Stability modeling of old railway embankments on very soft ground

Modélisation de stabilité d'un remblai du vieux chemin de fer sur sol très doux

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ABSTRACT

The stability of a 130 year old railway embankment built on very soft clayey ground was studied under train loads. The analysis was made by different computer programs based on limit analysis and FE-method with different material models. The assumptions and results were mutually compared.

RÉSUMÉ

La stabilité du remblai d´un chemin de fer de 130 ans, qui est construit sur sol très doux et argileux était étudiée au-dessous de fourgons. On avait fait l`analyse avec programmes séparés basés sur l`analyse limite et sur la méthode FE avec des modèles matières différentes. Les présomptions et les résultats étaient mutuellement comparés.

Keywords : geotechnical engineering, stability, excess pore water pressure, factor of safety

1 INTRODUCTION

The stability of 130 year old railway embankments, built on very soft clayey ground, was modeled and studied by using different computer programs. The site of the research was in southern Finland at Toijala-Turku railway section (Fig. 1) belonging to Finnish railway network. The examined cross-section of the embankment was selected with the aid of the initial stability calculations based on limit equilibrium methods. The purpose of the research was to investigate a possibility to increase axle loads of freight trains in that railway section and to compare the factors of safety in undrained state caused by train loads calculated by different limit equilibrium (LE) methods and finite element (FE) method program Plaxis.

2 GROUND CONDITIONS AND LABORATORY TESTS

According to the ground-penetrating radar investigations the height of the profile of the cross-section in the middle of the embankment is about 2.2 m sloping down into deep ditches on the both sides. Under the embankment there is 11 to 15 m thick soft soil of clay covered approximately 1.5 m thick dry crust. The analyzed cross-section is presented in Figure 2, where are also some results of weight sounding tests and a field vane test. The latter situated 12 m to the left from the centre line of the track, and the measured smallest shear strength value of the field vane test was about 13 kPa in the depth of 2 to 5 meters.

Undisturbed soil samples were taken near the field vane test point. Classification and strength index properties as well as oedometer and triaxial tests were made in the soil mechanics laboratory. The results of the classification and strength index tests of the clay are shown in Figure 3, where γ means bulk density, w water content, sk undrained shear strength by the fall cone test and S_t sensitivity. In the depth of 2 to 4 meters water content is 80…90 %, undrained shear strength is about 18 kPa (without correction) and sensitivity is about 20.

Conventional stepped oedometer tests were made to measure settlement properties and specially the pre-consolidation pressure (Salokangas 2008), although the results are not presented in this paper. The triaxial tests were the type anisotropically consolidated undrained compression tests.

Figure 1. The research area was situated near the city of Turku (highlighted area).

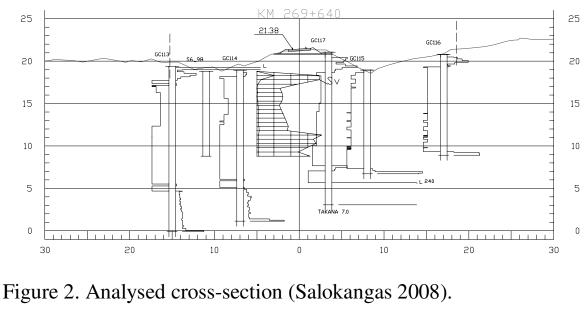

Figure 2. Analysed cross-section (Salokangas 2008).

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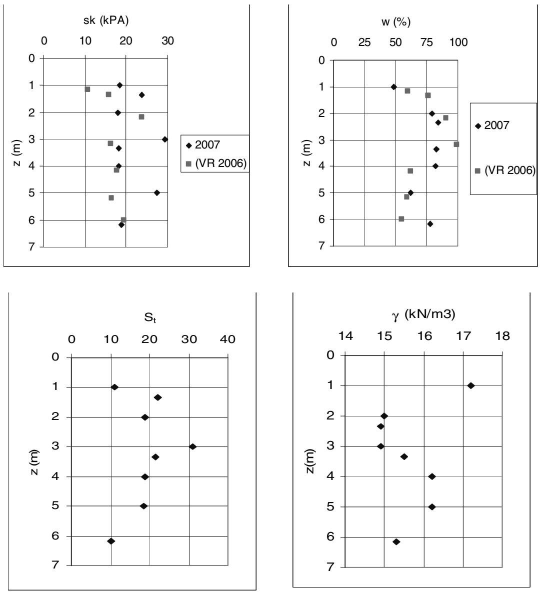

