Serviceability Assessment for a High Speed Railway Track in Overconsolidated Clay Formations

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1 Introduction

The European railway network is being supplemented by some newly constructed high speed lines for quick train connections between capital cities and metropolitan regions. The section Nuremberg – Ingolstadt referred to in this paper belongs to the north – south trunk line Berlin – Munich. This section will be completed and shall be opened to traffic in summer 2006. The railway track is designed for an operating speed of 300 kph (kilometres per hour). Accordingly, it has large curve radii and small grades. 30 % of the railway line is running through tunnels, 30 % on embankments, 25 % in cuts and 15 % on bridges or level terrain. The concrete slab-track system is used with welded steel rails.

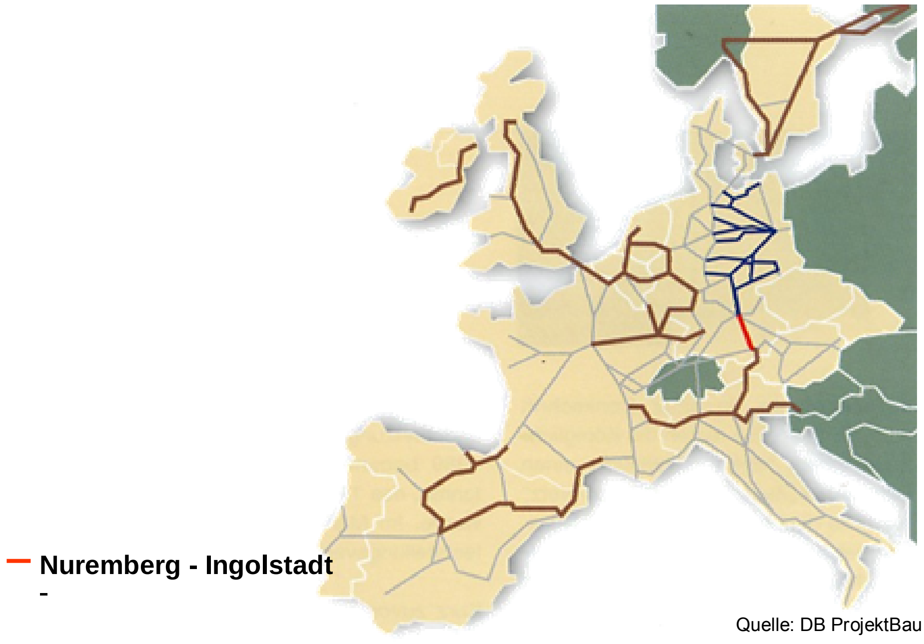

Figure 1: European high speed railway network

2 Serviceability requirements

Due to the operating speed v_e = 300 kph the railway track has to meet high requirements with respect to operational safety and comfort for passengers. Among other geometrical features the vertical displacements of the track are strictly limited. The rail fastening system on the concrete track slabs permits adjustments of 20 mm in the vertical direction. Since 5 mm are needed for settlements caused by dynamic actions of trains, the time dependent settlement of the ground occurring after placement of the slab track system caused by static loading, e. g. by the weight of an embankment, are normally limited to s_r = 15 mm [1]. In order to meet this strict serviceability requirement only soils with small compressibility are used for subgrade and subbase in the standard case, and they undergo severe quality control tests during placement and compaction.

For all structures like bridges and embankments the settlements have to be predicted by geotechnical analyses, and it must be shown that they comply with the requirements. The settlement predictions are essentials for the railway track serviceability assessment. Together with stability analyses for slopes and foundations and all design documents they are submitted to the supervising German Federal Railway Authorities (Eisenbahn-Bundesamt) for technical review and approval. On high speed railway tracks settlements have to be monitored during and after construction.

