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Ringsted-Fehmarn Railway

Slope Stability of Embankments

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The existing railway from Ringsted to Rødby (approximately 100 km) is to be upgraded with the objective to provide a double track, high speed connection to the Fehmarn Belt Fixed Link (tunnel). The upgrade consist of two parts. First part concern the upgrade of the existing double track from Ringsted to Vordingborg to a speed of 200 km/h. Second part include the construction of an additional track adjacent to the existing single track from Vordingborg to Rødby – both tracks are upgraded to the same speed. The geotechnical investigations located 33 soft soil areas. In order to comply with the requirements of constructing new railway tracks, no soft soil is allowed under new embankments. In order to leave soft soils the stability of the embankments has to be assessed.

The focus of this article will be the process of calculating slope stability, when constructing a new railway track adjacent to an existing track. In order to calculate the stability of the embankments in soft soil areas, these areas are modelled in the Limit Equilibrium program Slide. Here different failure mechanisms are investigated; circular and block failure, where after the most critical failure was modelled in the finite element program, PLAXIS.

1 RINGSTED-FEHMERN RAILWAY

In 2007 the first declaration between Denmark and Germany was signed. This was a declaration concerning an establishment of a fixed link across Fehmarn Belt. Then in 2009 this declaration was extended to comprise the upgrade of the hinterland infrastructure to the Fehmarn Belt fixed link included, herein the existing railway system from Ringsted to Rødby, The Ringsted-Fehmarn Railway.

The existing railway from Ringsted to Rødby is shown on Figure 1. The railway is approximately 100 km long. The upgrade consist of two parts. First part, marked with a red circle on Figure 1, concern the upgrade of the existing double track from Ringsted to Vordingborg. Second part, is marked with two blue circles on Figure 1, include the construction of an additional track adjacent to the existing single track from Vordingborg to Rødby – both tracks are upgraded to the same speed of 200km/h.

Figure 1. Map of Ringsted-Fehmarn Railway. The railway from Copenhagen to the future Fehmarn Belt tunnel is marked with colored lines, where yellow is the Ringsted-Fehmarn Railway.

The Ringsted-Fehmarn Railway project is divided into three civil work contacts: Ringsted-Vordingborg, Falster and Lolland. The article at hand will address the civil works on Falster and Lolland with main focus on soft soil below the railway embankments.

2 GEOTECHNICAL INVESTIGATION

In order to comply with the requirements of constructing a new railway track, no soft soils are allowed below new embankments, according to the railway guidance: BN1-8-1. Geotechnical investigations of the soils in Falster and Lolland were made with geotechnical boreholes conducted for each 100 m which lead to 800 boreholes.

The 800 boreholes were analyzed one by one and 33 soft soil areas were identified. In order to locate soft soil and delimit the soft soil areas extra boreholes were conducted on Falster and Lolland

Soft soil is classified as K0-soil in BN1-8-1 which has to be removed below new railway embankments. However with a stability analysis it can be proven that the embankment is stable with soft soil remaining underneath. Additional boreholes were conducted in order to make cross-sectional views of each of the soft soil areas.

In the Southern Part, there was 700 boreholes conducted in all, in order to locate the soft soils and ascertain the extent of each soft soil area.

3 STABILITY

Stability is a common geotechnical issue, which can be the stability of a retaining wall, such as sheet pile walls, or of slopes. The article at hand is about slope stability of railway embankments.

The theoretical solution of a slope stability problem has to fulfill both static and kinematic conditions. The static condition requires equilibrium in all stress points and all stresses in the soil cannot exceed the failure condition. Mohr-Coulomb criterion, Eq. (1) or (2).

