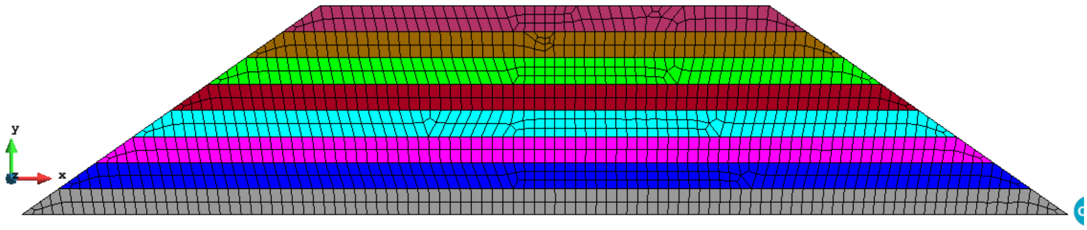
# EMBANKMENT CONSTRUCTION AND LONG TERM SIMULATIONS USING UNSATURATED SOIL THEORY

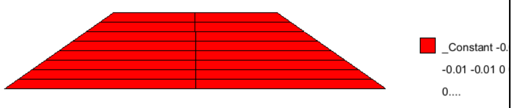
## Geometry description

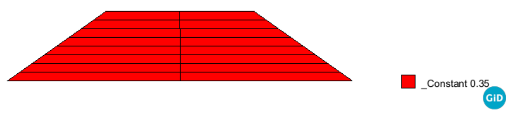
This document describes a model to analyse the behaviour of an embankment. The CODE_BRIGHT model simulates the construction phase and the long term response.




Geometry for the embankment including layers to model the construction process

The embankment has a maximum height of near 20 m. The embankment slope is 35º (1.4H/1V). The embankment will be supporting a road. All the layers are identical at the moment of construction.






Model with initial porosity of 0.35 and initial preconsolidation stress (history variable 1) of 0.1 MPa

The preconsolidation stress (*p*0*) can be input in two ways, as:

- Material parameter:
  Materials → Mechanical Data 2 → TEP Plastic parameters 2 → P5
- History variable:
  Conditions → Initial Stress → Hist var 1

The second option is necessary to incorporate zones with different compaction level during construction.

**PHASE 1.** Construction of the given section takes place from 0 to 90 days. This is simulated by means of a discretization of the construction process into 8 layers (far from the real layer number considered during construction).

Each layer is constructed during an interval of 10 days. During each interval, a ramp loading in time is considered to smooth the increase of stresses (weight is increased linearly during the interval). Simulation of the construction process is essential to accurately know the stress state, water content, porosity and plastic parameters after construction. These conditions reached are the initial conditions for the long-term response, which begins at the end of construction. During construction, evaporation or rain can occur. During construction, plastification takes place. This is observed by the variation (increase) of *p*0* which depends on the accumulated volumetric plastic strain.

In the model presented, **displacements are set to 0** at the end of construction. In more detail, at 80 days (end of construction) displacements are set to 0. This is done for several engineering reasons. In fact, construction movements take place in the real embankment but the geometry is continuously corrected by adding more soils to get the final geometry according to project design, in this case 20 m height. On the other hand, displacements produced during construction do not influence infrastructures constructed later on. The end of the construction process is the beginning of the long term process.

From 0 to 90 days, evaporation periods and rain periods are alternated. For instance, from 0 to 10 days, water pressure of -20 MPa is imposed on the boundary of layer 1 (the others have not been constructed yet). This produces evaporation of water. Then, from 10 to 20 days, it rains 1 mm/day ($1.157\times10^{-5}$ kg /$m^2$ /s) on the constructed surface, i.e. layer 2, etc. Finally, from 90 to 145 days a water pressure of -10 MPa is imposed on the boundary (top and slope surfaces).

**PHASE 2.** After construction, some intervals represent a series of 10 day periods with rain alternating between moderate and strong. Intervals with different rain intensity are considered:

- 145 to 155 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)
- 155 to 165 days with strong rain: $1.157\times10^{-4}$ kg /$m^2$ /s (10 mm/day)
- 165 to 175 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)
- 175 to 185 days with strong rain: $1.157\times10^{-4}$ kg /$m^2$ /s (10 mm/day)
- 185 to 195 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)
- 195 to 205 days with strong rain: $1.157\times10^{-4}$ kg /$m^2$ /s (10 mm/day)
- 205 to 215 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)
- 215 to 225 days with strong rain: $1.157\times10^{-4}$ kg /$m^2$ /s (10 mm/day)
- 225 to 235 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)
- 235 to 245 days with strong rain: $1.157\times10^{-4}$ kg /$m^2$ /s (10 mm/day)
- 245 to 255 days with moderate rain: $1.157\times10^{-5}$ kg /$m^2$ /s (1 mm/day)

**PHASE 3.** In this phase, inundation of the embankment is intended. From 255 forward, a constant 20 mm/day rain is considered up to the end of calculations. This precipitation corresponds to a very high value, as the objective is to reach conditions close to full saturation of the embankment.

