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Small extent, high risk: a landslide at the Kiel Canal and its investigation using FEM

De faible ampleur, mais d'un risqué élevé: un glissement de terrain au Canal de Kiel et son étude par la MEF

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ABSTRACT: The Kiel Canal is the most frequented canal worldwide and links the North Sea to the Baltic Sea. In 2015 an unusual slope movement of a 30 m wide section moving towards the canal was detected leading to a limitation for the traffic. The slope built by both cutting and embankment, consists of glacial sediments showing a typical disordered layering. A ground investigation with boreholes and CPTs showed sand lenses embedded in till as well as high and in parts artesian groundwater levels. An extensive laboratory testing program was carried out, including triaxial and permeability tests. The detection of a zone with softened glacial till was of particular significance. This irregularity can be seen as a potential sliding plane. Long term monitoring of the slope revealed a correlation between the slope movements and the local precipitation. A FEM analysis based on the above mentioned findings was carried out applying the method of phi-c reduction for the safety analysis of the slope. The resulting failure mechanism is in good agreement with the one observed in reality. To secure the moving slope, different solutions are analysed.

RÉSUMÉ: Le Canal de Kiel, reliant la mer du Nord et la mer Baltique, est le canal le plus fréquenté au monde. En 2015, un glissement de talus inhabituel vers le canal d'une section d'environ 30 mètres de long a été détecté. Le talus, construit par tranchées et remblais, est composé de sédiments glaciaux présentant une stratification désordonnée typique. Une investigation du sol au moyen de trous de sondage et d'essais de pénétration au cône a fait apparaître des lentilles de sable enchâssées dans du till, ainsi qu'une nappe phréatique élevée et partiellement artésienne. Un programme approfondi d'essais en laboratoire a été mis en œuvre, comprenant des tests triaxiaux et de perméabilité. La détection d'une zone de till glaciaire amolli a été d'une importance particulière. Cette irrégularité peut être considérée comme une plaine de glissement potentielle. La surveillance à long terme du talus a révélé une corrélation entre les glissements du talus et les précipitations locales. Une analyse MEF, basée sur les conclusions mentionnées en haut, a été réalisée pour déterminer la sécurité du talus, en appliquant la procédure de réduction c-phi. Le mécanisme de rupture qui en résulte correspond bien à celui observé en réalité. Diverses solutions de sécurisation du talus glissant sont étudiées.

Keywords: slope failure; Kiel Canal; FEM; safety analysis; monitoring

1 THE KIEL CANAL

The Kiel Canal links the North Sea to the Baltic Sea and is the most frequented canal worldwide. Over 30,000 ships per year use the artificial waterway between the Elbe estuary and the Kiel Bight. After its inauguration in 1895, along with the increase of the size and number of ships, the profile of the canal changed over time (see Figure 1).

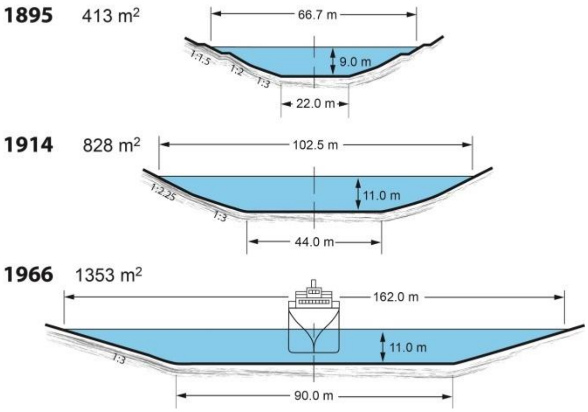

Figure 1. Development of Profiles of the Kiel Canal (WSA Kiel-Holtenau)

However, entering the canal from the east side, the first 20 km still show the profile from the beginning of the 20th century. A useable width of 44 m and narrow curve radiuses form a bottleneck for the modern ships. Currently, the German Federal Waterways and Shipping Administration is planning and executing the improvement of this section of the canal. Besides the enlarging of the cross-section, the adaption of curve radiuses and the flattening of slopes, several structures need to be adapted as well.

The ground profile along the waterway was shaped by glacial periods, resulting in disordered soil layers. Unlike the western part of the Canal, which is dominated by sand, mainly cohesive material (till) can be encountered in the eastern part. The landslide discussed in this paper is located 9 km before the Canal leads at Kiel into the Baltic Sea. The slope is built by both cutting and embankment.