The rules discussed here for settlements, for vertical deformations downwards, in principle do apply to vertical movements upwards, heave, as well. Heave may occur due to unloading of the ground by excavation. If the ground behaves essentially elastically then the heave deformations cease before the installation of the slab track system and are of no concern. However, if heave deformations are time dependent since they are caused by swelling soils, they require special attention. In extreme cases where large upward heave movements have to be anticipated and where the heave may occur irregularly such as in geologic formations with anhydrite deposits near the ground surface, the construction of high speed slab track systems may not be possible. In terrain with swelling soils, it must be demonstrated that the heave of the bottom of excavations will not exceed the permitted vertical deformations. Due to the initial setting of the rail fasteners on concrete slabs, the permissible vertical movement upwards amounts to 10 mm only.

Numerous cuts of the new high speed railway line Nuremberg – Ingolstadt had to be excavated in over-consolidated clay and clay-stone formations. Here, for the serviceability assessment of the slab track system, it was necessary to predict the time dependent heave deformations and to demonstrate that they would not exceed the limiting value of 10 mm.

While geotechnical procedures for the prediction of time dependent ground settlements under static loading are well established and documented in German standards, methods for the prediction of heave due to unloading of swelling soils do not belong to the routine. In the case reported here, the swelling problem had to be addressed by a scientific approach involving laboratory tests on undisturbed soil samples, analyses and field measurements according to the observational method. Eventually the question was posed whether the reliability of the heave prediction for excavations in swelling over-consolidated clays would be equivalent to the reliability of consolidation calculations for the prediction of time dependent settlements for embankments founded on normally consolidated clays.

3 Swelling

The geotechnical term „swelling“ refers to the process of time dependent volume increase associated with an increase in water content which a soil or rock may experience during and/or after unloading. Cohesionless soil does not swell. The bottom of excavations or cuts in cohesionless soil undergoes elastic deformations only, which occur rapidly. In cuts or excavations of clays and clay-stones however, time dependent bottom heave caused by swelling may occur in addition to the elastic deformations upon unloading.

Swelling processes can be driven by a chemical potential, by an osmotic or by a matric suction potential or by combinations of these. Along the railway line Nuremberg – Ingolstadt to depths of concern there were no rocks or soils such as anhydrite with a chemical potential. So in the case discussed here, the swelling processes were essentially controlled by the matric suction potentials of the over-consolidated clays and clay-stones.

The swelling potential of clays and clay-stones depends on their state. According to Bjerrum, referenced by Alonso [2], these materials may contain a “locked in strain energy” from earlier compaction, e. g. due to previous overburden loading. The degree to which the “strain energy” is “locked in” depends on the strength of diagenetic bonding. When the diagenetic bonds are loosened, e. g. by desiccation cracking under high temperatures, or by fissuring due to stress changes upon loading/unloading, or due to the dissolution of chemical cements, generally in nature by the influence of weathering, then the “locked in strain energy”, is activated and the swelling potential is mobilized. Gründer [3] and Razizadeh [4] had observed that the over-consolidated clays and clay-stones of the Keuper- and Triassic formations encountered along the railway line Nuremberg – Ingolstadt showed almost no swell as long as they were kept in an un-weathered state. In order to study their swelling potential the mentioned authors dried clay and clay-stone samples under elevated temperatures, thereby destroying the diagenetic bonds and initiating high matric suction stresses. As a result, the researchers ended up with high swelling pressures in volume controlled tests and with large volume increases in free swell tests respectively. Based on their observations Gründer [3] and Razizadeh [4] advised to prevent desiccation of excavated clay or clay-stone surfaces in earthwork practice in order to avoid swelling problems.

The in-situ swelling potential of the over-consolidated clays and clay stones along the railway line Nuremberg – Ingolstadt depends on the actually existing diagenetic bonds. In other words, the swelling potential depends on the degree of weathering. So, the first step in the procedure for the prediction of heave deformations was a geologic reconnaissance along the alignment. Degrees of weathering were assigned to pertinent sections of the ground profiles. The extent to which the clay-stone or over-consolidated clay had been affected by weathering was classified into 5 stages, w1 for un-weathered clay-stone to w5 for totally weathered clay. Rocks of stage w1 were not encountered to the depths of interest for the anticipated excavations. Clays of stage w5 were expected to be replaced with more competent soils, so only weathering stages w2 to w4 were of interest with respect to swelling heave predictions.

