5 Results of geotechnical calculations (Relevant paragraph of the paper: RESULTS OF GEOTECHNICAL CALCULATIONS OF THE EMBANKMENT)

Internal slope stability analyses of the embankment under static and seismic loading conditions

The internal slope stability analyses for the critical cross section of the examined embankment under static and seismic loading conditions were performed according to the methodology described in Eurocode 7 and Eurocode 8, respectively. The rail traffic load in the above analyses is modelled by applying a distributed load on the crest of the embankment (over 3.0m width) equal to P=69.27kPa. This load is further increased in case of static loading by multiplying it with a partial factor of actions equal to γ_F=1.30. Moreover, in static loading conditions, the shear strength parameters of the encountered formations are reduced through the soil parameters partial factors (γ_M), whereas the resulting soil resistance is divided by a resistance factor equal to γ_R=1.0. Thus, the required “equivalent safety factor” of the analyses is equal to $FS_{equiv.}$=1.0.

The results of slope stability analyses with the limit equilibrium method at the critical cross section, presented in the attached files (5-1_ResultsSlopeStability_LimitEq_ StaticLoading.pdf & 5-2_ResultsSlopeStability_LimitEq_SeismicLoading.pdf), indicate acceptable safety factor values, $FS_{equiv.}$=1.1. For the implementation of the limit equilibrium method the geotechnical software Larix-4 (v. 2.21, Cubus) was used.

Calculation of settlements due to the construction of the embankment

The geotechnical design of the examined embankment includes also the calculation of soil settlements in the critical cross section. The calculated immediate settlements are expected to be completed during the construction of the embankment. The examined embankment is founded on alluvial deposits, containing clayey-silty materials, and the groundwater level is encountered at small depth from the ground surface. Therefore the development of settlements due to consolidation is also expected.

A. Calculation of immediate settlements

The results of the pertinent calculations are summarized in Table 5-1.

Table 5-1. Calculation of immediate settlements

Layer	Thickness (m)	$\Delta\sigma'_v$ (applied stress at the center of the layer) (kPa)	E_s (oedometer Young’s modulus) (MPa)	Settlement (cm)
Leveling/improvement layer	1.0	244	50.0	0.49
Ib	10.0	223	14.0	15.9
II	10.0	only consolidation settlements are taken into consideration		
Ib	20.0	110	14.0	15.7
Total immediate settlement:				**32.1**

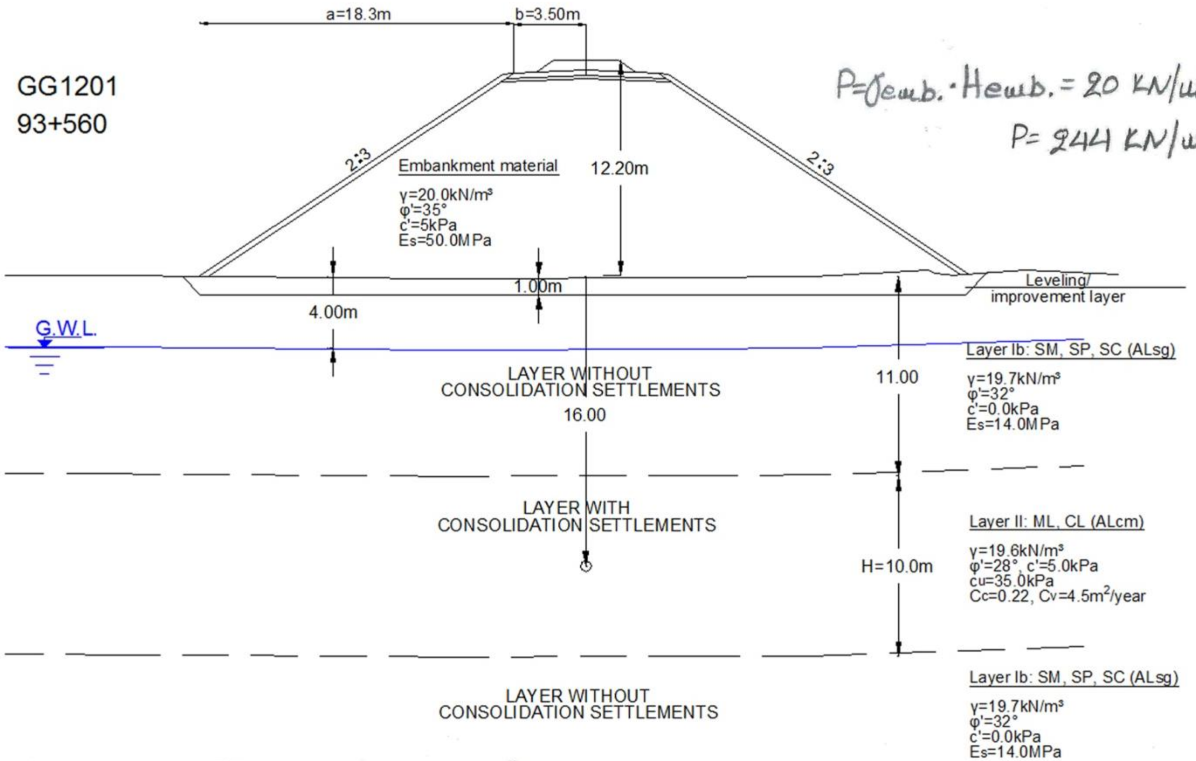
B. Calculation of consolidation settlements

