# Effective stress analysis of old railway embankments

## Analyse de l'usure effective des remblais de voies ferrées anciennes

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ABSTRACT

Stability analyses of old railway embankments on soft soils are commonly made using conventional limit equilibrium method (LEM) based on undrained strength of the subsoil. Alternatively it is possible to use effective strength parameters. According to the Finnish Railroad authorities (RHK), one has to use also the finite element method (FEM) for the effective stress analysis if the clay content in the subsoil is above 35 %. The reason for this is that one should account for the failure induced pore pressure. However, no guidelines are yet given on how this should be done.

This study compares stability analyses based on limit equilibrium method and finite element method applying strength reduction method (SRM) and gravity increase method (GIM). Analyses contain three old railway embankments constructed on clayey subsoil. FEM analyses (program Plaxis) will be accomplished using the simple Mohr-Coulomb material model and the more sophisticated Soft Soil model. The focus of the study is on how to account for the failure induced pore pressure.

RÉSUMÉ

Les analyses de stabilité des voies ferrées anciennes sur des sols mous sont fréquemment effectuées en utilisant la méthode conventionnelle de limite d'équilibre (LEM) basée sur la solidité du sous-sol non drainé. Une autre option possible est l'utilisation de paramètres de solidité effective. Selon les autorités ferroviaires finlandaises (RHK), on doit utiliser la méthode d'éléments finis (FEM) pour l'analyse de l'usure effective lorsque le contenu d'argile du sous-sol dépasse les 35%. Cet usage est justifié par la nécessité de rendre compte de la pression sur les pores occasionnée par une défaillance. Toutefois, aucun principe directeur n'est donné en ce qui concerne les procédés à suivre.

Cette étude compare les analyses de stabilité selon la méthode de limite d'équilibre et la méthode d'éléments finis en appliquant les méthodes de réduction de solidité (SRM) et d'augmentation de gravité (GIM). Les analyses ont été effectuées sur les remblais de trois voies ferrées anciennes construites sur un sol argileux. Des analyses FEM (programme PLAXIS) seront effectuées en utilisant le modèle simple Mohr-Coulomb ainsi que celui, plus sophistiqué, de sol mou. Le but de cette étude est de rendre compte de la pression sur les pores occasionnée par une défaillance.

Keywords : effective stress analysis, finite element method, FEM, stability, railway embankment, excess pore pressure, SRM, GIM, Soft Soil –model

## 1 INTRODUCTION

Stability of railway embankments on soft clays is commonly calculated with limit equilibrium method using undrained strength parameters. However, calculations with undrained strength might for some cases produce too small factors of safety. The calculated total factor of safety might even be less than 1.0 for existing embankments. On the other hand LEM calculations with effective strength parameters tend to overestimate the safety factor for undrained conditions. Also the often used assumption of circular slip surfaces might give a too high safety level. A major problem in effective stress analysis is the assumptions for stress and pore pressure distribution and the difficulty in accounting for failure induced pore pressure.

According to the guidelines by Finnish railway authorities [1], the failure induced pore pressure can be taken into account by using reduced effective strength parameters. The reduced strength parameters should be applied in conventional LEM analysis and when applying simple elastic-perfectly plastic models in the finite element method. In the study stability calculations with limit equilibrium method were accomplished using the following methods: Bishop`s Simplified, Janbu`s Simplified and GLE. Stability calculations with finite element method were made with two different methods using three different material models. Strength reduction method (SRM) is a well known method where the strength parameters $tan\varphi$ and $c$ of the soil are reduced until failure of the structure occurs [2]. Another method used in this study was gravity increase method (GIM), where the load influenced to the subsoil was increased until the failure occurred [3]. Practically this was made by increasing the unit weight of the embankment and the magnitude of the train load [4].

Material models used in the FEM calculations where the elastic-perfectly plastic Mohr-Coulomb (MC) model and two different hardening plasticity models; Modified Cam Clay (MCC) and Soft Soil model (SS). The yield surface of the Soft Soil model is an ellipsoid which shape/height is set with parameter M. The failure criteria itself is similar to conventional Mohr-Coulomb.

The simple Mohr-Coulomb model can't take into account the failure induced pore pressure while the more sophisticated hardening models can. That is why reduced strength parameters are used with MCC-model while the true failure state strength parameters are applied with MCC- and SS-models.

*Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*
*M. Hamza et al. (Eds.)*

*doi:10.3233/978-1-60750-031-5-1606*

## 2 INVESTIGATED EMBANKMENTS

Analyses have been made for three different existing embankments. All are railway embankments with poor stability on soft clays.

### 2.1 *Turku-Uusikaupunki*

The Turku-Uusikaupunki track is located in southwest Finland. The embankment stands almost totally inside the subsoil as a consequence of large settlements as illustrated in figure 1. The subsoil consists of very soft clay which undrained strength varies between 6 and 10 kPa. Effective strength parameters and unit weights used in the calculations are presented in table 1.

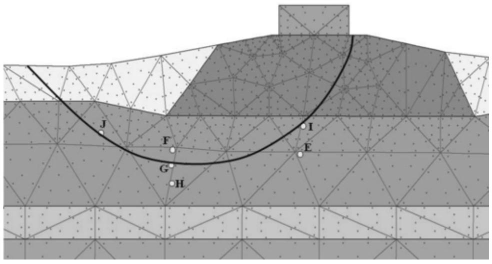



Figure 1. Cross section of the calculation site Turku-Uusikaupunki Km 222+600 m. Also illustrated failure surface and stress calculation points.

Table 1. Basic soil parameters for Turku-Uusikaupunki.

| Parameters: | Reduced strength | | | Failure state | | |
|---|---|---|---|---|---|---|
| | φ’ | c’ | γ | φ’ | c’ | γ |
| Embankment | 30 | 0,2 | 20 | 35 | 0,2 | 20 |
| Dry crust | 20 | 4 | 16 | 25 | 4 | 16 |
| Top clay layer | 20 | 4 | 15,3 | 25 | 4 | 15,3 |

### 2.2 *Kotka-Kouvola*

The Kotka-Kouvola track is located in southeast Finland. Cross-section used in FEM calculations is presented in figure 2. The railway embankment is 6…7 m high and lay’s on quite hard dry crust layer.

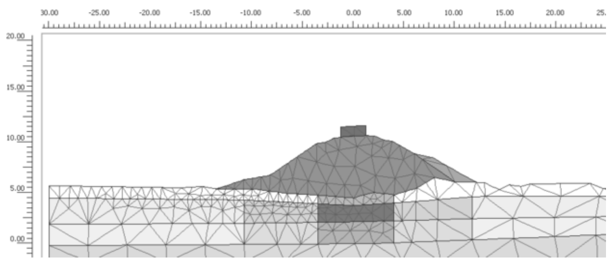



Figure 2. Cross section used in FEM calculation from the site Kotka-Kouvola Km236+300 – 236+620m.

Effective strength parameters and unit weights used in the calculations are presented in table 2. Multiple parameters in the cells indicate that the cross-section is divided vertically in multiple sections which are beside of the embankment, under the slope and under the embankment in that order. This is done to follow a simplified procedure to account for hardening under the embankment. The procedure is mainly intended for undrained strength analysis but the same division was used for all analyses. The soil parameters were determined from extensive laboratory tests made to samples taken both under and beside the embankments.

Table 2. Basic soil parameters for Kotka-Kouvola.

| Parameters: | Reduced strength | | | Failure state | | |
|---|---|---|---|---|---|---|
| | φ’ | c’ | γ | φ’ | c’ | γ |
| Embankment | 30 | 0,2 | 20,0 | 35 | 0,2 | 20,0 |
| Dry crust | 23 | 0 | 19,0 | 25<br>27<br>28 | 4<br>1<br>0 | 19,0 |
| Top clay layer | 23 | 0 | 15,3<br>16,0<br>16,8 | 25<br>27<br>28 | 4<br>1<br>0 | 15,3<br>16,0<br>16,8 |

### 2.3 *Tampere-Seinäjoki*

The Tampere-Seinäjoki track is located in western Finland. In this site the railway embankment was in a rather good shape and the subsoil consists of quite stiff silty clay. Effective strength parameters and unit weights used in the calculations are presented in table 3.