# APENDIX

CODE_BRIGHT has the following menus once installed inside GiD where the options of the case given can be checked:

Data > Problem Type (check CODE_BRIGHT version)
Data > Problem Data > General Data (see general data)
> Equations Solved (check that the problem is HM)
> Other numerical variables and tolerances
Data > Interval Data (time intervals, units of time to be used, etc)
Data > Materials (check parameters in TEP model, Intrinsic Permeability, Retention Curve)
Data > Conditions > Line: Force/Displ. y Flux (plot boundary conditions and check entity values)
> Surface: Initial Porosity, Initial Stress, Initial Unkn. (idem)

The mechanical constitutive model considered is the BBM (Barcelona Basic Model) which in CODE_BRIGHT is a particular case of the TEP general model.

# Elastoplastic deformations using TEP model

Thermo-Elasto-Plastic (**TEP**) is a general model for unsaturated soils including suction and temperature variations which includes the Barcelona Basic Model (BBM) as a particular case. This model is described in CODE_BRIGHT as follows.

For this model, equations are written assuming Soil Mechancs sign criterion ($p > 0$, $\varepsilon_v > 0$, compression). The mechanical constitutive equation takes the incremental general form:

$$d\boldsymbol{\sigma}' = \boldsymbol{D} d\boldsymbol{\varepsilon} + \boldsymbol{h} ds \qquad (1)$$

This equation is derived from:

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p = (\mathbf{D}^e)^{-1} d\boldsymbol{\sigma}' + \alpha \mathbf{I} ds + \Lambda \frac{\partial G}{\partial \boldsymbol{\sigma}'} \qquad (2)$$

where an elasto-plastic constitutive law has been selected that is based on a generalized yield surface that depends not only on stresses but on suction as well:

$$F = F\left(\sigma', \varepsilon_v^p, s\right) \qquad (3)$$

where $\varepsilon_v^p$ is the plastic volumetric strain. Using stress invariants this equation depends on:

$$F = F\left(p', J, \theta, \varepsilon_v^p, s\right) \qquad (4)$$

where:

$$p' = \left(\sigma'_x + \sigma'_y + \sigma'_z\right)/3 = p - \max\left(p_g, p_l\right) \qquad (5)$$

$$J = \left(0.5 \mathrm{trace}(\mathbf{s} : \mathbf{s})\right)^{0.5} \qquad \mathbf{s} = \boldsymbol{\sigma}' - p'\mathbf{I}$$

$$\theta = -(1/3)\sin^{-1}\left(1.5\sqrt{3}\det \mathbf{s} / J^3\right)$$

where I is the identity tensor.

For simplicity, a form of the classical Modified Cam-Clay model is taken as the reference isothermal saturated constitutive law. The yield surface is then written as:

$$F = \frac{3J^2}{{g_y}^2} - {L_y}^2\left(p' + p_s\right)\left(p_o - p'\right) = 0 \qquad L_y = M / g_y\big|_{\theta=-\pi/6} \tag{6}$$

The variable $P_o$ is considered dependent on suction and temperature as follows:

$$p_o = p^c\left(\frac{p_o^*(T)}{p^c}\right)^{\frac{\lambda(o)-kio}{\lambda(s)-kio}} \tag{7}$$

$$p_o^*(T) = p_o^* + 2(\alpha_1\Delta T + \alpha_3\Delta T\left|\Delta T\right|)$$

This function includes dependency on suction and temperature. The first one (dependency on suction) is taken via the elastoplastic compressibility parameter:

$$\lambda(s) = \lambda(o)\Big[(1-r)\exp\left(-\beta s\right) + r\Big] \tag{8}$$

The effect of suction on cohesion is represented by the variable $p_s$ which depends on suction and temperature:

$$p_s = p_{s0} + ks\exp(-\rho\Delta T) \qquad \Delta T = T - T_{ref} \tag{9}$$

,

Hardening depends on plastic volumetric strain according to the following evolution equation:

$$dp_o^* = \frac{1+e}{\lambda(0) - k_{io}}\, p_o^* d\varepsilon_v^p \tag{10}$$

Finally, the plastic potential is taken as:

$$G = \alpha\frac{3J^2}{{g_p}^2} - L_p^2\left(p' + p_s\right)\left(p_o - p'\right) \qquad L_p = M / g_p\big|_{\theta=-\pi/6} \tag{11}$$

and $\alpha$ is an non-associativity parameter. Using the stress invariants *p*' and *q*, and considering $g_p$ =1 (see manual), it results in:

$$F = q^2 - M^2\left(p' + p_s\right)\left(p_o - p'\right) \qquad\qquad G = \alpha q^2 - M^2\left(p' + p_s\right)\left(p_o - p'\right) \tag{12}$$