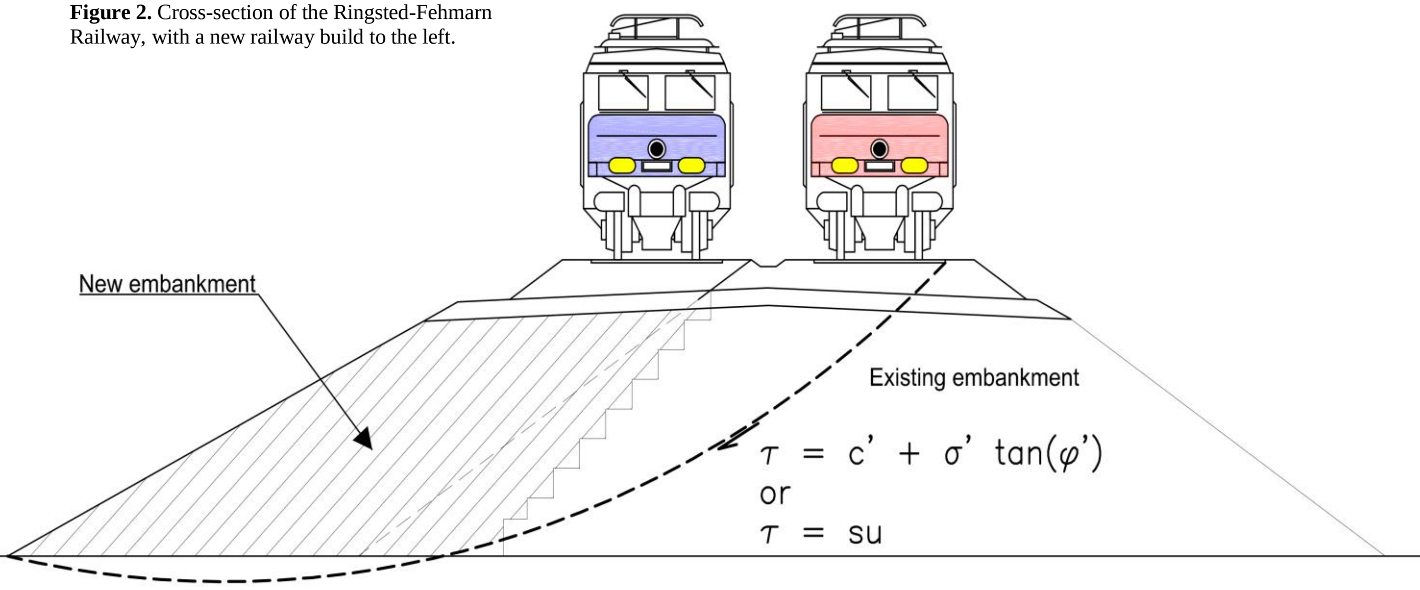
$$\tau_F = c' + \sigma' \tan(\varphi') \quad \text{(drained)} \qquad (1)$$

Or

$$\tau_F = s_u \quad \text{(undrained)} \qquad (2)$$

The kinematic conditions are that there's only strain in the failure mechanism and not in the stiff soil element, and that the plastic strain in the failure mechanism are at failure.

Figure 2. Cross-section of the Ringsted-Fehmarn Railway, with a new railway build to the left.



The static conditions are in general hard to fulfill. All equilibrium equations along with the failure condition cannot be fulfilled at every point. Especially close to the surface it is hard to fulfill the static conditions.

Therefore limit equilibrium analysis is used. It uses the Mohr-Coulomb failure criterion to determine the shear strength along the sliding surface. This is a calculation based on the kinematic conditions and gives an upper bound result. A circular failure mechanism is shown in Figure 2 , where a new embankment is placed to the left of a existing embankment.

The limit equilibrium is then the factor of safety(FOS) calculated as the relationship between the mobilized shear force and the shear strength. This relationship has to be greater or equal to 1 before the slope is stable.

In order to calculate the factor of safety the limit equilibrium method from Morgenstern and Price (M. and P., 1962) is used, which takes both moment and force equilibrium into account. For calculation the conventional program Slide 6.0 is used.

4 PROCEDURE

The existing 100 km long railway has been mapped and modelled in 3D and therefore is it possible to extract any giving cross-section. Cross-sections for 33 soft soil areas were exported. Due to diversities in the extensions of each area, different number of cross-sections were exported in each area, with a maximum of 11 cross-sections down to 1. A principle cross-section is shown in Figure 3.

Three boreholes has been placed in the cross-section, see Figure 3. For each borehole layers and soil properties have been determined. The hatched area is the new railway embankment plus replacement of soft soil, built up by sand/gravel. In order to analyze the existing and future stability of the embank, cross-sections showing both the existing and new geometry was imported to the limit equilibrium program SLIDE.