Figure 3. Classification and strength index properties of the clay. From left, upper row: Undrained shear strength by fall cone test sk, water content w. Lower row: Sensitivity S_t, bulk density γ.

3 TRACK LOADS

According to the guideline of the Finnish Rail Administration (RAMO 3 2005) the dimensioning load for the embankment is a train at rest. In the analysis the surface load of 35.2 kN/m^2 was used, approximating 25 t axle loads of the train engine.

4 IN SITU MEASUREMENTS

Pore pressure gauges were installed to soft clay under the embankment. The measurements were done when a heavy freight train was stopped in position. The line load from the train was determined to be 46.7 kN/m approximating uniform vertical load of 18 kPa under railway sleepers. The pore water pressure was measured from 5 measuring points by using two kinds of pore pressure sensors of 2 bar and 5 bar pressure ranges, respectively. All devices were suitable to measure only static state of the pore water pressure. Three of the pore pressure sensors were installed near the centerline under the embankment on different levels from the surface. The rest two sensors were placed about 5 m to the left from the centerline. The exact location and pressure ranges used in measurements as well as measured and calculated results are shown in the table 1.

Table 1. Location of pore pressure sensors, measured and calculated excess pore water pressures

No.	Pressure range, bar	To the left from centerline m	Level, m	Measured kPa	Calculated, model SSCM., kPa
1	2	0.5	16.4		3.8
2	2	1.7	14.1		3.4
3	5	2.3	12.1	2.5	2.6
4	5	4.8	15.7	1.7	2.0
5	5	5.7	16.4	2.0	1.4

The pore water pressure was first measured just after installation so that the balancing of the excess pore pressure due to installation could be followed. In all five measuring points the balancing of the overpressure was detected.

When the freight train arrived the pore pressures increased gradually until the train moved on after 17 minutes from arrival. After the departure of the train the balancing of the excess pressure took approximately 1 hour. The excess pore water pressure could not entirely reach the maximum value during the 17 minutes stop as can be seen in Figure 4. The excess pore water pressure that mobilized during this period was small. The measured overpressures in points 3 to 5 were 2.5, 1.7 and 2.0 kPa, respectively.

The results obtained in points 1 and 2 were discarded because the sensors were stuck firmly to the rods used in measuring.

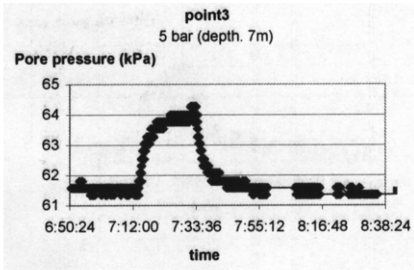

Figure 4. The measured pore water pressure during the 17 minutes long train stop recorded in the measuring point 3.

5 CALCULATION METHODS

Two different computer programs were used to calculate the stability of the embankment; Slope/W 2004 (Krahn 2004) and Plaxis v. 8.6 (Brinkgreve et al 2004). In Slope/W the analysis was based on Bishop's Method. In FEM based Plaxis-program elastoplastic Mohr-Coulomb model (MCM) and Soft-Soil-Creep model (SSCM) were applied as material models.

The analysis using Slope/W program were done using both $\varphi = 0$ and c' – φ' -methods. Estimated reduced undrained shear strength values s_u determined by vane tests were used in $\varphi = 0$ calculations. When using c' – φ' – method the effective strength parameters, effective cohesion c' and effective friction angle φ', were obtained from undrained triaxial tests.

