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7. Terrain settlement – program "Settlement"

7.1 Computation of geostatic stress in soil body

The basis for computation of settlement is the determination of stress state in a soil body and its change due to surcharge or due to lowering the ground water table. The stresses in the body are determined at individual points of a mesh. The mesh is defined in the **„Settings"** dialog window (**Fig.7.1**).

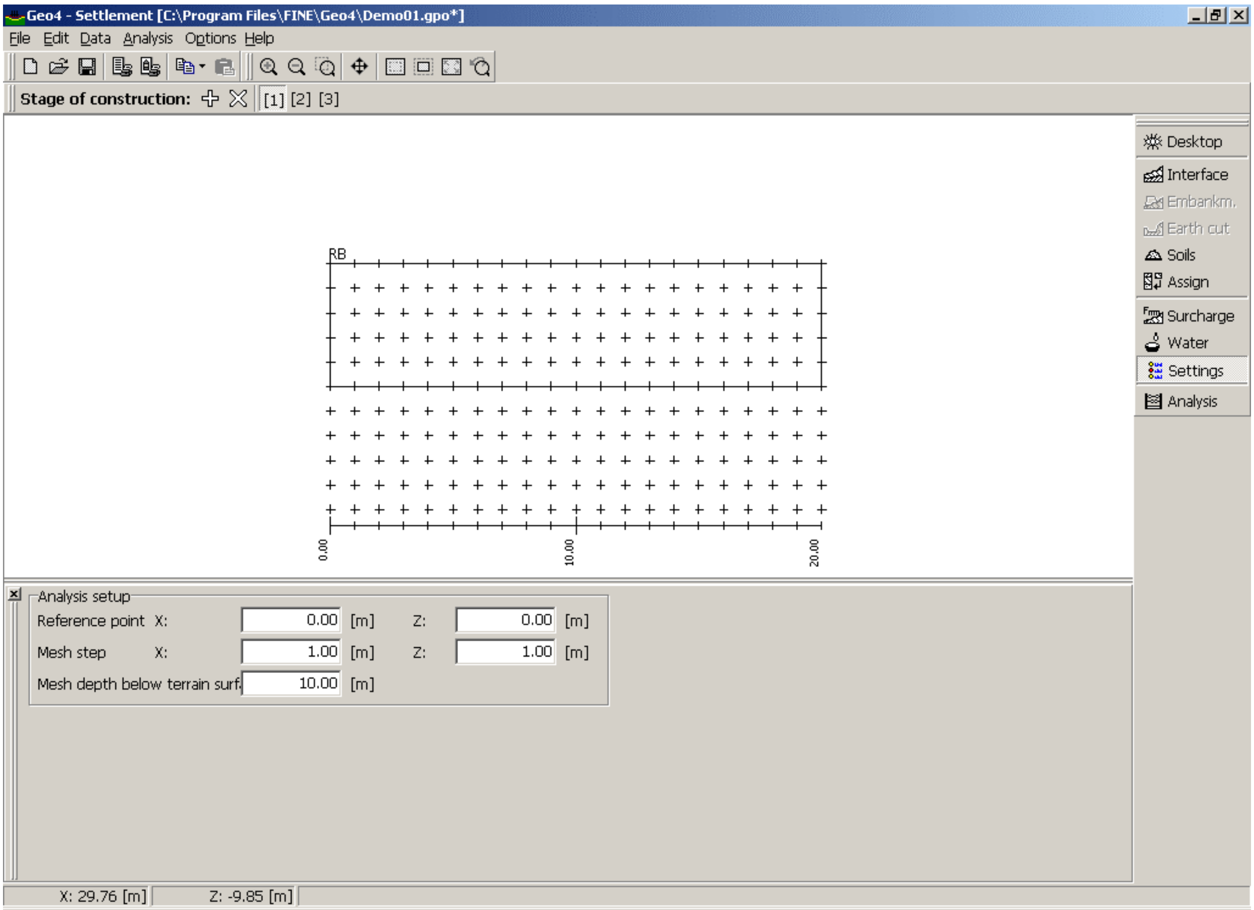

Fig.7.1 Dialog window „Settings"

The mesh density affects the final results – a finer subdivision leads to more accurate results but the analysis takes a long time and the results plotted at individual points are difficult to read. It appears that subdivision into 20-30 points is reasonable.