For the calculation of consolidation settlements it is assumed that the deformation of the compressible layer will occur in only one dimension. Therefore the theory of one-dimensional consolidation is implemented. The examined layer is divided into sub-layers of small thickness and the equation corresponding to normally consolidated clays, is applied (see Folder 4). The laboratory oedometer test results for the clayey layer (Layer II), indicate low values of preconsolidation stress, p'_c. Thus it considered that the clayey layer is normally consolidated.

In order to determine whether the operation of the Railway Line will be affected by the magnitude of the remaining consolidation settlements, the Owner of the Project has set an available time period equal to 14 months for the completion of the embankment construction. In case the remaining settlements after the above time period are greater than 3.0cm to 5.0cm (maximum values decided from the owner of the project), the installation of vertical wick drains is required in order to increase the rate of consolidation settlements. The settlement calculations were carried out by taking into consideration an improvement layer of 1.0m thickness. The settlements due to the construction of the embankment are calculated using a Microsoft excel calculation sheet. The results are presented in the attached files: 5-3_SettlementCalculationSheet_NoDrains.pdf & 5-4_SettlementCalculationSheet_WithDrains.pdf. These results refer to the settlement developed at the embankment axis as well as at the toe of the embankment. For more precise calculations of the consolidation settlements the examined layer is divided into sub-layers of small thickness.

In order to provide to the students analytical explanation about the methodology used for a) the determination of the consolidation settlements and b) the calculation of consolidation rate, the performed calculations are presented in detail in Figures 5-1 to 5-4, by applying the equations mentioned in Folder 4 only for settlements at the embankment's axis. The calculations are indicatively carried out for the total thickness of the clayey layer, without dividing it to sub-layers of smaller thickness.

In order to investigate the effect of variation of laboratory test results on the settlement calculations, the students have the opportunity to perform these calculation several times by changing each time the value of a particular geotechnical parameter. In this way, the effect of this variation on the results of the geotechnical calculations will be evaluated. The coefficient of consolidation is considered as a typical geotechnical parameter for this type of investigation, as it significantly affects the rate of consolidation settlements and thus the possible requirement for installation of vertical wick drains.



$P = \gamma_{emb.} \cdot H_{emb.} = 20\ kN/m^3 \cdot 12.20m \rightarrow$

$P = 244\ kN/m^2$

Calculation of consolidation settlement (axis of embankment)

At depth z=16m from the ground surface (in the middle of the clayey layer II)