Each soil layer was modelled as a Mohr-Coulomb material. Hereafter the water surface was modelled, the surface can be seen in Figure 4 indicated by a blue line. The water surface in clay is placed beneath the sub-ballast and in sand it is the raised to 1/3 of the embankment height, this goes for an undrained calculation. In the drained calculation is it placed for all material in 1/3 of the embankment height.

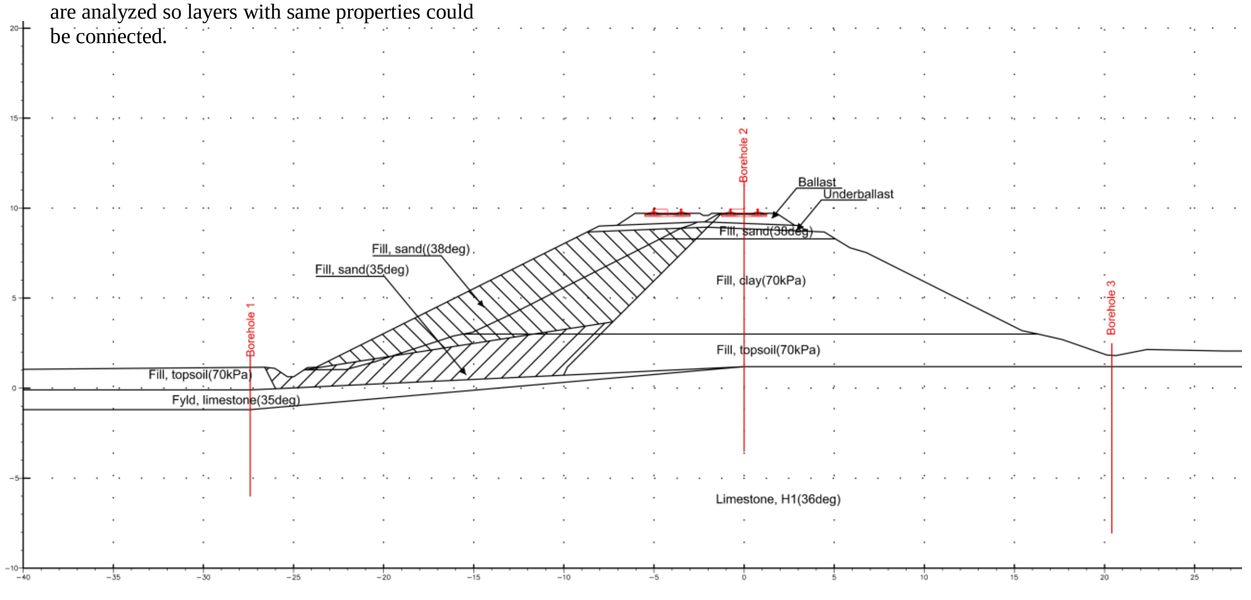


Figure 3. Cross-section of the Ringsted-Fehmarn Railway, with boreholes inserted. The boreholes are analyzed so layers with same properties could be connected.

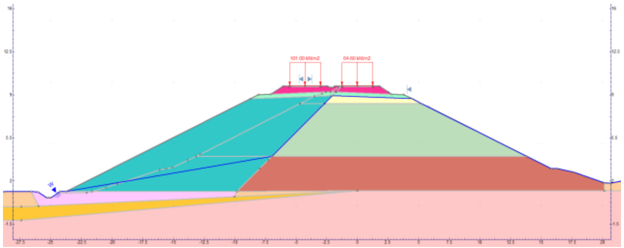


Figure 4. Cross-section of the Ringsted-Fehmarn Railway imported in SLIDE.

For each cross-section various load cases have been calculated. Load case nr. 1 the static load from a train is modelled. Load case nr. 2 the radius of curvature, which decide whether centrifugal forces has to be taken into account along with the magnitude of the centrifugal force. Load case nr. 3 is a future estimation of the load from a train. The load cases can then be modelled as critical load either on the old track or on the new track. In all a total of eight different cases was calculated for each cross-section, six in the undrained calculation and two in the drained calculation (centrifugal forces can be neglected in the drained case when looking at cohesive material in embankments).