When determining the stress state in a soil body, the program inserts fictitious layers in the locations with stress discontinuities (GWT, interfaces between layers). The vertical normal pressure in the i^{th} layer is provided:

$$\sigma_{zi} = \sum h_i \gamma_i$$

where:

h_i - thickness of the i^{th} layer

σ_{zi} - normal stress in the i^{th} layer

γ_i - bulk weight in the i^{th} layer

The bulk weight of a soil in the layer below the GWT is determined depending on inputted soil parameters as follows (**Fig. 7.2**):

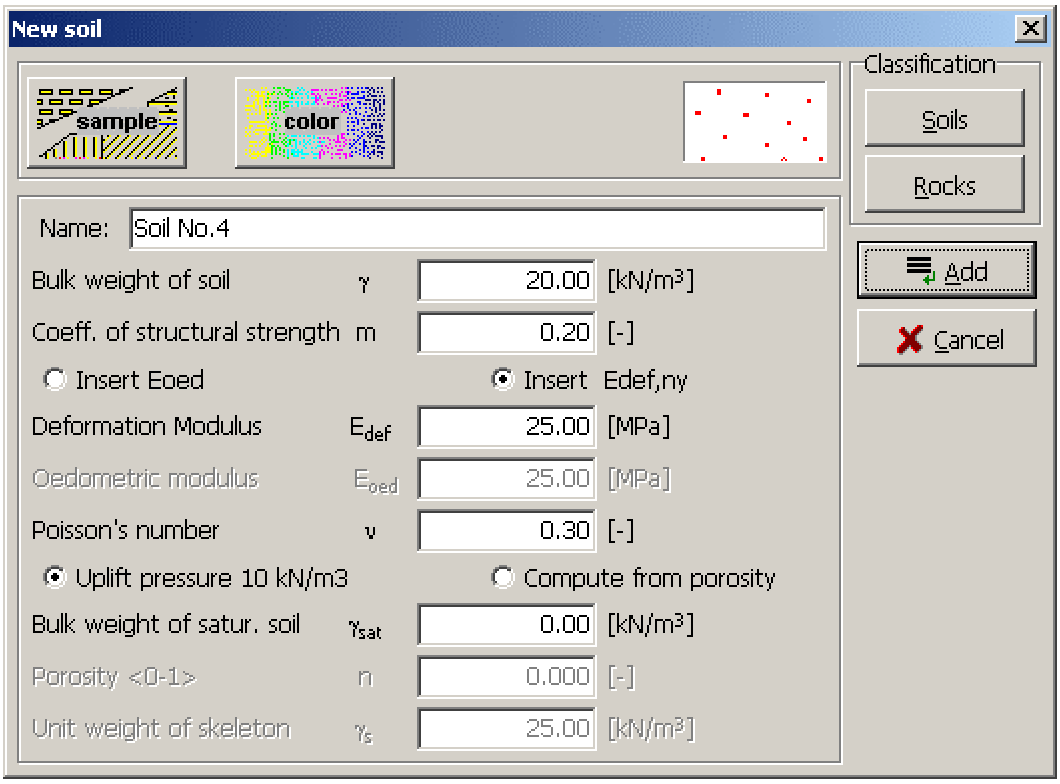

Fig. 7.2 Input of parameters of soil γ_{su}

- option “**Uplift pressure 10 kN/m3**” as:

$$\gamma_{su} = \gamma_{sat} - 10$$

- option “**Compute from porosity**“ as:

$$\gamma_{su} = (1 - n) * (\gamma_s - 10)$$

The stress values and the stress state change is then computed at individual points of the mesh (**Fig. 7.3**).