The train load was modeled as a separate layer of soil in all Slope/W calculations. The vertical stress due to the train was added to the pore water pressure of the soil. This way the increase of the stress of the train was compensated in the top layer and the stress concentrated only to the soft layers of clay. In limit equilibrium analysis a combination of circular and planar failure surface was applied. The groundwater level was estimated from the results of the pore water pressure measurements. The calculations were done according to the guidelines B 15 (Railway Administration 2006). On the bases of the results of field vane tests and weight soundings the soil beneath the embankment was divided into four different layers (Figure 5). On the top under the embankment is a 1.5 m thick dry crust. Under the dry crust the soft soil clay was modeled to depth of 10 m by dividing it into three separate layers. It was not necessary to continue modeling deeper, because the weakest layers were just under the dry crust. When c' – φ' – method was used, the clay under the dry crust was modeled as one thick layer. The parameters used in Slope/W calculations are collected into the table 2, where μ is the correction factor, linked to the liquid limit, s_u is the undrained shear strength by field vane test, c' is the effective cohesion, φ' is the effective friction angle and γ is the bulk density.

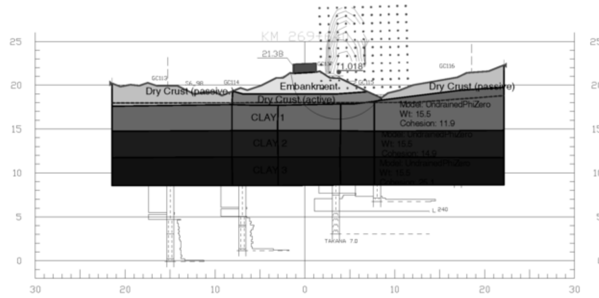

Figure 5. Slope/W: Soil layers and calculation model.

Table 2: The parameters used in Slope/W analysis.

Layer	μ	s_u, kPa	μ s_u, kPa	c', kPa	φ', °	γ, kN/m^3
Embankment				1	32	20
Dry crust			30			17,3
Clay 1	0,88	13,5	11,9	8,2	18,2	15,5
Clay 2	0,93	16	14,9			15,5
Clay 3	0,93	23	25,1			15,5

In the Plaxis analysis the cross-section of the research site was modeled by using the coordinates of Slope calculations as input data and the soft clay was modeled as one thick layer. The analysis was conducted using two different methods in which the loading history of the embankment was possible to take into account. Both calculations methods start from the initial state estimated by the results of soundings. In the initial state the initial stresses of soil were determined. After the initial state the different construction phases of the embankment were added in undrained state. After each phase of the construction the soft soil was allowed to consolidate to the drained state so that the excess pore water pressure, caused by the increment of the embankment, was zero. This way the modeling was continued to the state of today. In the first method the modeling was done by calculating the excess pore water pressure in undrained state caused by the train load after which the c' – φ' -reduction in undrained state was done and the factor of safety was calculated. The second way to calculate the factor of safety was based on load increase. In this method the bulk density of the embankment, or to be exact, the gravity, and the train load were gradually increased until the ultimate limit state was reached. In this case, the factor of safety responded straight to the increase of the breaking load. By increasing the weight of the embankment and the train load the increase of the excess pore water pressure was taken into consideration. The used element net applied is shown in Figure 7 and the soil parameters in tables 3 and 4.