4 Constitutive model

The amount of volume change ε_v a soil element experiences when it swells depends on the state of stress. The larger the overburden stress σ_z is, the smaller the heave due to swelling ε_z will be. If the vertical stress is high enough, no heave will take place. The vertical stress under which no heave occurs is called swelling pressure σ_{z0}. For one-dimensional conditions, the relationship between the vertical component of swelling strain ε_z and the vertical stress component σ_z at location z can be plotted as a straight line on a semi-logarithmic scale (Figure 2) expressed by the following formula [5]:

$$\varepsilon_z = -C_b * \ln (\sigma_z / \sigma_{z0}) \qquad (1)$$

Equation (1) is valid for compressive stresses only in the range $\sigma_{z0} > \sigma_z > \sigma_c$ for stresses smaller than the swelling pressure σ_{z0} and greater than the minimum stress σ_c. The two controlling parameters, swelling index C_b (inclination of the swelling curve in the semi-logarithmic plot), and swelling pressure σ_{z0} have to be determined by laboratory testing. The limiting minimum stress σ_c in the case presented here equals the weight of the railway track plus non-swelling soil overburden above the swelling strata including any probable soil replacement that will be discussed later on.

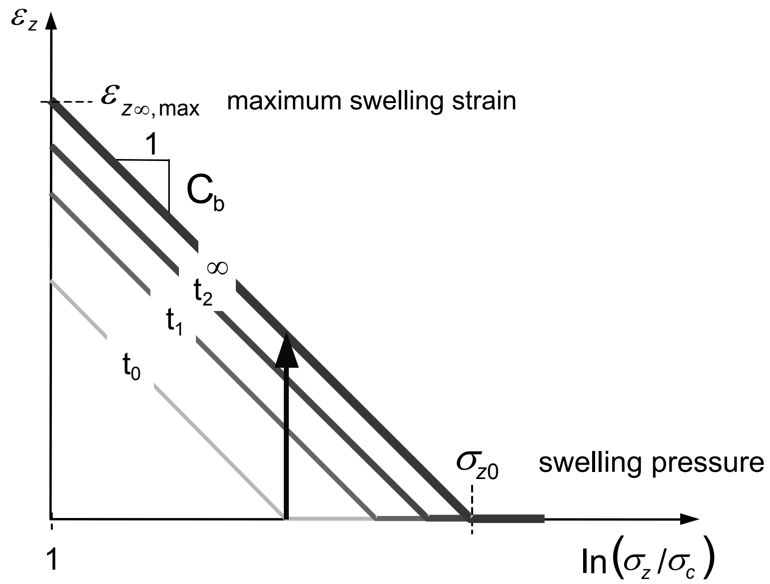

Figure 2: Vertical swelling strain ε_z as a function of vertical total stress σ_z at time t_i

Equation (1) denotes the total possible volume increase $\varepsilon_{z,max}$ provided there is enough water available to balance the entire swelling potential of the soil. It describes the final stage of the time dependent swelling process rather than the process itself. Under the assumptions that there is enough water available, that the swelling process commences immediately after the change in the state of stress due to the excavation, that the state of total stress then remains constant, and that the swelling process develops steadily, the time dependent strain can be expressed by equation (2) after Kiehl [6]:

$$\varepsilon_z(t') = -C_b * \ln(\sigma_z / \sigma_{z0}) * [1 - \exp(-t'/\eta_q)] \qquad (2)$$

