ONE-DIMENSIONAL CONSOLIDATION

This documents verifies that the principles of consolidation are correctly implemented in PLAXIS. The problem involves the time-dependent solution of one-dimensional (1-D) consolidation.

Used version:

- PLAXIS 2D - Version 2018.0
- PLAXIS 3D - Version 2018.0

Geometry: In PLAXIS 2D, the variation of excess pore pressures during loading of a soil column with height equal to 1.0 m and width 0.1 m is studied. The load is applied at the top of the soil column. The groundwater flow boundary conditions are set to *Closed* at the bottom and at the sides of the model (impermeable boundaries), while the top boundary is set to *Seepage*. In this way, half-closed layer drainage condition is simulated.

In PLAXIS 3D, the model is extended by 0.1 m in y-direction. The bottom and all four side groundwater flow boundaries are set to *Closed*. The top boundary is set to *Seepage*. Figure 1 illustrates the model geometry in both PLAXIS 2D and PLAXIS 3D.

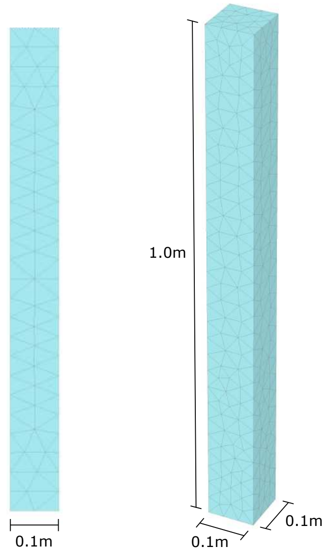


Figure 1 Model geometry and generated mesh in PLAXIS 2D and PLAXIS 3D

Materials: The soil is modelled as *Linear elastic* and the drainage type is set to *Undrained A*. Poisson's ratio is selected equal to 0.0 in order to prohibit transverse strain. Permeability equals 0.001 m/day in every direction. The adopted material parameters are:

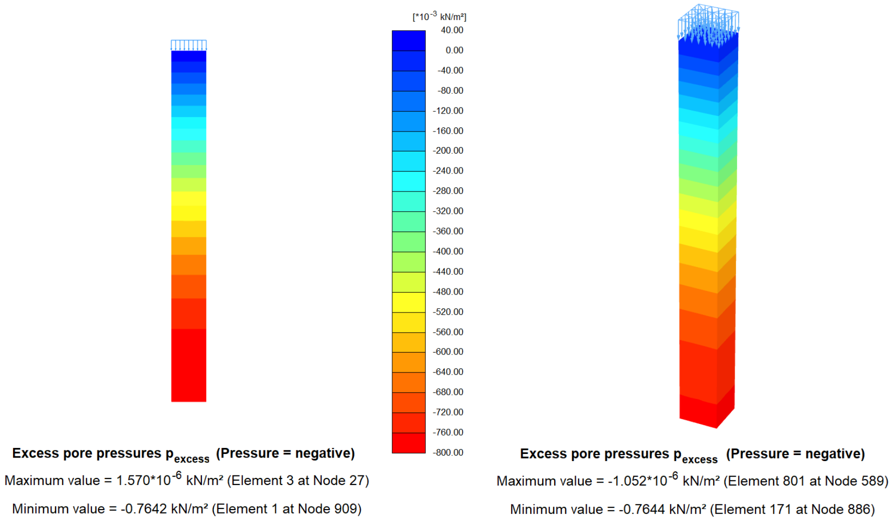
Soil: Linear elastic Undrained A E'=1000 kN/m^2 ν'=0.0 k=0.001 m/day

Meshing: In both PLAXIS 2D and PLAXIS 3D, the *Fine* option is selected for the *Element distribution* and the *Coarseness factor* is set equal to 1. The generated mesh is illustrated in Figure 1.

Calculations: Initial stresses are generated in the Initial Phase by using the *K0* *procedure* as *Calculation type*. In Phase 1, a *Plastic analysis* is performed, in which the distributed load (1 kN/m) is activated and the groundwater flow boundaries are adjusted as described above. The *Reset displacements to zero* option is selected for this phase. Ten Phases follow in which consolidation analyses are performed, with time intervals of 0.1, 0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, 30.0 and 50.0 days respectively. The *Use pressures from previous phase* option is used for the *Pore pressure calculation type*.

With respect to the adopted *Numerical control parameters*, the *Iterative parameters* are manually defined. The *Tolerated error* is set equal to 0.001 and the *Desired minimum number of iterations* is set equal to 2 (to prevent up-scaling of the time step). The *First time step* varies per consolidation Phase, defined as $\Delta t/100$, where Δt is the corresponding time interval. The default values of the remaining parameters are valid.

Output: Figure 2 illustrates the excess pore pressure distribution at the end of Phase 6 (t=2 days) in PLAXIS 2D and PLAXIS 3D.



