plastic strain is assumed to be zero.

In the Soft-Soil model, the yield function as defined in Eq. (6.4) is only active to model the irreversible volumetric straining in primary compression and is used as the cap of the yield contour. In order to model failure behaviour, a perfectly-plastic Mohr-Coulomb type yield function is introduced. This yield function represents a straight line in $p'$-$q$-plane. The line is indicated in Fig. 6.2 as the ’Mohr-Coulomb failure line’. The inclination of the failure line is smaller than the inclination of the $M$-line.

The total yield contour, as shown by the bold lines in Fig. 6.2, is the boundary of the elastic stress area. The failure line is fixed, but the cap may increase in primary compression. Stress paths within this boundary only give elastic strain increments, whereas stress paths that tend to cross the boundary generally give both elastic and plastic strain increments.

For general states of stress, the plastic behaviour of the Soft-Soil model is defined by a total of six yield functions; three compression yield functions and three Mohr-Coulomb yield functions. The total yield contour in principal stress space, resulting from these six yield functions, is indicated in Fig. 6.3.
6.3 PARAMETERS IN THE SOFT-SOIL MODEL

The parameters of the Soft-Soil model coincide with those of the Soft-Soil-Creep model. However, since the Soft-Soil model does not include time dependent behaviour, the modified creep index \( \mu^* \) is missing. In conclusion, the Soft-Soil model requires the following material constants:

**Basic parameters:**

- \( \lambda^* \): Modified compression index [-]
- \( \kappa^* \): Modified swelling index [-]
- \( c \): Cohesion [kN/m²]
- \( \varphi \): Friction angle [°]
- \( \psi \): Dilatancy angle [°]

**Advanced parameters (use default settings):**

- \( v_{ur} \): Poisson’s ratio for unloading / reloading [-]
- \( K_0^{NC} \): Coefficient of lateral stress in normal consolidation [-]
- \( M \): \( K_0^{NC} \)-parameter [-]

Instead of a direct input of \( M \), input is required for the coefficient of lateral earth pressure in a state of normal consolidation \( K_0^{NC} \), from which \( M \) is calculated automatically (see Eq. 6.8). Note that in the current model the meaning of \( M \) differs from the Modified Cam-Clay model where \( M \) is related to the material friction.
**Modified swelling index and modified compression index**

These parameters can be obtained from an isotropic compression test including isotropic unloading. When plotting the logarithm of the mean stress as a function of the volumetric strain for clay-type materials, the plot can be approximated by two straight lines (see Fig. 6.1). The slope of the primary loading line gives the modified compression index, and the slope of the unloading (or swelling) line gives the modified swelling index. Note that there is a difference between the modified indices $\kappa^*$ and $\lambda^*$ and the original Cam-Clay parameters $\kappa$ and $\lambda$. The latter parameters are defined in terms of the void ratio $e$ instead of the volumetric strain $\varepsilon_V$.

![Figure 6.4 Parameters tab for the Soft-Soil model](image)

Apart from isotropic compression tests, the parameters $\kappa^*$ and $\lambda^*$ can be obtained from one-dimensional compression tests. Here a relationship exists with the internationally recognized parameters for one-dimensional compression and unloading, $C_c$ and $C_s$. Another relationship exists with the Dutch parameters for one-dimensional compression, $C_p$ and $C_p'$. All relations are summarized in Table 6.1.

**Table 6.1a Relationship to Cam-Clay parameters**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\lambda^* = \frac{\lambda}{1 + e}$</td>
</tr>
<tr>
<td>2.</td>
<td>$\kappa^* = \frac{\kappa}{1 + e}$</td>
</tr>
</tbody>
</table>

**Table 6.1b Relationship to Dutch engineering practice**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.</td>
<td>$\lambda^* = \frac{J}{C_p}$</td>
</tr>
<tr>
<td>4.</td>
<td>$\kappa^* = \frac{1 - \nu_{ur}}{1 + \nu_{ur}} \frac{3}{C_p}$</td>
</tr>
</tbody>
</table>
Table 6.1c  Relationship to internationally normalized parameters

<p>| | |</p>
<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>( \lambda^* = \frac{C_c}{2.3 (1 + e)} )</td>
</tr>
<tr>
<td>6.</td>
<td>( \kappa^* = \frac{1 - \nu_{ue} C_s}{1 + \nu_{ue} (1 + e)} )</td>
</tr>
</tbody>
</table>

Remarks on Table 6.1:

- In relations 1 and 2, the void ratio, \( e \), is assumed to be constant. In fact, \( e \) will change during a compression test, but this will give a relatively small difference in void ratio. For \( e \) one can use the average void ratio that occurs during the test or just the initial value.