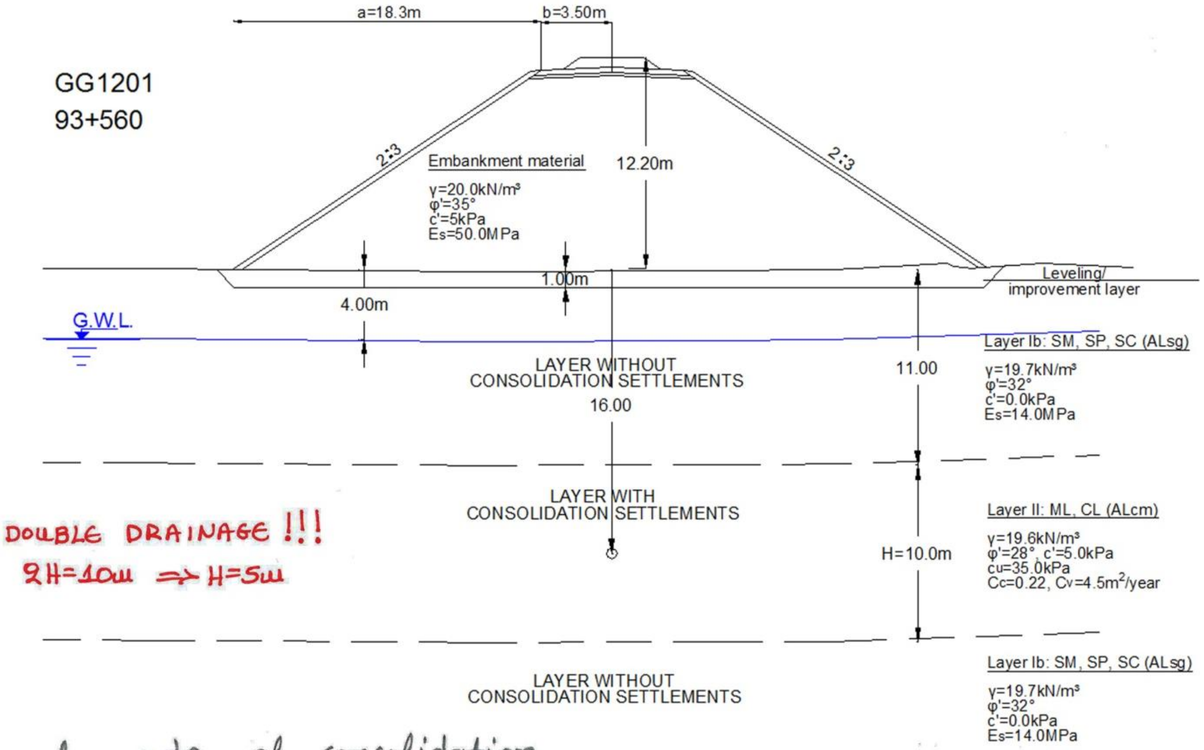
$\sigma'_{vo} = 195\ kPa$ (for z=16m)

$\left.\begin{matrix} a/z = 1.14 \\ b/z = 0.22 \end{matrix}\right\}$ I= 0.34 (Figure 5-3) Therefore $\Delta\sigma'_v = 2 \cdot I \cdot P = 2 \cdot 0.34 \cdot 244 \rightarrow \Delta\sigma'_v = 165.9\ kPa$

Ultimate consolidation settlement: $S_c = H \cdot \frac{C_c}{1+e_o} \log\left(\frac{\sigma'_{vo}+\Delta\sigma'_v}{\sigma'_{vo}}\right) = 10m \cdot \frac{0.22}{1+0.90} \log\left(\frac{360.9}{195}\right) \Rightarrow$

$S_c = 0.31\ m$ or $S_c = 31\ cm$

Figure 5-1. Calculation of consolidation settlements



Calculation of rate of consolidation

For time $t = 14$ months or 1.16 years (time period determined by the Owner of the Project)

Time factor $T_v = \frac{C_v \cdot t}{H^2} \rightarrow T_v = \frac{4.5\, m^2/yr \cdot 1.16\, yr}{25\, m^2} \rightarrow T_v = 0.21$