2 FAILURE MODE

In 2015, the first sign of unusual slope movement was noticed. Minor slope failures in the range of up to one meter can be observed regularly in this area. But in this case, the moving slope section had a width of approx. 30 m and started 8.2 m above the water level of the canal. A maintenance road runs alongside the canal, the shift of the formerly straight lane helped visually identify the slope movement. The slope above the road (inclination 1:2.75) as well as the underwater slope is affected by the landslide. At the top end of the landslide, the settlement is clearly visible and along the bank, the armourstones show an offset. However, an investigation of the underwater slope using a sounding vessel showed no clear boundary of the landslide.

Meanwhile, the regional Waterways and Shipping Administration (WSA Kiel-Holtenau) took precautions due to the unsecure slope such that oncoming traffic was prohibited and the speed limit for ships was reduced. The Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau, BAW) was asked to investigate the landslide. During a site visit, icicles in the lower part of the onshore slope indicated water outlet.

From February 2016, the displacement of measuring points within the slope (points P, B1 to B6) and along the maintenance road (points 1 to 11) are being monitored. The position of the slope points is depicted in Figure 2, the points along the road are shown in Figure 4.

Figure 2. Measuring points in the slope

As illustrated in Figure 3, over a 16 month period the slope moved about 16 cm both downwards and in the direction of the canal. The points showing no offset (1, 9, 10, 11, B5, B6) are located outside of the moving slope section.

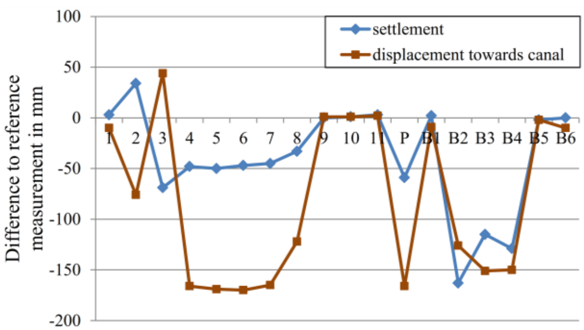

Figure 3. Movement of control points in the period from 02.2016 till 06.2017

At this point, two aspects must be taken into account: major displacement took place before the start of the regular geodetic surveying and the development of these displacements is not evenly distributed over time. An investigation of the seasonal development of the recorded displacements is presented in Chapter 3.4.

Given that the extend of the moving slope section underwater was not clear, further investigations were needed. In the subsequent chapter, the ground investigation and the laboratory tests carried out are described.

3 INVESTIGATION

3.1 Ground investigation

Along the Kiel Canal, data from various cone penetration tests (CPTs) and boreholes is available. One CPT is located on the maintenance road on the centre line of the moving slope section. The existing boreholes are further away, so a ground investigation programme was required and designed.

The slope was deemed unsafe for heavy drilling equipment, therefore the investigation was carried out along both sides of the slope and from a pontoon. 3 rotary core drillings (●) and 5 CPTs (◆) were sunk, the layout is illustrated in Figure 4. The CPTs and boreholes were arranged in pairs. The small numbers underneath the symbols indicate their total depth.

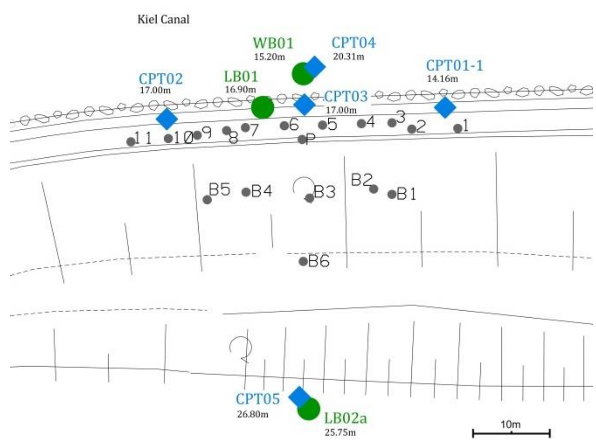

Figure 4. Exploration and control points

In order to receive high quality soil samples, especially of the anticipated glacial till, a triple tube core barrel was used. The soil cores had a diameter of 10 cm and a length of 1 m. In addition, 13 undisturbed samples of 30 cm length were obtained for executing triaxial and oedometer tests. One of which was obtained within the sand layer. At certain depths, obstacles, mainly stones, prohibited the recovery of cored samples.