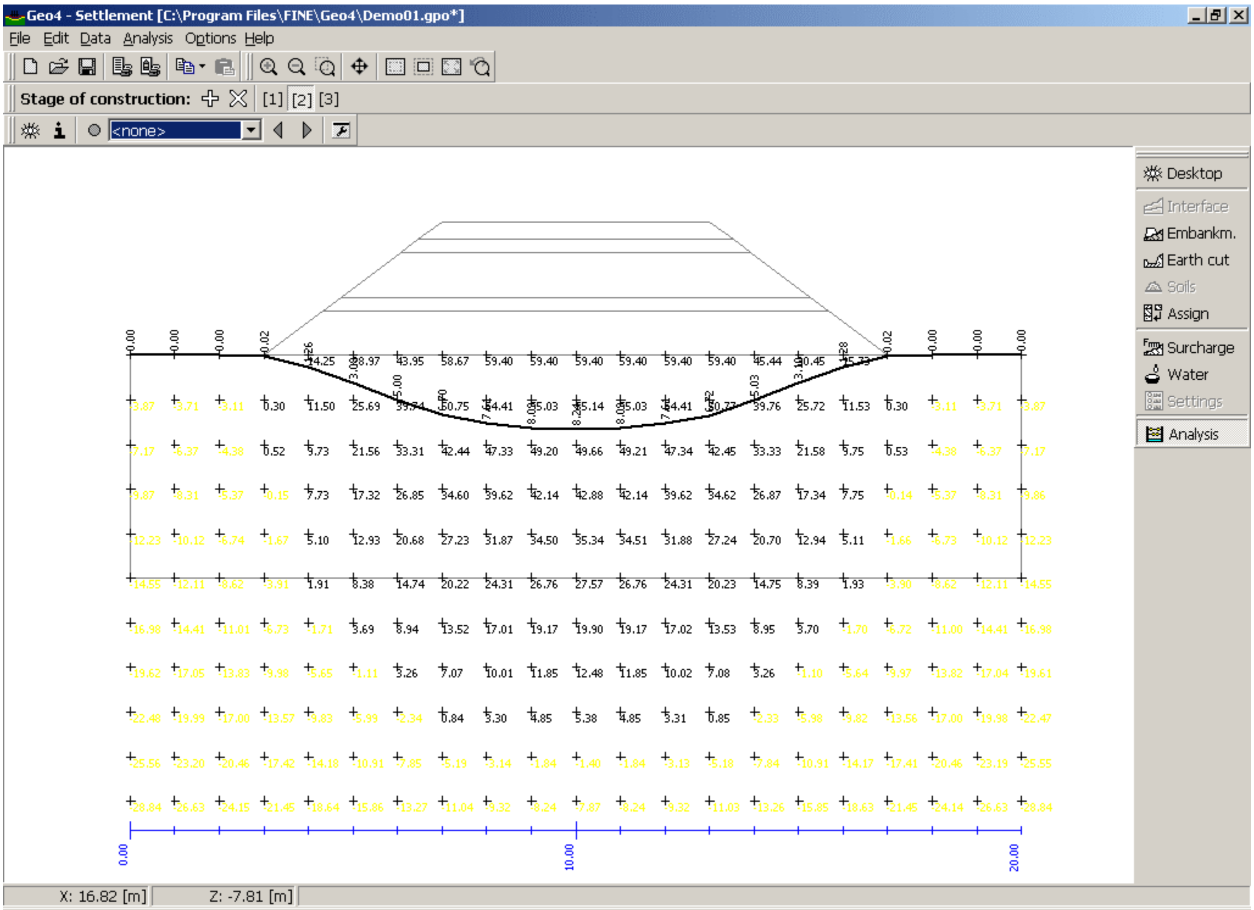

Fig. 7.3 Stress values and stress state change at individual mesh points

7.2 Computation of stress increment due to surcharge

The theory of elastic half-space is used to compute stresses at individual points of a soil body due surcharge. Stress increment at a point of the body due to an infinite strip loading is determined according to **Fig. 7.4**:

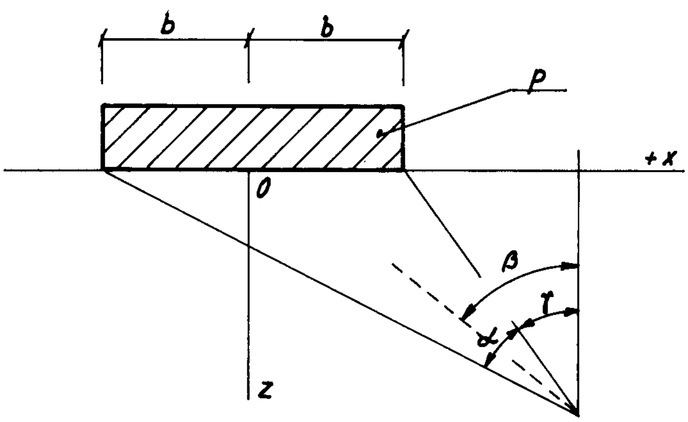

Fig. 7.4 Stress due to infinite strip loading

$$\sigma_z = \frac{p}{\pi}(\alpha + \sin\alpha \cos 2\beta)$$

$$\beta = \gamma + \frac{\alpha}{2}$$

The trapezoidal surcharge is subdivided in the program in 10 segments. Individual segments are treated as strip loadings. The resulting earth pressure is a sum of partial surcharges from individual segments.

The stress increment due to concentrated load is found as follows (**Fig. 7.5**):

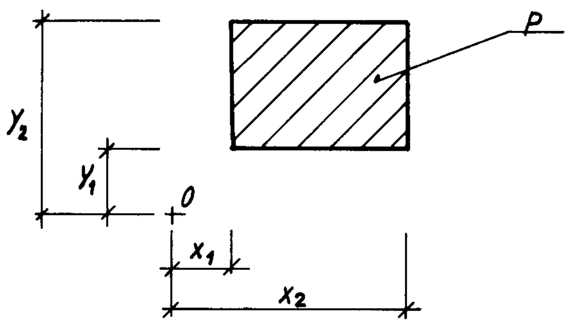

Fig.7.5 Surcharge with respect to point „O“

$$\Delta\sigma_z = \frac{p}{2\pi}\left(\frac{x_2 z S_2}{y_2 S_{2x}^2} + \frac{x_2 z^3}{y_2 S_{2y}^2 S_2} - \frac{x_2 z S_3}{y_1 S_{2x}^2} + \frac{x_2 z^3}{y_1 S_{1y}^2 S_3} - \frac{x_1 z S_4}{y_2 S_{1x}^2} + \frac{x_2 z^3}{y_2 S_{2y}^2 S_4} + \frac{x_1 z S_2}{y_1 S_{1x}^2} - \frac{x_1 z^3}{y_1 S_{2y}^2 S_1} + \right.$$

$$\left. + arctg\frac{x_2 y_2}{z S_2} - arctg\frac{x_2 y_1}{z S_3} - arctg\frac{x_1 y_2}{z S_4} + arctg\frac{x_1 y_1}{z S_1}\right)$$

where:

$$S_{2x} = \sqrt{x_2^2 + z^2} \qquad S_1 = \sqrt{x_1^2 + y_1^2 + z^2} \qquad S_3 = \sqrt{x_2^2 + y_1^2 + z^2}$$

$$S_{2y} = \sqrt{y_2^2 + z^2} \qquad S_2 = \sqrt{x_2^2 + y_2^2 + z^2} \qquad S_4 = \sqrt{x_1^2 + y_2^2 + z^2}$$

An embankment is transformed for computational purposes into a given number trapezoidal surcharges. It is assumed that there is no settlement in the embankment, not even at subsequent stages of construction.

7.3 Computation of settlement

The settlement in individual layers receives the form

$$s = \frac{Max(0, \sigma_{z1,i} - \sigma_{z2,i} - m_i \sigma_{or2,i}) h_i}{E_{oed,i}}$$

where:

- $\sigma_{z1,i}$ - is the vertical component of stress in the center of the i^{th} layer **in the current stage of construction**
- $\sigma_{z2,i}$ - is the vertical component of stress in the center of the i^{th} layer **in the previous stage of construction**,
- $\sigma_{or2,i}$ - is the vertical component of geostatic stress in the center of the i^{th} layer **in the previous stage of construction**,
- m_i - correction coefficient of surcharge (structural strength in the i^{th} layer),
- h_i - thickness of the ith layer (mesh points distance),
- $E_{oed,i}$ - oedometric modulus of the i^{th} layer - evaluation from the deformation modulus is carried out as follows

$$E_{oed} = \frac{1}{1 - \frac{2v^2}{1-v}} E_{def}$$

The terrain settlement is then defined as a sum of settlements of individual layers.