Excess pore pressures p_{excess} (Pressure = negative)

Maximum value = 1.570*10^{-6} kN/m² (Element 3 at Node 27)

Minimum value = -0.7642 kN/m² (Element 1 at Node 909)

Excess pore pressures p_{excess} (Pressure = negative)

Maximum value = -1.052*10^{-6} kN/m² (Element 801 at Node 589)

Minimum value = -0.7644 kN/m² (Element 171 at Node 886)

Figure 2 Excess pore pressure distribution in PLAXIS 2D and PLAXIS 3D (t=2 days)

Figure 3 presents the development of the relative excess pore pressure p/p_0 over time t (days) at a point located at the bottom boundary of the model.

Verification: The problem of 1-D consolidation is described by the following differential equation for the excess pore pressure p:

$$\frac{\partial p}{\partial t} = c_v \frac{\partial^2 p}{\partial z^2} \tag{1}$$

where z is the depth above the bottom soil boundary (in PLAXIS 2D this is denoted as y).

The coefficient of consolidation c_v is given as:

$$c_v = \frac{kE_{oed}}{\gamma_w} \tag{2}$$

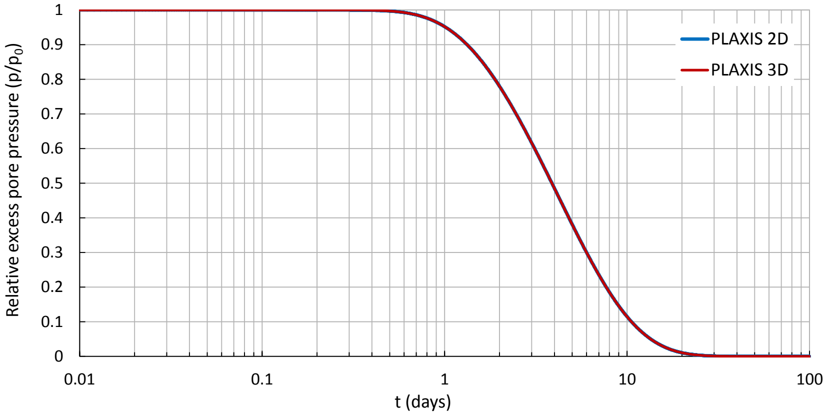


Figure 3 Development of excess pore pressures over time at a point located at the bottom of the model

in which:

$$E_{oed} = \frac{(1-\nu')E'}{(1+\nu')(1-2\nu')} \tag{3}$$

The analytical solution of this equation, i.e. the relative excess pore pressure p/p_0 as a function of time t and depth z is presented by Verruijt (2001) as:

$$\frac{p}{p_0}(z,t) = \frac{4}{\pi}\sum_{j=1}^{\infty}\frac{(-1)^{j-1}}{2j-1}\cos\left((2j-1)\frac{\pi}{2}\frac{y}{H}\right)\exp\left(-(2j-1)^2\frac{\pi^2}{4}\frac{c_v t}{H^2}\right) \tag{4}$$

Figure 4 presents the results obtained from PLAXIS and the analytical formulation presented above. Each one of the considered consolidation times is plot in the form of the dimensionless time factor T_v, calculated as $T_v = (c_v t)/(H^2)$. H equals the height of the soil column (half-closed layer). Depth z is normalized over H.

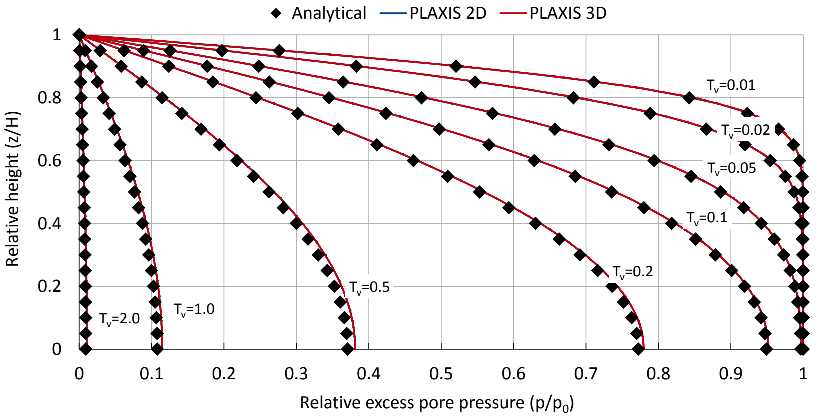


Figure 4 Development of relative excess pore pressures p/p_0 over time (T_v) and depth (z/H) obtained in PLAXIS 2D, PLAXIS 3D and analytically

It is concluded that the numerical solution from PLAXIS 2D and PLAXIS 3D is in entire agreement and very close to the analytical solution. The numerical solution differs from the analytical at the second decimal point. The consolidation rate is slightly lower than the theoretical one. This is caused by the used implicit integration scheme. Important to mention is that the excess pore pressure initially calculated (Phase 1) in PLAXIS is 0.98 $\times p_{external}$, instead of 1.0 $\times p_{external}$. This is due to the fact that the pore water in PLAXIS is not completely incompressible (refer to Section 6.2 of the Reference Manual).

REFERENCES

[1] Verruijt, A. (2001). Soil mechanics. Delft University of Technology.