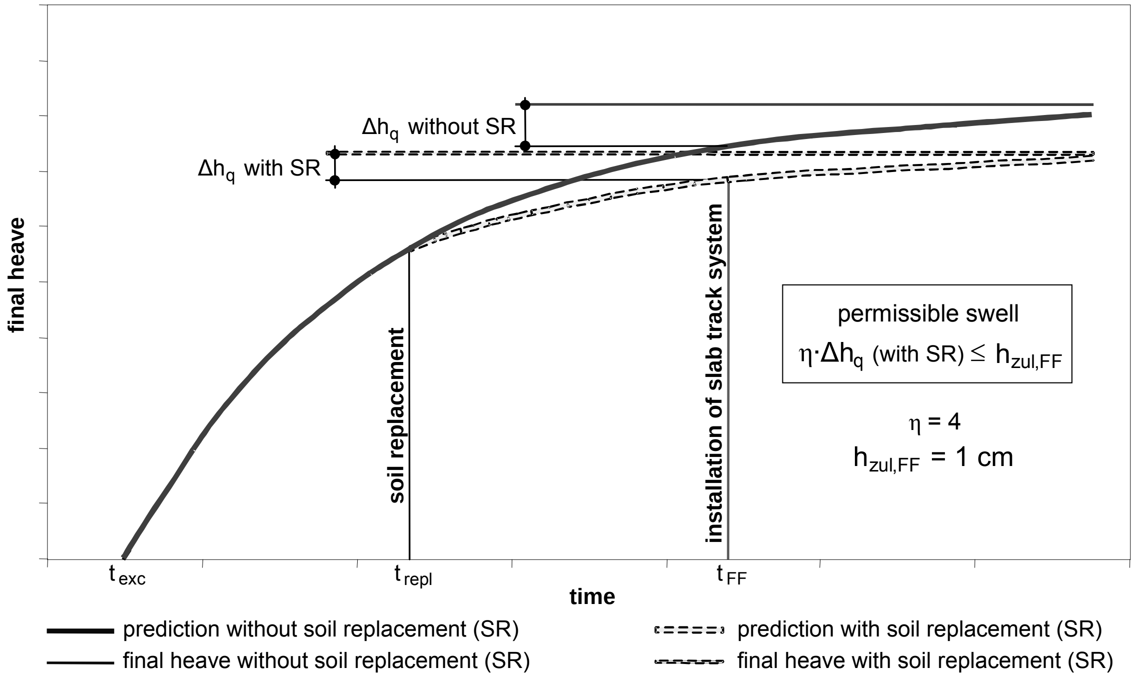

Figure 3: Development of swelling heave with time

The time reference factor η_q is determined from free swell tests. The specific time t' defines a normalised time scale which is independent of the thickness of the swelling soil layer. The influence of the thickness of the swelling layer D_{layer} is taken into account by formula (3), where the length of the swell test sample is denoted by D_{sample} [7].

$$t' = t * (D_{sample} / D_{layer})^n \qquad (3)$$

In case of consolidation under loading n = 2. In the present case the exponent n is derived from in-situ swelling heave measurements obtained by extensometers.

Like any other constitutive model in soil mechanics, the one-dimensional approach presented here, involves a number of simplifying assumptions. However, in analogy to the common procedure for the calculation of time dependent settlements under static loading conditions with account of the consolidation of the ground, this geotechnical swell model can be adequately used for the prediction of heave. The parameters needed are the swelling pressure σ_{z0} and the swelling index C_b to be determined by laboratory swell tests on undisturbed soil samples, the parameters n and η_q to be derived from swell tests in the laboratory and field measurements and the expected changes in the state of stress which can readily be estimated.

5 Laboratory tests

The swelling potential depends on the amount of clay size particles, on the plasticity index and the shrinkage limit as parameters indicative of the clay minerals involved, on the in-situ water content, respectively the initial porosity, on the matric suction potential and on the stress history. The electrolyte content of the pore water may also influence the swelling process. The soil profiles along the railway line Nuremberg – Ingolstadt where over-consolidated clays and clay-stones were encountered in 4 different geologic formations (Feuerletten, Amaltheenton, Opalinuston, Tertiärton) were analysed with respect to the parameters related to the swelling potential. Zones of the ground prone to swelling, for which these parameters matched reasonably well, were determined in each of the 4 geologic clay formations, and undisturbed soil samples were obtained for swell tests. All together 169 swell tests were executed in 4 German geotechnical laboratories for the determination of the swelling parameters C_b and σ_{z0}. Figure 4 gives an example of test results for the over-consolidated clay of the "Amaltheenton" formation. The diagram shows 4 different lines indicative of the 4 different weathering stages studied. Clearly, the swelling index C_b, the inclination of the lines, increases with the degree of weathering, and the swelling pressure σ_{z0}, the stress at zero swelling strain, decreases with the degree of weathering.