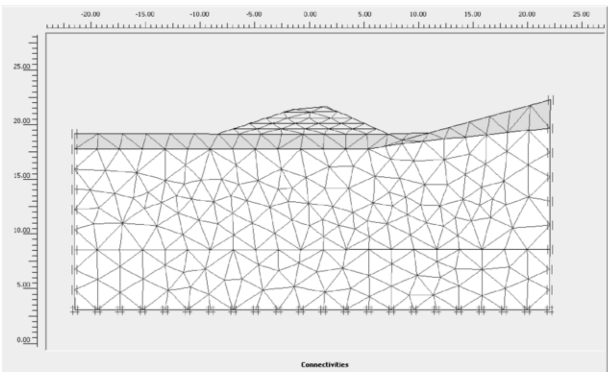

Figure 6. Plaxis element net and soil layers

Table 3: Material parameters used in MCM calculations

Layer	model	γ_{sat} kN/m^3	k_x m/day	k_y m/day	E^{ref} MPa
Embankm.	MCM	19	1	1	60
Dry crust	MCM	17,3	3,48E-4	1,74E-4	40
Clay	MCM	15,5	9,50E-5	4,75E-5	11
Sand	MCM	19	1	1	60
		ν	c' kPa	φ' °	
Embankm.	MCM	0,35	2	34	
Dry crust	MCM	0,35	30	1	
Clay	MCM	0,35	8,2	18,6	
Sand	MCM	0,35	1	36	

Table 4: Material parameters used in Soft-Soil-Creep calculations

Layer	model	γ_{sat} kN/m^3	k_x m/day	k_y m/day	μ* 10^{-3}
Embankm.	MCM	19	1	1	
Dry crust	MCM	17,3	3,48E-4	1,74E-04	
Clay	SSCM	15,5	9,50E-5	4,75E-05	4,64
Sand	MCM	19	1	1	
		λ*	κ*	c' kPa	φ ' °
Embankm.	MCM			2	34
Dry crust	MCM			30	1
Clay	SSCM	0,165	0,015	8,2	18,6
Sand	MCM				

6 CALCULATION RESULTS

There is a great difference between safety factors depending on which one of the methods φ = 0 or c'-φ'-method was applied in the Slope/W program. If the safety factor is calculated according to Bishop's method, the safety factor was F = 1.14, whereas by using c'-φ'-method the factor of F = 1.93 was obtained.

It was not found a big difference between the results of two different material models in Plaxis calculations. The safety factors determined by using MCM were slightly smaller than by using SSCM. The MCM gave the factor of safety F = 1.65 when c' - φ' -reduction was used and F = 1.71 when load increase was applied. By using the Soft-Soil-Creep model the respective factors of safety were F = 1.72 and F = 1.79. Calculated excess pore water pressures determined by SSCM correlated well with the values measured during the train loading (Figure 7). The corresponding sliding surface at failure can be seen by plotting incremental shear strains (Figure 8). An example of a stress path by p'-q-coordinates is presented in Figure 9.

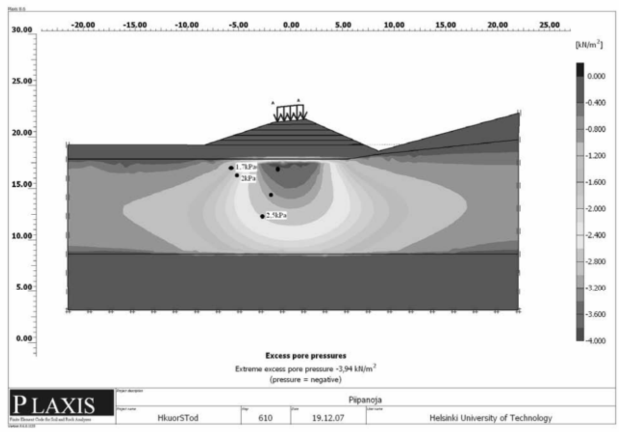

Figure 7. SSCM calculated pore water pressure distribution.

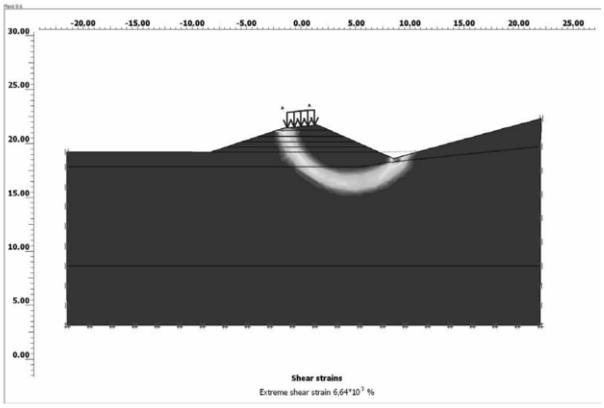

Figure 8. The sliding surface at failure.