3.2 Laboratory tests

As main soil types, sand and glacial till was investigated. As can be seen by the grain size distribution (Figure 5), the sand can be subdivided into glacial basin sand (red curves) and glacial melt water sand (blue curves). The till shows a typical widely graded grain size distribution (see Figure 6). In the upper part of the slope, directly underneath the topsoil, a 2.5 m layer of glacial loam was encountered. Its characteristics correspond closely to those of the till. Soil properties such as water content, Atterberg limits and organic content were analysed. A summary of the test results is given in table 1.

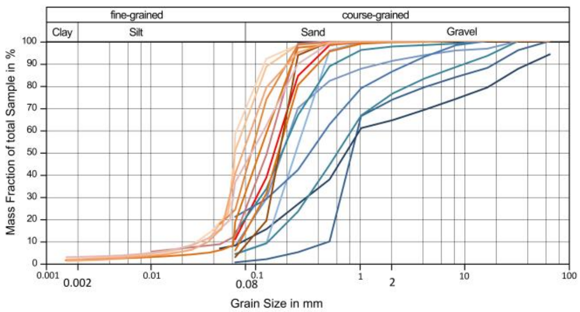

Figure 5. Sieve curves sand

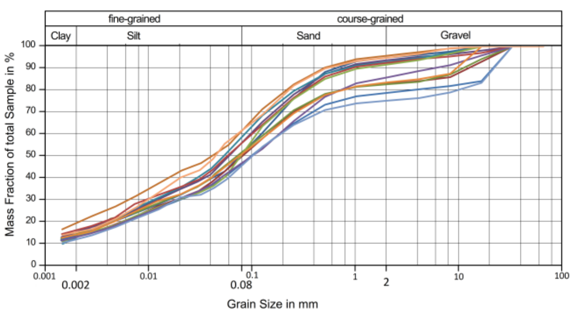

Figure 6. Sieve curves glacial till

Table 1. Soil properties

Property	**Till**	**Sand**
Water content of undisturbed samples in %	11,9	
Ignition loss in %	1.6	1.1
Lime content in %	15	6,7
Permeability in m/s	$2{\cdot}10^{-8}$	$2.3{\cdot}10^{-4}$
Plasticity Index in %	8.1	
Bulk unit weight in kN/m³	21.9	
Submerged unit weight in kN/m³	12.3	

The permeability of the till specified in Table 1 is derived from the average value of two tests. It is assumed that the in-situ permeability will locally be significantly higher due to irregularities like embedded sand bands.

The consistency of the cohesive soil samples was tested, the resulting plasticity index in combination with the liquid limit indicate a sand-clay-mixture.

For additional information regarding the distribution of the undrained shear strength along the soil cores, a pocket penetrometer was used. Most samples could be characterised as stiff. Though, in some ranges of depth, the till was softened and had a low cu-value.

Furthermore, on four undisturbed glacial till samples, consolidated drained triaxial shear tests were carried out. The consolidation stresses varied from 100 kPa to 600 kPa. The resulting graphs for $\sigma_3 = 100$ kPa are shown in the next chapter 4.1, Figures 12 and 13. The analysis of all tests results in an effective friction angle of 37° and an effective cohesion of 4.25 kPa.

To determine the stiffness of the soil, a couple of oedometer tests were carried out. Since the soil is highly preconsolidated, the reloading cycles were evaluated by plotting the stiffness as a function of vertical soil stress as illustrated in Figure 7.

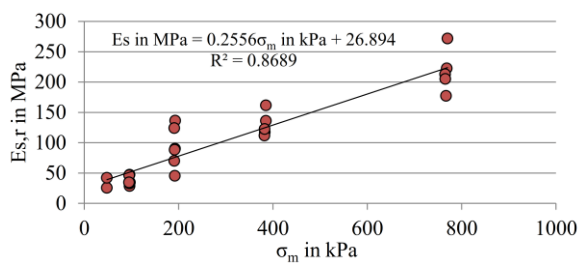

Figure 7. Stiffness modulus of till (reloading cycles)

3.3 *Interpretation of CPTs and drillings*

In general, the CPTs showed results as expected: where till was encountered, the tip pressure shows a slight linear increase with depth, while the absolute values remain small. Tip pressures from 4 MPa up to 33 MPa indicate sand. In combination with the assessment of the boreholes, the CPTs led to the following soil model (Figure 8 and 9):