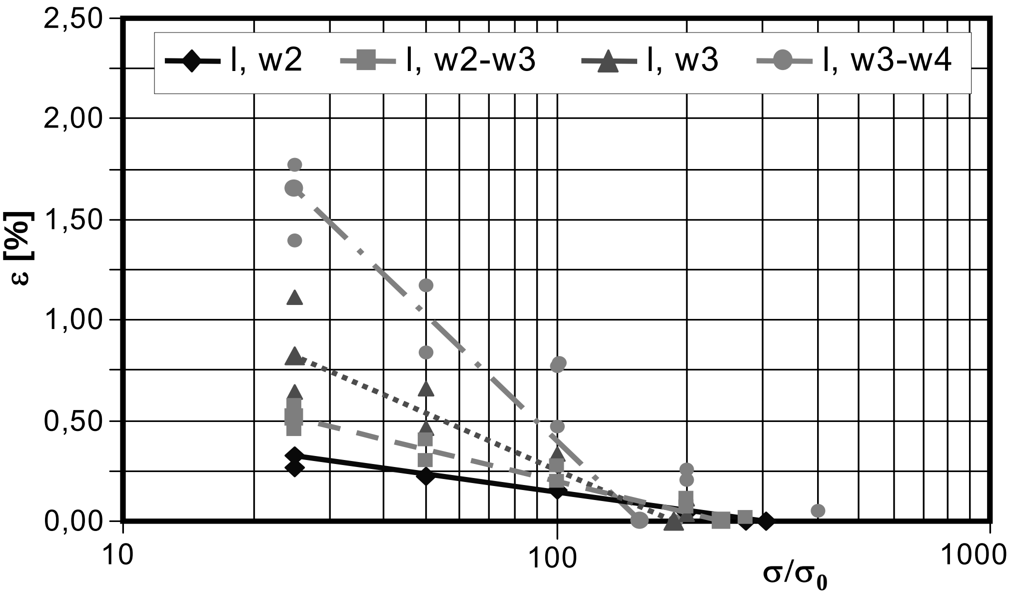

Figure 4: Swelling strain vs. stress diagrams for over-consolidated clay of the geologic formation Amaltheenton with different degrees of weathering

Three different methods were employed for the swell tests: a) free swell tests, b) Huder & Amberg tests and c) combined swelling-pressure – heave tests. For the free swell test a) the prepared soil sample is placed in an oedometer, submitted to a vertical load equivalent to the overburden stress at the depth from where the sample had been retrieved. Then the water supply valve is opened and the sample can suck water to swell freely in the vertical direction as the vertical loading is removed stepwise. For each unloading step the height of the sample is measured when the vertical movement ceases, and the corresponding volume change is plotted versus vertical stress as shown in Figure 5 a).

Swell tests b) after Huder & Amberg [8] are also carried out in an oedometer and the sample is also loaded to the overburden stress. But then the sample is unloaded and reloaded before the water supply valve is opened and the stepwise unloading – swelling process is initiated. Figure 5 b) shows the stress-strain plot. Due to the additional unloading-reloading cycle the sample undergoes more severe mechanical disturbance than in case of the free swell test, the diagenetic bonds are destroyed more substantially, the swelling potential is activated to a greater extent, and consequently more pronounced volume changes are measured by the Huder & Amberg test b) than by the free swell test a).

In the combined swelling-pressure – heave tests c) the sample is given the opportunity to suck water without any surcharge load in a constant volume confinement in the first stage of the test. When the final swelling pressure σ_{z0} is reached the sample is unloaded stepwise and allowed to swell freely in the second stage of the test. Since the disturbance of diagenetic bonding is a minimum in tests according to method c), the swelling index C_b determined in the combined swelling-pressure – heave test c) is smaller than after test methods a) and b). [7; 9]