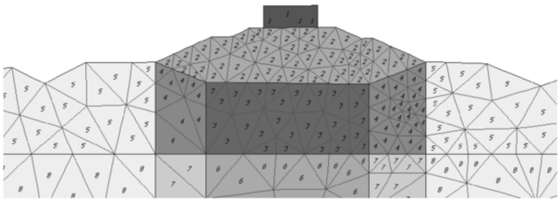


Figure 3. Cross section used in FEM calculation from the site Tampere-Seinäjoki Km236+300 – 236+620m.

Table 3. Basic soil parameters for Tampere-Seinäjoki.

| Parameters: | Reduced strength | | | Failure state | | |
|---|---|---|---|---|---|---|
| | φ’ | c’ | γ | φ’ | c’ | γ |
| Embankment | 30 | 0,2 | 20,0 | 35 | 0,2 | 20,0 |
| Top clay layer | 28,5 | 0 | 18,0<br>18,2<br>18,5 | 34<br>36<br>38 | 4<br>1<br>0 | 18,0<br>18,2<br>18,5 |
| Second clay layer | 25 | 0 | 17,0<br>17,2<br>17,5 | 32<br>33<br>35 | 3<br>2<br>2 | 17,0<br>17,2<br>17,5 |

## 3 COMPARISON BETWEEN SR- AND GI-METHODS

SR- and GI-methods were used parallel with finite element method. In these two methods the factor of safety is determined differently as mentioned previously. In SRM the factor of safety is determined from the relation between the input soil strength and the limit strength which causes a failure in the structure as presented in equation 1.

$$F_{tot} = \frac{\tan \varphi_{input}}{\tan \varphi_{reduced}} = \frac{c_{input}}{c_{reduced}} \qquad (1)$$

The factor of safety in GI method is simply determined from the relation between original unit weight (or gravity) and the limit unit weight directed to subsoil, see equation (2).

$$F_{gi} = \frac{g_{\lim it}}{g_{actual}} = \frac{g_{\lim it}}{\approx 9{,}81 m/s^2} = \frac{\gamma_{end}}{\gamma_{original}} \qquad (2)$$

There is no simple answer for the question which method is better. SRM is well known and there is a lot of research data available and it effect’s in the whole cross-section in the same way. However, the SRM method is a standard procedure only for the Mohr-Coulomb model. For more sophisticated models it has to be applied individually. On the other hand GIM illustrates better the real situation where the embankment is loaded to the failure. Disbenefits are that the operation doesn't effects in the whole cross-section and it's partly dependent of the geometry of the supposed embankment [4]. Nevertheless the calculated safety factors were almost identically with these different methods as presented in section 7.

## 4 ASSESSING OF M-PARAMETER IN SOFT SOIL - MODEL

In the Soft Soil model the M-parameter determines the shape of the yield surface. According to Plaxis manuals the M-parameter is set in a manner that the model yields a realistic coefficient of earth pressure at rest. However, in stability calculation it is more important to match the yield surface near the failure line. In the study two parallel calculations with Soft Soil model were accomplished. One with the M-parameter adjusted to match the coefficient of lateral earth pressure in normally consolidated condition and another where the M-parameter was adjusted to match with the friction angle $\varphi$. In Figure 4 examples of two calculated stress paths are shown together with the estimated yield surface and a triaxial stress path. In addition, an undrained stress path for Mohr-Coulomb model is also shown.

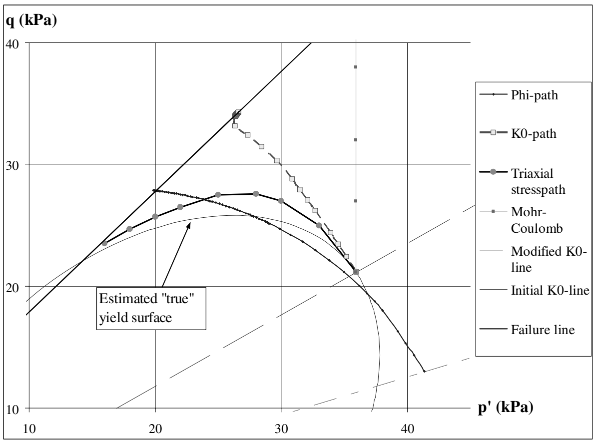


Figure 4. Failure line, investigated stress path and two different calculated stress paths caused by the difference of the M-parameter.