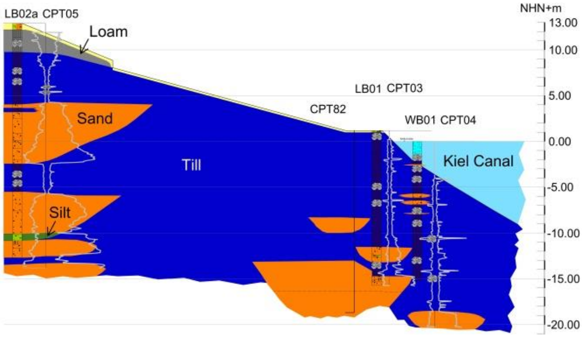

Figure 8. Soil model, cross section

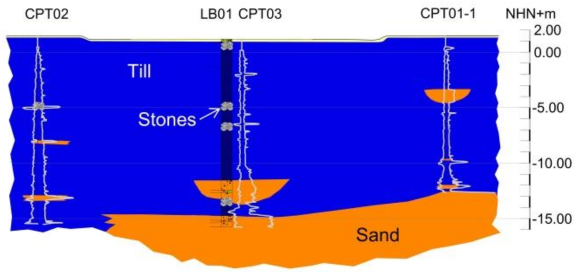

Figure 9. Soil model, longitudinal section

The exact position of the sand lenses is unknown, especially the lateral extent is estimated. It is likely, that further similar sand deposits existing within the slope have not been investigated.

3.4 *Identification of weak zones*

Underneath the maintenance road, softened till was found at a depth of 6.10 m to 8.10 m. Here, a low cu-value of 19 kPa was derived using the pocket penetrometer, compared to cu-values above and underneath this 2 m-zone of over 100 kPa. In the corresponding CPT 03 at a depth of 5.5 m as well as at 6.6 m unusual high tip resistance values are observed. These are indicators for stones, embedded in sand bands. So it is assumed that locally, the permeability is increased.

Due to the CPTs on the maintenance road next to the moving slope section more such permeable zones were detected. CPT01-1 shows a loose sand zone at a depth of 4 m, CPT02 indicate a stone or a thin dense sand band at 5 m depth.

3.5 *Influence of water*

In the drilling protocols, the till is described as earth-moist, moist or wet. Regarding the water level during drilling, the following observations were made: The groundwater level in the sand lenses above the slope (LB02a) was approximately 5 m above the canal water level. Artesian groundwater conditions (maximum 1.35 m above ground level) were investigated in some sand lenses underneath the maintenance road and the underwater embankment. This indicates that the groundwater flow towards the canal is hindered by the low permeability cohesive soil and that an increased groundwater potential can be assumed in the sand deposits.

On the basis of this consideration, it was investigated whether an influence of precipitation on the landslide can be detected. Figure 10 shows the daily precipitation measured at a weather station 8 km far away at Kiel-Holtenau. The data was provided by the German National Meteorological Service (DWD). The displacements and settlements of two control points, on the maintenance road (5) and in the slope (B4), are shown as well.

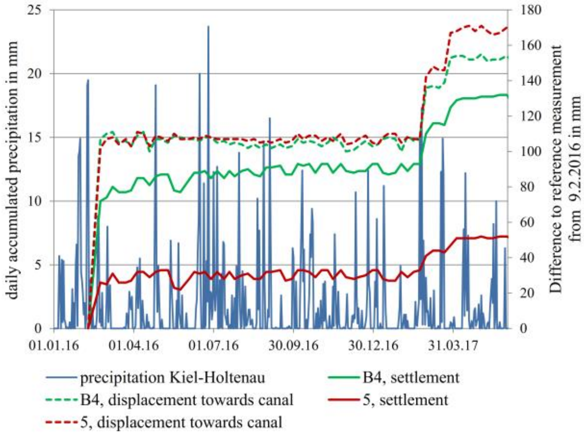

Figure 10. Correlation of displacements (points 5 and B4) with precipitation

It can be seen, that the displacements remain nearly constant and rise significantly after two heavy precipitation events during winter. In the warmer seasons, the rain events with even more precipitation show no influence.

To further investigate the failure mechanism of the slope, a FEM calculation is performed.

4 FEM CALCULATION

4.1 Model setup and calibration

The recalculation of the landslide is carried out using a 2D Plaxis model as shown in Figure 11. The dimensions of the finite element model are chosen according to DGGT (2014), with edge sizes of elements from 0.4 m to 8.0 m. The area which is supposed to contain the sliding surface has a finer discretisation. All in all, 2935 15-node triangular elements form the mesh.