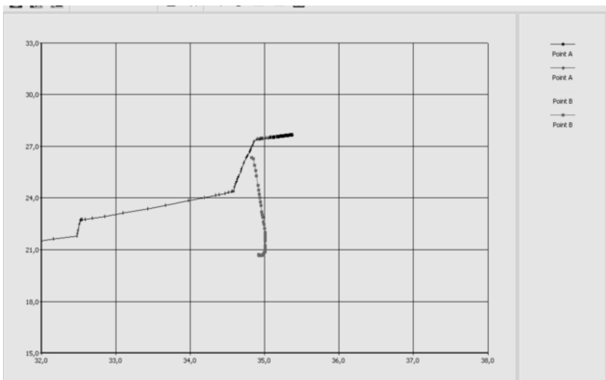

Figure 9. Stress paths in p'-q-coordinates (p' horizontal), MCM. The analyzed point is near the failure surface in soft clay. The starting position is the intersection of two curves: The curve downward means c'-φ'-reduction and the curve upward is based on the load increase.

7 CONCLUSIONS

On the bases of this research the most important factors affecting the stability of the embankment are the strength parameters, which are determined for the soil and they are independent of what method or program is used in the analysis. The determination of the parameters must be decided by each designer.

When using limit equilibrium methods one must pay special attention to the determination of the layers and strength parameters of soil. Several field vane tests and weight soundings must be done beforehand so that the layers could be found out as strictly as possible. Additionally other soil tests must be done sufficiently. The thickness and the shear strength of the dry crust have essential influence on the stability of the embankment especially in the case, where the surrounding environment is flat and the length of failure surface short, as was in the case examined. This is why the modeling of the dry crust should be done most carefully, but it is difficult to get the correct parameters for dry crust because the material is usually non-homogeneous containing varying amount of water and cracks.

The safety factors obtained by using undrained shear strength values were lower than the factors obtained by using the effective strength parameters. There is one other matter that causes confusing and is related to the analysis of limit equilibrium calculations based on effective parameters. The problem is, how to take account the effect of the pore water pressure to the shear strength of the soil. The present modeling of it is inadequate in the sense that the influence of the increase of the pore water pressure during the train loading up to failure is not considered in calculations. The pore pressure that is used in the analysis was kept constant and was determined at the measuring instant. As a distinction of this the undrained shear strengths are the values which are measured in ultimate state and include the current pore pressure. By using effective parameters the failure is reached by calculation. The difference between the obtained safety factors can be explained by the difference of the used methods. It seems that the use of undrained strength parameters in stability analyses is the most sensible way in such cases, when pore pressure measurements are not accessible or cannot be trusted for some reason.

The calculations using Plaxis program were initially conducted by using two totally different approaches. When using c' – φ' -reduction method, the effective parameters are reduced causing the failure straight to move closer to the ultimate stress state. Additionally, in c' – φ' -reduction the excess pore pressure distribution due to train load in the previous phase was used. Thus the increase of excess pore pressure up to failure is not considered. Moreover, during c' – φ' -reduction analysis all material models are working similarly as Mohr-Coulomb model, because the calculations do not include the processing of stress dependent parameters. In practice the calculations are done by considering the modulus of elasticity of the materials constant during the previous phases. This was the reason why there was not a big difference between the results of different material models in c' – φ' -reduction method calculations.

The other modeling method was based on the increase of load. The bulk density of the embankment and the train load were raised until the failure happened. The method allowed the development of the excess pore pressure accordingly. There were only minor discrepancies between the results obtained using different models in the examined site. On the other hand, when the geometry of the site is more complicated, the discrepancies between the modeling methods will increase. This is why it is the designer's duty to make a decision which modeling method is most suitable for particular site.

Calculated excess pore water pressures responded the measured values reasonable well. On the bases of these results and experience Plaxis is suitable for determining the excess pore water pressures in fully saturated state.

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