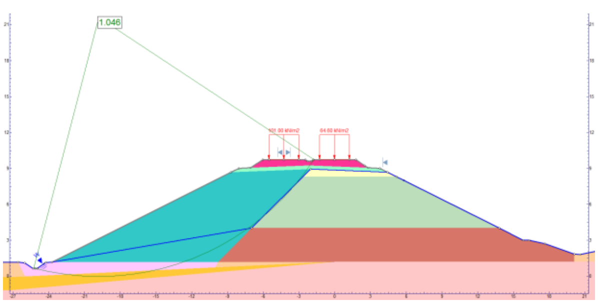


Figure 5. Cross-section of the Ringsted-Fehmarn Railway. Imported to SLIDE and calculated with a circular failure mechanism.

The factor of safety for each load case was then compared and the case with the lowest factor was then imported into the finite element program PLAXIS. Here the soil layers were modelled as Mohr-Coulomb materials again and a phi-c reduction conducted. In Figure 6 a calculated failure mechanism from PLAXIS is illustrated.

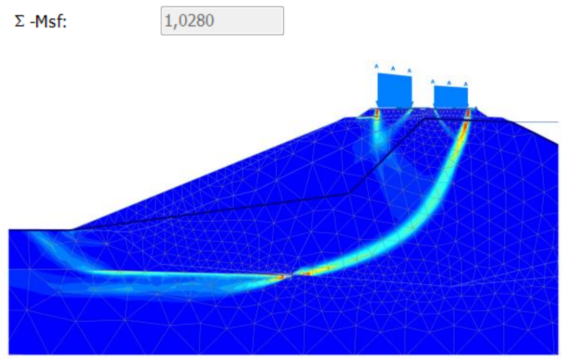


Figure 6. Cross-section of the Ringsted-Fehmarn Railway, imported to PLAXIS. The failure mechanism is a combination of circular and non-circular lines.

5 RESULTS

Failure mechanisms are generally assumed to have a circular form, although some combinations with soft soils under the embankment have a tendency towards slide failure (block). In the Ringsted-Fehmarn Railway project the procedure was to use a circular failure mechanism first and then analyze the calculation with the lowest factor of safety in more detail. This lead to some rather unbelievable failure mechanism. An example is shown in Figure 7, where the railway embankment is placed upon a thin layer of Peat/Gyttja. The soft soil layer extend to both sides of the embankment as well.

Most of the existing soft soil has to be removed in order to make the embankment stable with the future loads/requirements. The new embankment construction is shown in Figure 7.

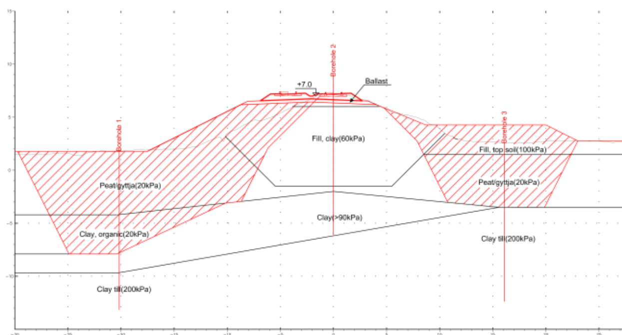


Figure 7. Cross-section of the embankment in soft soil area, where the soil in the red hatched area is replaced with sand/gravel material.

The new embankment is now stable with a factor of safety of approximately 1.3, this is calculated with the use of a circular failure. The embankment is calculated with design values, and thereby a factor of safety by 1.0 is needed. To avoid failure to the right side, a side embankment has to be placed on top of the terrain to make the embankment stable. In order to clarify that the correct failure mechanism is found, the cross-section was calculated by forcing a block failure by making a slip surface beneath the filled sand/gravel material. This failure showed a factor of safety higher than the circular failure, $FOS_{block} = 1.4$.