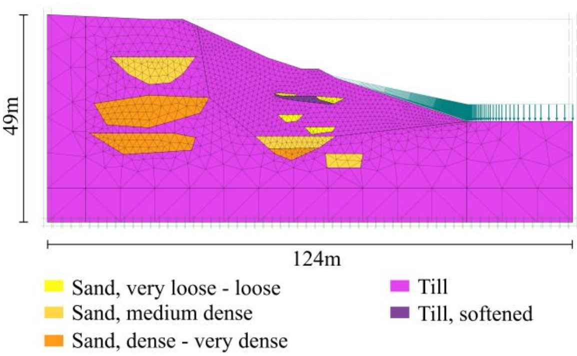

Figure 11. Plaxis model

The soil was modelled using the Hardening soil model. The material parameters used in the calculation are listed in Table 2.

The calibration of the material parameters was carried out on test results of undisturbed samples from a depth near the assumed sliding surface. For the zone with the softened glacial till the parameters are adapted to the weakest soil behaviour. Figure 12 shows the stress-strain behaviour derived from triaxial tests. With σ_3 = 100 kPa the stress level was chosen accordingly. The corresponding volume expansion is shown in Figure 13.

Table 2. Material parameters

Parameter	**Sand, very loose - loose**	**Sand, medium dense**	**Sand, dense – very dense**	**Till**	**Till, softened**
colour					
γ_{unsat} in kN/m³	18	18.5	19	22	22
γ_{sat} in kN/m³	20	20.5	21	22	22
E_{50}^{ref} in MPa	20	60	90	12.5	10
E_{oed}^{ref} in MPa	20	60	90	11.5	9.5
E_{ur}^{ref} in MPa	60	180	270	82.1	70
m	0.5	0.5	0.5	0.8	0.8
e_{init}	0.5	0.5	0.5	0.34	0.34
c_{ref} in kPa	0	0	0	4.25	3
φ in °	30	35	38	37	25
ψ in °	0	5	8	3.4	0
OCR	2	2	2	2	2
k_x in m/d	43.2	17.3	8.6	0.43	0.43
k_y in m/d	43.2	17.3	8.6	0.04	0.04

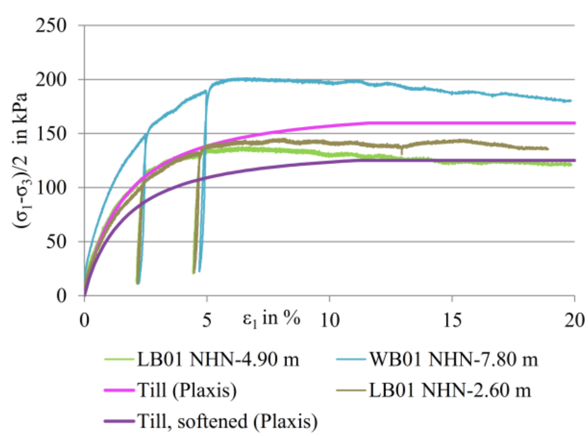

Figure 12. Stress-strain behaviour till

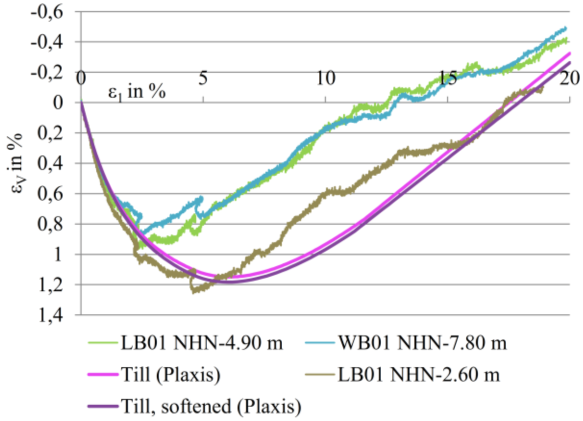

Figure 13. Volumetric expansion till

The governing failure mechanism is a shear failure, therefore the focus was put on the triaxial tests during calibration. Particular attention was paid to the strain range up to 5 %. The magenta curves representing till were generated with the built-in soil-test module in Plaxis. Empirical values were used for sand.

To realistically represent the initial stress state, two main calculation phases are executed before the calculation starts with the actual status. First, a flat ground surface with a high groundwater level is assumed. Secondly, the excavation of the Canal is simulated by creating the Canal profile and lowering the groundwater level to the Canal bottom.