If the end of influence zone has not been found (the mesh has not been generated into a sufficient depth) the program will prompt the following message.

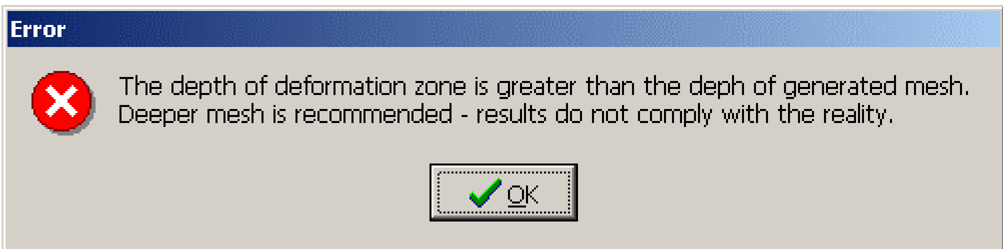

Fig. 7.6 Error message – depth of influence zone

In such a case it is necessary to increases the mesh depth. To that end, used the „**Settings**“ dialog window.

8. Terrain settlement above excavation – program „Depression"

The program „**Depression**" serves to compute settlement above a circular excavation, or above two excavations of the same diameter. It also determines depression on a terrain surface. The well-known theories after Peck, Limanov and Fazekas are used to provide the theoretical background. These theories deliver results, which corresponds rather well to reality. It is, however, important for the user to become familiar with the theory used in the analysis. An incorrect input, e.g., of non-homogeneous subsoil may lead to extremely high deformations, which are far from reality. We thus strongly recommend reading the following section.

8.1 Determination settlement for homogeneous subsoil

Computation of settlement above a circular excavation in homogeneous subsoil is identical for all theories. The first step is to determine the radial loading of a circular excavation as

$$p = \sigma_z \left(\frac{1 + K_r}{2}\right)$$

where

σ_z – geostatic stress in the excavation center,
K_r – coefficient of pressure at rest of cohesive soil (see Section 2.5)

Displacements of the slope ceiling is provided by

$$u_a = (1+\nu)\frac{p}{E} r \frac{h_S + (1-2\nu)r}{h_S - r}$$

$$u_b = -(1+\nu)\frac{p}{E} r \frac{h_S + (1-2\nu)r}{h_S + r}$$

where

h_s – depth of the excavation center,
r – the excavation radius,
E - modulus of elasticity of the surrounding rock,
ν - Poisson's number of the surrounding rock.

The maximum terrain settlement and size of depression are given by

$$u = (1-\nu^2)\frac{p}{E}\frac{4r^2 h_S}{h_s^2 - r^2}$$

$$L = 2\sqrt{h_s^2 - r^2}$$

When the deformation of tunnel ceiling is prescribed, the maximum settlement is found from the following expression

$$u = 4u_a r \frac{h_S(1-\nu)}{(h_s + r)(h_s + r + 2\nu r)}$$

8.2 Computation of settlement for layered structures

To determine settlement of layered subsoil, the program first computes settlement of the interface between the first layer above the excavation and other layers of the overburden (**u_{int}**) and the size of depression along interfaces between individual layers (**L_{int}**). The procedure is the same as already discussed in the previous section. The size of terrain surface depression (**L**) is determined next – see **Fig. 7.7**.