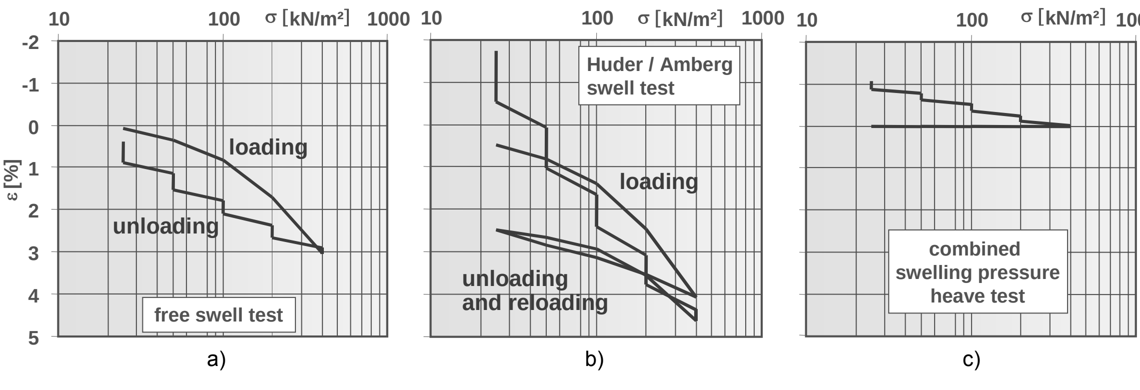

Figure 5: Loading paths for different swell tests: a) free swell test, b) Huder & Amberg swell test, c) combined swelling pressure – heave test

6 Limitation of swelling heave by partial soil replacement

With swelling parameters determined by laboratory tests the anticipated maximum swelling heave $h_{z,max}$ was predicted according to equation (1) for all cuts in over-consolidated clays and clay-stones of the railway line Nuremberg - Ingolstadt. Depending on the geologic conditions, the degree of weathering and the depth of excavation values $h_{z,max}$ between 0 and 46 mm were determined for maximum heave. Since these deformations exceeded the permissible limit in some situations, technical measures had to be designed for their reduction [10]. Figure 6 shows the predicted heave of 5 analysed cross sections of a typical cut as an example. The plot indicates that the predicted vertical deformations decrease rapidly with depth. So it can be concluded that the replacement of the upper layers of the swelling soil with non-swelling soil effectively reduces the total amount of heave.