From the diagram of Figure 5-4 : $U_t = 0.50$

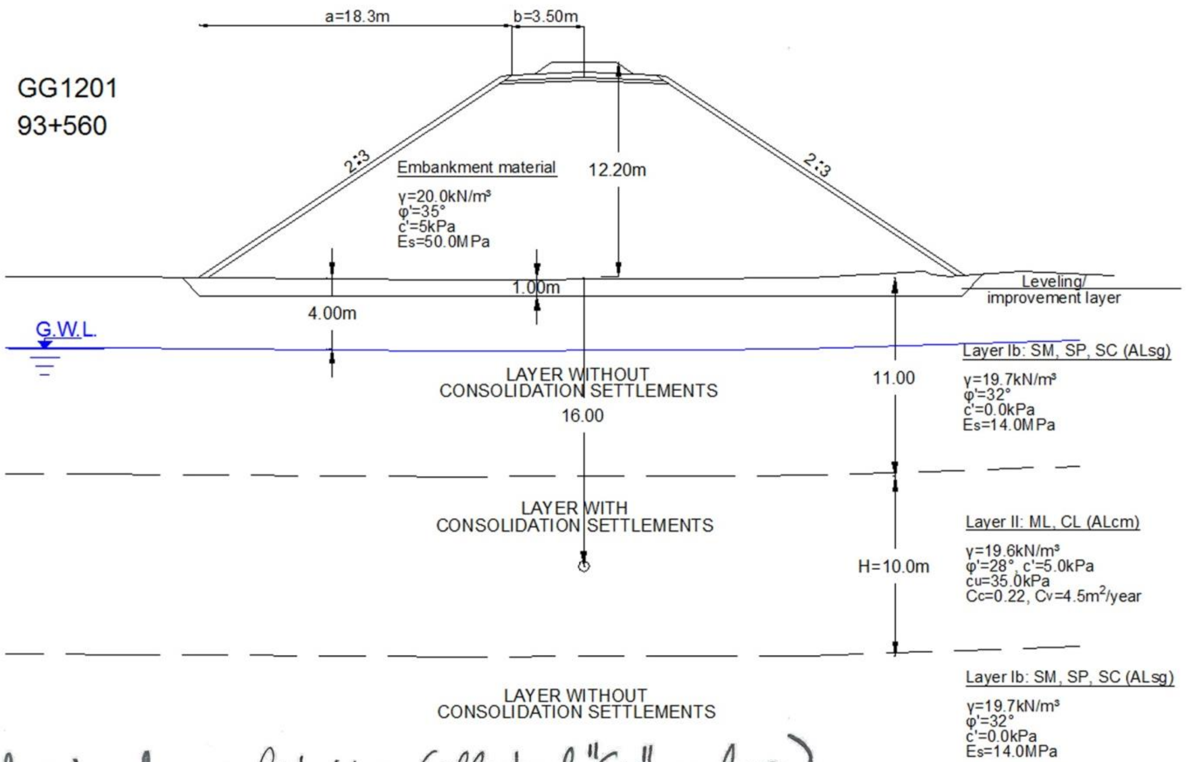
The consolidation settlement after t=14 months is equal to : $S_{t=14} = 0.50 \cdot 31\,cm \rightarrow S_t = 15.5\,cm$

The remaining settlement after t=14months is : $S_c - S_t = 31 - 15.5 = 15.5\,cm$

Remaining settlement : 15.5cm > 3.0-5.0cm NOT ACCEPTABLE!!!

REQUIREMENT FOR INSTALLATION OF VERTICAL WICK DRAINS

Figure 5-2. Calculation of consolidation rate (without wick drains)



Calculation of rate of consolidation (effect of "Cv" value)

For "Cv" value three times greater than the initial value: $C_{v2} = 3 \cdot 4.5 \rightarrow C_{v2} = 13.5\, m^2/yr$

Then $T_{v2} = 3 \cdot T_{v1} \rightarrow T_{v2} = 0.63$

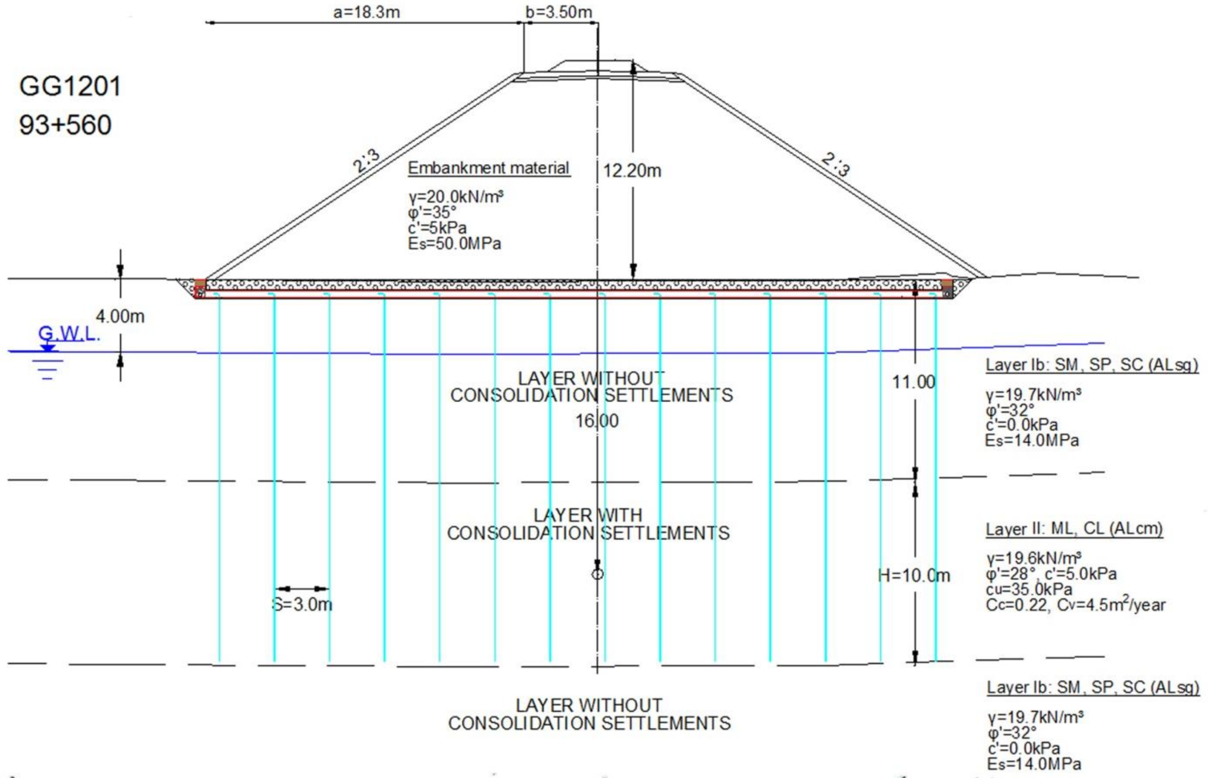
From the diagram of Figure 5-4: $U_t = 0.83$