As the effective stress path for undrained conditions follows close to the initial yield surface, the shape of the yield surface much determines at which shear stress level the failure line is reached, influencing thus strongly also on the safety factor. If the shape of the yield surface is known, the M-parameter is possible to adjust to match with the true yield surface [4].

## 5 INFLUENCE OF STIFFNESS PARAMETERS

Relation of the stiffness parameters $\lambda^*$ and $\kappa^*$ determines the hardening effect of the soil model. The larger difference in undrained conditions is between lamda and kappa, the closer stress path follows the initial yield surface. In Figure 5 the infuence on this stiffness relation to the factor of safety is shown for one case. One can see that influence is significant if the lamda/kappa –relation is 20 or less. If the stress path should follow closely the yield surface of the model, which is a safe approximation, one should choose a rather high stiffness relation.

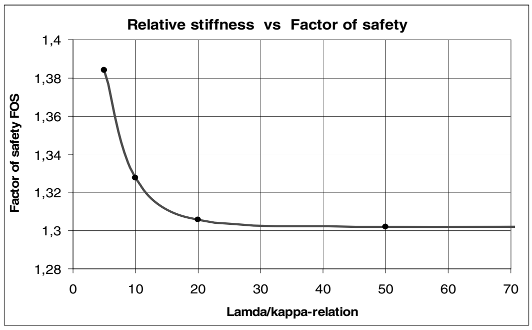


Figure 5. Relation between stiffness parameters and factor of safety.

## 6 PORE PRESSURE

A major difference in LEM and FEM calculations are on the distribution of stress and pore pressure. In undrained effective stress analysis with LEM the traffic load and the pore pressure it induces is assumed to act solely under the traffic load, see figure 6. In finite element analysis the load and thus also the excess pore pressure is distributed over a wider area. In figure 6 excess pore pressure calculated with the soft soil model is also shown. Now the excess pore pressure is mainly between 20 and 30 kPa for a large part of the failure surface, while it was 40 kPa for only a small part of the failure surface in LEM analysis.

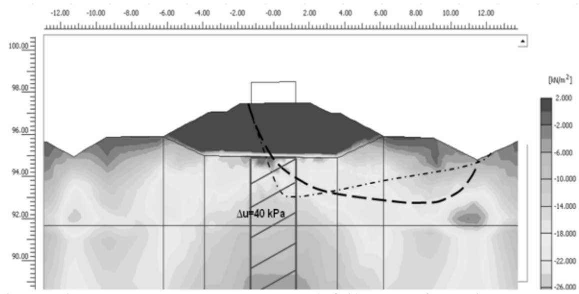


Figure 6. Excess pore pressures and failure surfaces in FEM- and LEM-calculations.

Because of the difference described above, the slip surface calculated with the two methods differs distinctly. The slip surface from LEM-calculation is presented with dash-dot-line and the failure surface from FEM-calculation with long dash-line. In LEM the most critical failure surface is found to go deeper below the traffic load, while the failure surface from FEM calculation follows a more realistic path. In the study it was further observed, that the factors of safety from LEM-calculations are quite parallel with FEM-results if the embankment is low. If the embankment is high like for the Kotka-Kouvola case, the slip surface can not reach the excess pore pressure area and that leads to too high factor of safety.

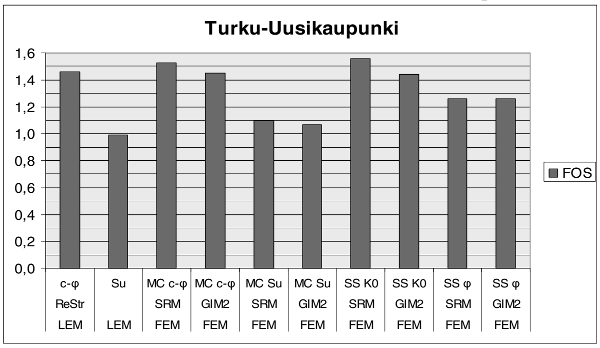
## 7 CALCULATION RESULTS

Main results from the calculations are presented in tables 4-6. Results from the calculation accomplished with Modified Cam Clay –model were so varying in consequence of some problems related in the model that those results are left out from this summary. Descriptions of the symbols and abbreviations used in the tables are presented below:

FOS = Factory of Safety
c-φ = Effective strength parameters (non-circular surface)
ReStr = Calculated with reduced strength parameters
Su = Undrained strength (circular slip surface)
MC = Mohr-Coulomb –model (reduced strength)