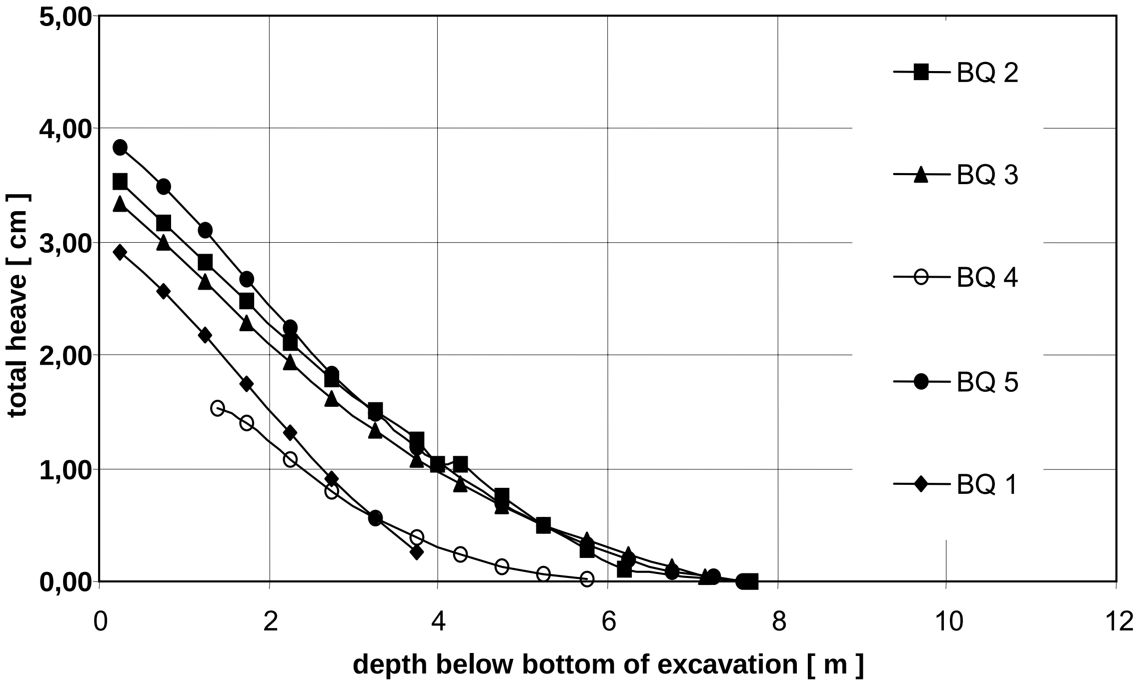

Figure 6: Example of swelling heave vs. depth below bottom of excavation computed for 5 cross sections

The amount of heave to be expected after placement of the concrete slabs of the slab track system was the governing design criterion for the decision whether or not soil replacement was necessary. In order to obtain this value, the development of heave with time was computed according to equations (2) and (3) with parameters η_q and n based on laboratory tests and on field measurements. The time delay between excavation and placement of the track ($t_{FF} – t_{exc}$) was estimated and the difference Δ_h between total expected heave $h_{z,max}$ and heave until placement of the slabs h_{FF} was computed. Figure 3 schematically shows this difference, the expected heave Δh_q after placement of the concrete slabs at time t_{FF} for the case of no replacement of the upper layer of the swelling soil and for the case where a layer of the swelling soil with a certain thickness would be replaced with non-swelling soil.

The required thickness of the soil replacement was designed with a safety factor η = 3 to 4 (Figure 3) to make sure, that the expected heave after installation of the track would definitely be smaller than 10 mm. It turned out, that depending on local conditions, the upper 0,5 m to 1,3 m of the swelling soil had to be replaced with non-swelling soil. The ground deformations were monitored in the field by 13 extensometers. Results of these measurements were used to update the parameters η_q and n and to carry out improved runs of time-swelling computations.

Differential heave within a cross section or over short distances in track direction was of particular concern. There is no method to predict heave differences caused by variations of soil properties other than engineering judgement. To account for inhomogeneous ground conditions, the soil replacement was executed thicker than required according to design calculations. In practice, the soil replacement was finally carried out with layers of 0,5 m, 0,7 m, 0,8 m and 1,3 m.

Field measurements have demonstrated that up to now the swelling heave predictions are on the conservative side. The slab track system has been placed as designed, the rails have been installed, and test runs of high speed trains are scheduled for the autumn of 2005.

7 Conclusions

The methodology for the prediction of swelling heave presented here for the serviceability assessment of the slab track high speed railway line in cuts of over-consolidated clays and clay-stones follows the same steps as a conventional settlement analysis: Geological reconnaissance, sampling and laboratory testing are executed to develop a geotechnical model and assign characteristic material parameters to the soils and/or rocks involved. With simplifying constitutive mathematical models time dependent deformations are computed for anticipated changes in the state of total stress which initiate pore liquid movement.

The pore-water plays an important role in consolidation settlement analyses as well as in swelling predictions. For nearly saturated soils the increase in pore pressures under loading and the dissipation of excess pore pressures with time can be predicted quite reliably according to the theory of consolidation. On the other hand, the pore water movement that causes volume changes due to unloading after the development of matric suction depends on the availability of water. If no water is available, swelling may never start. If water is available only after a certain period of time, swelling may start with some delay. So, while it appears quite reasonable to predict total possible maximum swelling heave $h_{z,max}$, the prediction of the actually occurring swelling deformation of the ground at a specified time seems to be somewhat uncertain. In the case study presented here, extensive field measurements have been carried out to judge the state of the ground with respect to swelling at any time. Additionally, sealing and drainage elements were installed in order to prevent inhomogeneous wetting which could initiate differential heave. With these supplementary features in mind, it was finally concluded, that the reliability of the swelling heave predictions could be assessed a degree of reliability equivalent to the reliability of settlement predictions. So eventually the serviceability assessment presented here was accepted and the consent of the supervising authorities for test operation of trains at 300 kph on the new railway line Nuremberg – Ingolstadt in Germany from autumn of 2005 could be gained.

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