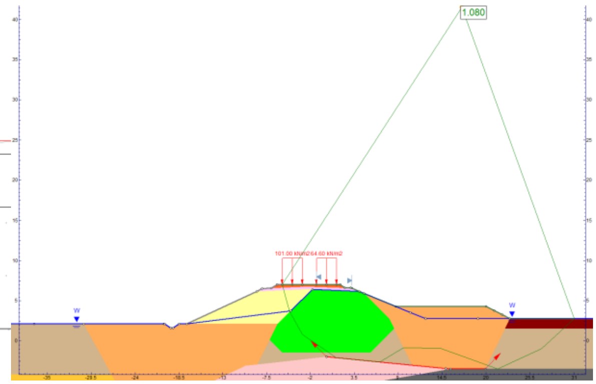
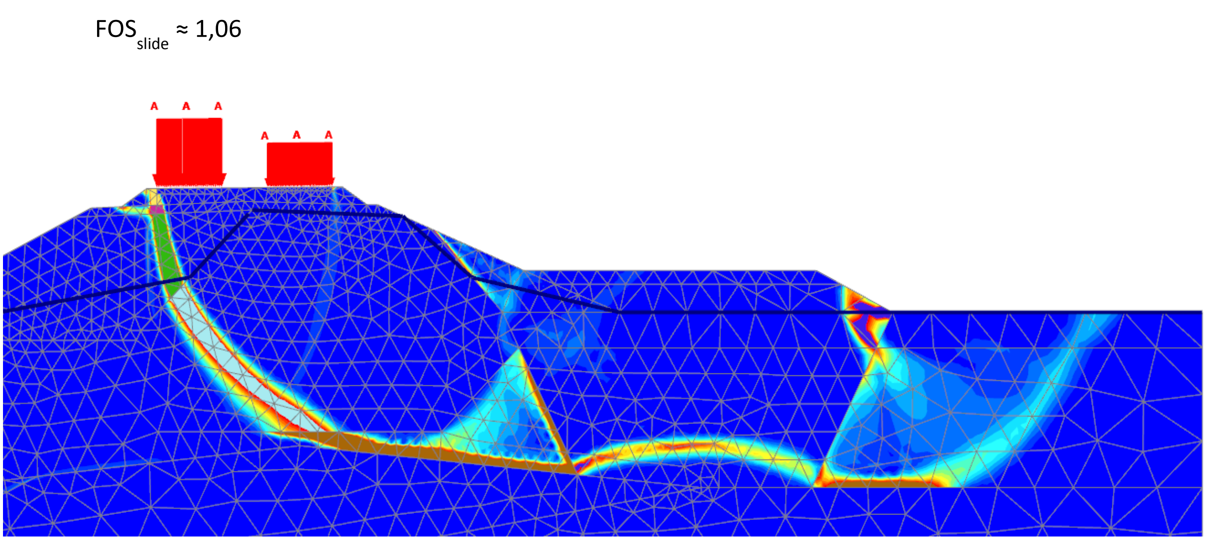


Figure 8. Optimized failure mechanism from SLIDE with a factor of safety of 1.08.

Though the calculation in SLIDE lead to a factor of safety well on the safe side of 1.0 the two failure mechanisms are approximations, and a more correct failure could be found by the use of the finite element method. However SLIDE also provides an optimization feature. This feature will, based on the calculated failure mechanism, optimize the failure mechanism so it can be combined of circular and straight lines. An optimized block failure is shown in Figure 8, where the factor of safety is lowered to a value of 1.08. This value is significantly different from the results calculated for a circular or block failure. The question however is whether the failure mechanism is implausible or even physically correct.

Do we believe in the result from SLIDE? A finite element model was made in PLAXIS to clarify whether the failure mechanism is correct. The result

Figure 9. Strain in a phi-c reduction calculation from PLAXIS. FOS in PLAXIS found to be 1.06.



is shown in Figure 9.

The same failure mechanism is found by PLAXIS. This verifies the failure mechanism found in SLIDE. Perhaps is the question that neither circular or block failures give the "correct" failure. They will always be approximations and a finite element calculation is always required to verify the results specially in soft soil areas. With this said, the designer should always look at the failure mechanism, because the feature optimized failure mechanism can show failures which do not make any sense as illustrated in Figure 10.

REFERENCES

Morgenstern, N.R. & Price, V.E. 1965. The Analysis of the Stability of General Slip Surfaces, *Geotechnique*, vol. 15, no.1, 77–93.

Figure 10. Implausible optimized failure mechanism from SLIDE.