- In relations 4 and 6 there is no exact relation between \( \kappa^* \) and one-dimensional swelling indices, because the ratio of horizontal and vertical stress changes during one-dimensional unloading. For the approximation it is assumed that the average stress state during unloading is an isotropic stress state, i.e. horizontal and vertical stress equal.

- The factor 2.3 in relation 5 comes from the difference between the logarithm to base 10 and the natural logarithm. The factor 1.3 in relation 6 is the result of \( 3 / 2.3 \).

- The ratio \( \lambda^*/\kappa^* \) will generally be in the range between 3 and 7.

**Cohesion**

The cohesion has the dimension of stress. Any effective cohesion may be entered, including a cohesion of zero. When using the standard setting the cohesion is set equal to 1 kPa. Entering a cohesion will result in an elastic region that is partly located in the ‘tension’ zone of the stress space, as illustrated in Fig. 6.2. The left hand side of the ellipse crosses the \( p' \)-axis at a value of \(-c \cot \phi \). In order to maintain the right hand side of the ellipse (i.e. the cap) in the ‘pressure’ zone of the stress space, the isotropic pre-consolidation stress \( p_p \) has a minimum value of \( c \cot \phi \). This means that entering a cohesion larger than zero may result in a state of ‘overconsolidation’, depending on the magnitude of the cohesion and the initial stress state. As a result, a stiffer behaviour is obtained during the onset of loading. It is not possible to specify an undrained shear strength by means of a high cohesion and a friction angle of zero. Input of model parameters should always be based on effective values.

**Friction angle**

The effective angle of internal friction is specified in degrees and represents the increase of shear strength with effective stress level. A zero friction angle is not allowed. On the other hand, care should be taken with the use of high friction angles. It is often better to use \( \varphi_c \), i.e. the critical state friction angle, rather than a higher value based on small strains.
Moreover, using a high friction angle will substantially increase plastic computational effort.

**Dilatancy angle**

For the type of materials where the Soft-Soil model should be used for, dilatancy can generally be neglected. A dilatancy angle of zero degrees is included in the standard settings for the Soft-Soil model.

**Poisson’s ratio**

In this case, Poisson’s ratio is purely an elasticity constant rather than a pseudo-elasticity constant as used in the Mohr-Coulomb model. Its value will usually be in the range between 0.1 and 0.2. If the standard setting for the Soft-Soil model parameters is selected, then the value $\nu_{ur} = 0.15$ is automatically adopted. For loading of normally consolidated materials, Poisson's ratio plays a minor role, but it becomes important in unloading problems. For example, for unloading in a one-dimensional compression test (oedometer), the relatively small Poisson's ratio will result in a small decrease of the lateral stress compared with the decrease in vertical stress. As a result, the ratio of horizontal and vertical stress increases, which is a well-known phenomenon for overconsolidated materials. Hence, Poisson's ratio should not be based on the normally consolidated $K_0^{NC}$-value, but on the ratio of difference in horizontal stress to difference in vertical stress in oedometer unloading and reloading:

$$\frac{\nu_{ur}}{1 - \nu_{ur}} = \frac{\Delta\sigma_{xx}}{\Delta\sigma_{yy}} \quad \text{(unloading and reloading)} \tag{6.7}$$

**$K_0^{NC}$-parameter**

The parameter $M$ is automatically determined based on the coefficient of lateral earth pressure in normally consolidated condition, $K_0^{NC}$, as entered by the user. The exact relation between $M$ and $K_0^{NC}$ gives (Brinkgreve, 1994):

$$M = 3 \sqrt{\frac{(1 - K_0^{NC})^2}{(1 + 2K_0^{NC})^2}} + \sqrt{\frac{(1 - K_0^{NC})(1 - 2\nu_{ur})(\lambda^* / \kappa^* - 1)}{(1 + 2K_0^{NC})(1 - 2\nu_{ur})\lambda^*/\kappa^* - (1 - K_0^{NC})(1 + \nu_{ur})}} \tag{6.8}$$

The value of $M$ is indicated in the input window. As can be seen from Eq. (6.8), the parameter $M$ is also influenced by Poisson's ratio $\nu_{ur}$ and by the ratio $\lambda^*/\kappa^*$. However, the influence of $K_0^{NC}$ is dominant. Eq. (6.8) can be approximated by:

$$M \approx 3.0 - 2.8 K_0^{NC} \tag{6.9}$$