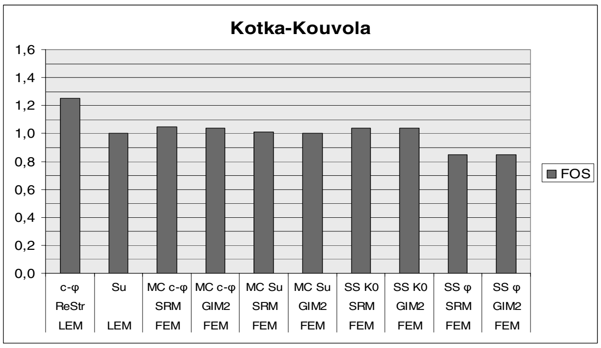
SS $K_0$ = Soft Soil –model with M-parameter adjusted by $K_0$ . Calculated with failure state strength parameters.
SS φ = Soft Soil –model with M-parameter adjusted by ϕ'. Calculated with failure state strength parameters.
SRM = Strength Reduction Method
GIM2 = Gravity Increase Method
LEM = Limit Equilibrium Method
FEM = Finite Element Method

Table 4. Calculation results from the site Turku-Uusikaupunki.



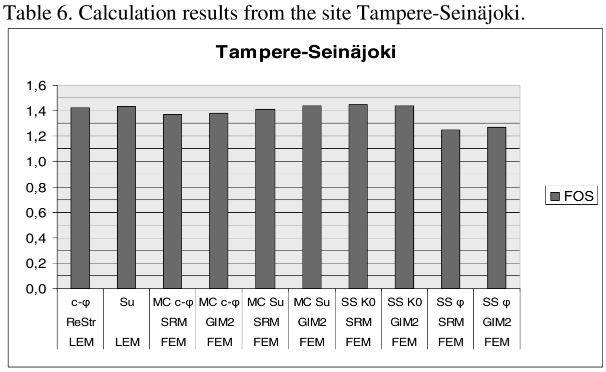

In the first research site Turku-Uusikaupunki there was a significant difference between calculations with undrained strength and with effective strength parameters tanφ` and c`. The FOS was between 1,00…1,05 with undrained strength and between 1,45…1,55 with the effective strength parameters. Exception was Soft Soil calculations where M-parameter was adjusted to match with friction angle. Those calculations produced a safety factor of 1,25.

Table 5. Calculation results from the sites Kotka-Kouvola.




In the second site Kotka-Kouvola the results were quite homogenous. Exception was limit equilibrium calculations with effective strength parameters. From those calculations the average result was approximately 20 % higher than with the other methods. The low safety factors are partly explained by applying too low strength for the embankment material.

Table 6. Calculation results from the site Tampere-Seinäjoki.




In the third site Tampere-Seinäjoki the results were also quite homogenous as presented in table 6. Surprisingly calculations with undrained strength parameters produced even higher safety factors than the calculation with effective strength parameters. Also in this research site the lowest factors were achieved with Soft Soil model and M-parameter match with φ`.

## 8 CONCLUSIONS

Certainly the results of this study were not totally comprehensive but many conclusions can be made. For equal conditions LEM and FEM is usually found to produce both factors of safety and critical failure surfaces close to each other [5] [6]. FEM gives little supplemental information if the calculations are made with undrained strength. However, for undrained effective stress analysis this picture is somewhat changed even for simple soil models in the FEM analysis. The simplified load and excess pore pressure distribution applied in LEM yields that the most critical non-circular failure surface is often found to go deep under the traffic load for shallow embankments.

It is also known that conventional Mohr-Coulomb material model do not consider enough the failure induced pore pressure in soft clays. This was also verified in the study while the Soft Soil model with M-parameter adjusted by friction angle produced notably lower safety factor in each case although a reduced strength was applied in the MC-model.

Results with Soft Soil model were quite promising and indicate that with appropriate material model and parameters the failure induced pore pressure is possible to take account. The procedure is though rather sensitive to the chosen value of parameter M in the Plaxis Soft Soil model.

## ACKNOWLEDGEMENTS

This paper is based on the Master's Thesis research: Stability analysis of existing railway embankments based on finite element method. The research is funded by the Finnish railway authorities (RHK).

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