Therefore: $S_{t=14} = 0.83 \cdot 31\, cm \rightarrow S_{t=14} = 25.7\, cm$ (consolidation settlement after 14 months)

Remaining settlement after 14 months: $S_c - S_t = (31 - 25.7)\, cm \simeq 5.0\, cm$ ACCEPTABLE!

NO REQUIREMENT FOR INSTALLATION OF VERTICAL WICK DRAINS.

Figure 5-3. Calculation of consolidation rate for increased "C_v" value (without vertical drains)



Calculation of consolidation rate with vertical wick drains ($s=3.0m$ and $r_w=0.033m$)

After time $t=14$ months or $t=1.16$ yr

Time factor and degree of consolidation for vertical drainage

$T_v = \frac{C_v \cdot t}{H^2} \rightarrow T_v = 0.21$

From the diagram of Figure 5-4: $U_{tv} = 0.50$

Time factor and degree of consolidation for radial drainage (due to wick drains)

$T_r = \frac{C_h \cdot t}{(1.05 \cdot S)^2} \Rightarrow T_r = 1.05$ (for $C_h = 2 \cdot C_v = 9.0 m^2/yr$)

$n = \frac{0.525 \cdot S}{r_w} \rightarrow n = 47.73$ and $F_n = \frac{n^2}{n^2-1}\ln(n) - \frac{3n^2-1}{4n^2} = 3.117$

$U_{tr} = 1 - e^{-\frac{8T_r}{F_n}} \rightarrow U_{tr} = 0.93$

Average degree of consolidation: $U = 1-(1-U_{tv})(1-U_{tr}) \rightarrow U = 0.965$

Consolidation settlement after $t=14$ months: $S_{t=14} = 0.965 \cdot 31cm = 29.9\ cm$

Remaining settlement after $t=14$ months: $S_c - S_t = (31-29.9)cm = 1.1\ cm$. ACCEPTABLE

Figure 5-4. Calculation of consolidation rate with vertical wick drains

Accompanying files

5-1. Limit Equilibrium Method-Results of Slope Stability Analyses-Static Loading
Filename: **5-1_ResultsSlopeStability_LimitEq_StaticLoading.pdf**

5-2. Limit Equilibrium Method-Results of Slope Stability Analyses-Seismic Loading
Filename: **5-2_ResultsSlopeStability_LimitEq_SeismicLoading.pdf**

5-3. Results of Settlements' Calculation – Without Vertical Drains
Filename: **5-3_SettlementCalculationSheet_NoDrains.pdf**

5-4. Results of Settlements' Calculation – With Vertical Drains
Filename: **5-4_SettlementCalculationSheet_WithDrains.pdf**

Relevant Reference

Athanasopoulos, G. A., (1986), "Concise Theory and Problems of Soil Mechanics", University of Patras Editions (in Greek), 235p.

Barnes, G.E., (2005), "Soil Mechanics-Principles and Practice", Palgrave Macmillan Edition, 540p.

Salgado, R. (2007), "The Engineering of Foundations", McGraw-Hill Intern. Edition, 896p.