The variation of stress-stiffness with suction and, especially, the variation of swelling potential with stress and suction have been considered. The elastic component of the model (volumetric strains):

$$d\varepsilon_v^e = \frac{k_i(s)}{1+e}\frac{dp'}{p'} + \frac{k_s(p',s)}{1+e}\frac{ds}{s+0.1} + (\alpha_o + 2\alpha_2\Delta T)dT \tag{13}$$

where:

$$k_i(s) = k_{io}\left(1 + \alpha_i s\right) \tag{14}$$

$$k_s(p',s) = k_{so}\left(1 + \alpha_{sp}\ln p'/p_{ref}\right)\exp\left(\alpha_{ss}\, s\right)$$

For deviatoric elastic strains, a constant Poisson's ratio is used. Alternatively, a constant value of the shear modulus *G* can be used.

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Input of the parameters for this model in CODE_BRIGHT is as follows:

PARAMETERS FOR ICL=21 (**TEP** Elastic Parameters), ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | $\kappa_{io}$ | - | Initial (zero suction) elastic slope for specific volume - mean stress | **0.01** |
| P2 | $\kappa_{so}$ | - | Initial (zero suction) elastic slope for specific volume – suction | **0** |
| P3 | *Kmin* | MPa | Minimum bulk module | **10** |
| P4 | Void | | | **-** |
| P5 | $\nu$ | - | Poisson's ratio | **0.35** |
| P6 | $\alpha_{ss}$ | - | Parameter for $\kappa_s$ (only for expansive material) | **0** |
| P7 | Void | | | **-** |
| P8 | $\alpha_i$ | - | Parameter for $\kappa_i$ (only for expansive material) | **0** |
| P9 | $\alpha_{sp}$ | - | Parameter for $\kappa_s$ (only for expansive material) | **0** |
| P10 | $p_{ref}$ | MPa | Reference mean stress (only for expansive material) | **0.01** |

PARAMETERS FOR ICL=22 (**TEP** Thermal Parameters), ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | $\alpha_o$ | $^oC^{-1}$ | Parameter for elastic thermal strain | **0** |
| P2 | $\alpha_1$ | MPa $^oC^{-1}$ | Parameter for plastic thermal strain | **0** |
| P3 | $\alpha_2$ | $^oC^{-2}$ | Parameter for elastic thermal strain | **0** |
| P4 | $\alpha_3$ | MPa$^oC^{-2}$ | Parameter for plastic thermal strain | **0** |
| P5 | $T_{ref}$ | $^oC$ | Reference temperature | **0** |

PARAMETERS FOR ICL=23 (**TEP** Plastic Parameters 1), ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | $\lambda$ (0) | | Slope of void ratio - mean stress curve at zero suction | **0.075** |
| P2 | *r* | | Parameter defining the maximum soil stiffness | **0.75** |
| P3 | $\beta$ | MPa$^{-1}$ | Parameter controlling the rate of increase of soil stiffness with suction | **35** |
| P4 | $\rho$ | $^oC^{-1}$ | Parameter that takes into account decrease of tensile strength due to temperature | **0.1** |
| P5 | *k* | | Parameter that takes into account increase of tensile strength due to suction | **0.01** |
| P6 | $p_{s0}$ | MPa | Tensile strength in saturated conditions | **0** |

PARAMETERS FOR ICL=24 (**TEP** Plastic Parameters 2), ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | $p^c$ | MPa | Reference pressure | **0.1** |
| P2 | *M* | | Critical state line parameter | **1.2** |
| P3 | $\alpha$ | | Non-associativity parameter | **0.99** |
| P4 | $e_o$ | | Initial void ratio | **0.59** |
| P5 | $p_o^*$ | MPa | Initial pre-consolidation mean stress for saturated soil | **0.035** |

PARAMETERS FOR ICL=25 (**TEP** Parameters Shape Yield Surf.), ITYCL=3 Von Mises

PARAMETERS FOR ICL=26 (**TEP** Parameters Shape Plastic Pot.), ITYCL=**3**
Von Mises