Then, the as-is state is modelled: the groundwater level is adjusted to the depth measured during the soil investigation. A 10 cm thick layer of softened till is placed around the sand lenses. This is done by interface elements.

The model includes a steady state groundwater flow calculation, i.e. the flow pressure on the sliding mass is taken into account. In this simulation phase, the slope remains stable, the maximum deformation is 3.3 cm. The next phase is the safety analysis, also known as „phi-c-reduction“.

4.2 *Safety analysis*

In this case, the stepwise reduction of both the cohesion and the friction angle corresponds to an increasing softening of the till due to water contact. The reduction is applied to an area of till next to send lenses underneath the maintenance road, where signs of softening were found during soil investigation (deep purple in Figure 11). The dimension of the area is chosen such that the position of the moving slope section matches the one observed in reality. The evaluation is made using equation (1):

$$\sum M_{sf} = \frac{c_{\text{original}}}{c_{\text{reduced}}} = \frac{\tan\varphi_{original}}{\tan\varphi_{reduced}} \qquad (1)$$

where M_{sf} (unitless) is the safety factor, c (kPa) the cohesion and φ (°) the friction angle.

After 1000 steps, the failure pattern and the values of M_{sf} are evaluated at two points inside the sliding body. If M_{sf} becomes an approximately constant value, it can be presumed that a failure mechanism has fully developed. As shown in Figure 14, this is the case for $M_{sf} = 8$. The safety factor corresponds to a friction angle of 4.8°. The slope failure is illustrated in Figure 15. The absolute values of the displacements are not relevant.

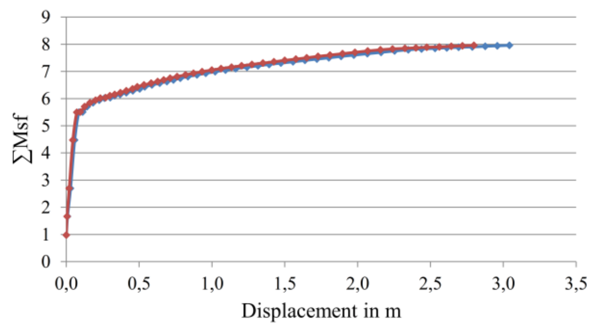

Figure 14. M_{sf} as a function of displacement

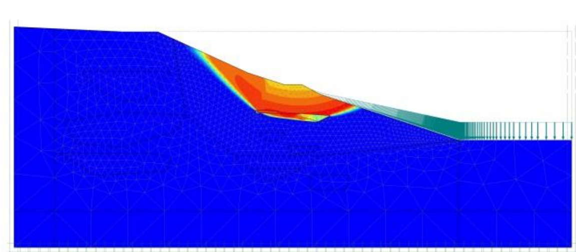

Figure 15. Slope failure

In the model, softening was only simulated for a limited area. In nature, the reduction of shear strength occurs everywhere in the till where coarse-grained material borders the cohesive soil. Since the investigations only provide punctual information about the subsoil, the layout of possible further softening zones is not known. But the subsoil excavation as well as the finite element analysis leads to a failure mechanism in good accordance with the one in reality.

It can be assumed that the embankment slips before the shear strength is reduced locally to $\varphi = 4.8°$ as a result of further unexplored softening zones.

5 RECONSTRUCTION

There are two basic options for the reconstruction: reducing the load on the slope or installing structural retaining elements. In view of the forthcoming expansion of the Kiel Canal, the first option was chosen. First of all, using only light equipment, a longitudinal drainage directly above the moving slope section was installed. Then, the upper soil was excavated from the side in stages down to one meter below the maintenance road. The material was replaced by gravelly sand. At the toe of the slope, alongside the road, a new drainage was installed and connected to the existing one. To reconstruct the road, the soil there was excavated, replaced by sand and a geogrid in combination with recycled concrete were used.

Figure 16. Slope with collecting pipe in the centre (WSA Kiel-Holtenau)

Figure 17. Refurbished maintenance road (WSA Kiel-Holtenau)

6 REFERENCES

DGGT (ed.) 2014. Empfehlungen des Arbeitskreises Numerik in der Geotechnik - EANG. Berlin: Ernst & Sohn.

DWD Climate Data Center. ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/climate/daily/kl/recent/ Recent daily station observations for Station Nr. 02564, Kiel, Germany. Accessed: 13/11/2017.

WSA Kiel-Holtenau. http://www.wsa-kiel.wsv.de/Nord-Ostsee-Kanal/. Accessed: 01/10/2018