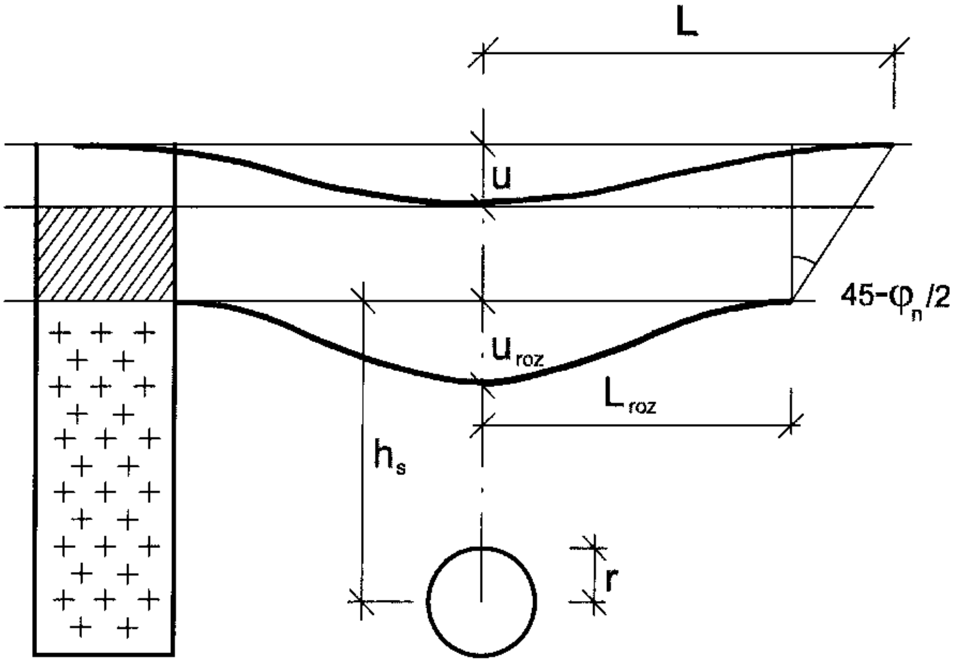

Fig. 7.7 Computation of settlement for layered subsoil

The first layer thickness of overburden above the excavation is most important for computation of settlement. The subsequent layers of overburden transmit the deformation towards the terrain surface. The actual computational procedure of evaluation of terrain settlement (**u**) depends on the selected method.

1) analysis after Limanov

$$u = \frac{F}{L}$$

where

L – length of depression

F – volume of heaving per 1m given by

$$F = u_{\text{int}} \pi \frac{L_{\text{int}}}{2}$$

where

L_{int} – length of depression along interfaces between layers above overburden

u_{int} – settlement of a given interface (see **Fig. 7.7**).

2) analysis after Fazekas

$$u = u_{\text{int}} \frac{L_{\text{int}}}{L}$$

where

L – length of depression
L_{int} – length of depression along interfaces between layers above overburden
u_{int} – settlement of a given interface (see **Fig. 7.7**).

3) analysis after Peck

$$u = u_{\text{int}} \frac{L_{\text{int}}}{5L_{\text{inf}}}$$

where

L_{int} – length of depression along interfaces between layers above overburden
u_{int} – settlement of a given interface (see **Fig. 7.7**).
L_{inf} – distance of inflex point of depression from excavation axis at the terrain surface

Distance L_{inf} is found using the coefficient k_{inf} .(L_{inf}=L/k_{inf}). Magnitude of this coefficient depends on average soil or rock in overburden – the literature offers values of k_{inf} in the range of 2,1-3,5.
Based on parametric study using the finite element method we recommend the following values:

Gravel soil	k_{inf}=3.5
Sand and gravel soils , rocks	k_{inf}=3.0
Fine-grained soils	k_{inf}=2.5
Fine-grained soils	k_{inf}=2.1

8.3 Determination of shape of depressions

Shape and size of Depression above a excavation is important when determining settlements of structures in the vicinity of excavation. The program handles three types of curves.

1)Curve after Avershin

$$s_i = u(1 - \frac{x_i}{L})^4 e^{\frac{4x_i}{L}}$$

where

s_i – settlement at a point having coordinate x_i
u – the maximum terrain settlement
L – size of depression.

2)Curve after Gauss

$$s_i = ue^{\frac{-x_i^2}{2L_{\text{inf}}^2}}$$

where

s_i – settlement at a point having coordinate x_i
u – the maximum terrain settlement
L_{inf} – distance of inflex point of depression from excavation axis at the terrain.