PARAMETERS FOR ICL=27 (**TEP** Integration Control Parameters), ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | *Tole1* | | Yield surface tolerance (typically 1.e-8) | **1e-7** |
| P2 | *Tole2* | | Elastic integration tolerance (typically between 1.e-4 and 1.e-6) | **1e-3** |
| P3 | *Tole3* | | Plastic integration tolerance ( typically between 1.e-4 and 1.e-2) | **1e-3** |
| P4 | $\mu$ | | Integration weight (ranges from 0 to 1) (typically 1) | **1** |
| P5 | *Index* | | -1 elastoplastic matrix (typical value)<br>+1 elastic matrix | **-1** |
| P6 | *Itermaxc* | | Maximum allowed subincrementations (execution continues) | **0** |
| P7 | *Itermaxs* | | Maximum allowed subincrementations (execution stops) | **0** |

# Hydraulic model

For the consideration of water in an unsaturated soil (accumulation and flow) it is necessary to consider the retention curve (degree of saturation vs suction), intrinsic permeability (tensorial parameter in Darcy's law) and relative permeability (function that corrects hydraulic conductivity in Darcy's law for unsaturated soils).

**RETENTION CURVE** (ICL=6). PARAMETERS FOR ITYCL=1 (Van Genuchten proposed a mathematical equation for retention curve called Van Genuchten model):

| | | | | |
|---|---|---|---|---|
| P1 | $P_o$ | MPa | Measured $P$ at certain temperature | **1** |
| P2 | $\sigma_o$ | N m$^{-1}$ | Surface tension at temperature in which $P_o$ was measured (usually $\sigma_o$=0,072 N/m at 20ºC) | **0** |
| P3 | $\lambda$ | - | Shape function for retention curve | **0.5** |
| P4 | $S_{rl}$ | - | Residual saturation | **0** |
| P5 | $S_{ls}$ | - | Maximum saturation | **1.0** |
| P6 | $a$ | - | Parameter for porosity influence on retention curve: $P_o(\phi)=P_o \exp(a(\phi_o-\phi)$ | **0** |
| P7 | $b$ | - | Parameter for porosity influence on retention curve: $\lambda(\phi)= \lambda \exp(b(\phi_o-\phi))$ | **0** |
| P8 | | | | **-** |
| P9 | $\phi_o$ | | Reference porosity for porosity influence on retention curve | **0** |

ITYCL=1: Van Genuchten model:

$$S_e = \frac{S_l - S_{rl}}{S_{ls} - S_{rl}} = \left(1 + \left(\frac{P_g - P_l}{P}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda}$$

$$P = P_o \frac{\sigma}{\sigma_o}$$

**INTRINSIC PERMEABILITY** (ICL=7). PARAMETERS FOR ITYCL=1

| | | | | |
|---|---|---|---|---|
| P1 | $(k_{11})_o$ | m$^2$ | Intrinsic permeability, 1st principal direction. | **10$^{-14}$** |
| P2 | $(k_{22})_o$ | m$^2$ | Intrinsic permeability, 2nd principal direction. | **10$^{-14}$** |
| P3 | $(k_{33})_o$ | m$^2$ | Intrinsic permeability, 3rd principal direction. | **10$^{-14}$** |
| P4 | $\phi_o$ | | Reference porosity for read intrinsic permeability. If $\phi_o$=0, permeability will be constant. | **0** |
| P5 | $\phi_{min}$ | | Minimum porosity (porosity will not be lower than this value). | **0** |

For a porous material than undergoes volumetric deformations, permeability can be considered a function of porosity (Kozeny's model):

| | |
|---|---|
| $\mathbf{k} = \mathbf{k}_o \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_o)^2}{\phi_o^3}$<br>$\phi_o$ : reference porosity<br>$\mathbf{k}_o$ : intrinsic permeability for matrix $\phi_o$ | which is used in Darcy's la (generalized form):<br>$\mathbf{q}_\alpha = -\frac{\mathbf{k} k_{r\alpha}}{\mu_\alpha}\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right)$ |

where viscosity, density and relative permeability are defined in other laws.

**RELATIVE PERMEABILITY** (ICL=14). PARAMETERS FOR ITYCL=6 (generalized power):

| | | | | |
|---|---|---|---|---|
| P1 | Void | | | **-** |
| P2 | $A$ | | Constant | **1** |
| P3 | $\lambda$ | | Power (typically 3) | **3** |
| P4 | $S_{rl}$ | | Residual saturation (default = same value as for retention curve) | **0** |
| P5 | $S_{ls}$ | | Maximum saturation (default = same value as for retention curve) | **1** |

Generalized power equation for relative permeability,

$$k_{rl} = AS_e^{\lambda}$$

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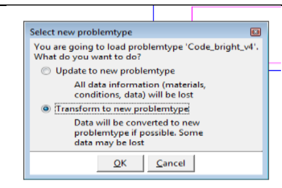
For this type of calculations, it is convenient to mesh the domain using quadrilateral elements. It is also possible to use quadratic triangles.

| | |
|---|---|
| A question appears regarding the way to transform it. You should answer "Transform to new problemtype". |  |