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Revetment damage as a result of geotextile colmation by flocculated ochreous products and possible repair methods

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ABSTRACT: During the last years some severe local damage to bank revetments incorporating a geotextile have occurred, for which the reason has been a severe reduction of the hydraulic performance of the nonwoven filter layer as a result of accumulation and incorporation of ochreous products flocculated from the groundwater. This report describes the conditions of a specific application case leading to this type of failure and gives some criteria for repair methods. Two filter variants had been designed for this purpose, based on a very open nonwoven-woven composite and on a coarse mineral filter. Due to a heavy seepage-water exit the geotextile was impossible to be installed. Thus only a pilot repair project could be carried out by using the mineral filter. A report on its behaviour is given based on an observation time of about 9 years.

1 HISTORY

In 1982 a bank revetment of the German tidal river Weser, consisting of ferro-concrete slabs on a bitumen bound sand-filter layer, built in 1967/69, was destroyed completely on its whole length of more than 3 km by a tidal wave (Fig. 1).

The main reasons for failure had been the slabs' low unit weight per area in connection with a low system permeability and the breakdown of the sand filter which had lost its bitumen binding and subsequently could be eroded through the small joints existing between the slabs.

In 1983/84 the slab revetment was restored completely in a slightly modified manner, using now a geotextile instead of the bitumen-bound sand filter, being installed directly upon the present slightly compacted sand. At the same time the permeability and drainage capacity of the cover-layer system were enhanced considerably. The toe of the revetment was protected the same as before by a sheet-pile wall of 7 m length, tied in the ground with a length of about 6 m.

In spring 1992 first local damage to the restored revetment appeared at the toe of slope.

Figure 1. Ferro-concrete slab revetment damaged by tidal wave in 1982

1.1 *Modified construction of the revetment restored in 1983/84*

Repairs to the totally destroyed revetment (see 1) were performed by re-using – for economic reasons – as far as possible the existing ferro-concrete slabs with dimensions of 2.60 m x 1.20 m x 0.22 m and a weight of 1,72 t = 0.55 t/m^2. With regard to slope inclination of 1 : 3, the stability of the slabs to uplift was sufficient only for water pressures caused by water level differences of $\Delta h < 0.3$ m. Possible higher pressures due to tidal fluctuation of the external water levels of up to 4 m or wave heights of up to H = 1.5 m were now to be excluded by a drainage system of stone chippings 8/32 mm, layer thickness 0,10 m, which had been installed between a nonwoven filter layer of about 500 g/m^2, O_{90} = 120 µm, thickness 5 mm, and the now modified slab cover layer. The permeability of the cover layer had been significantly improved by leaving out every third slab.

The remaining uncovered chipping areas of the drainage layer were closed by mortar-grouted armourstone, maximum stone length 10-30 cm, to act as drainage openings (Fig. 2). The mortar-grouting mass was confined to max. 40 l/m^2 to leave armourstone drainage openings of sufficient permeability

Figure 2. Ferro-concrete slabs with drainage openings (mortar grouted armourstone) after revetment restoration 1983/84

Table: Revetment weight per unit area upon the geotextile filter layer in the dry and under water

	drainage-opening area				**ferro-concrete-slab area**			
	t (m)	ρ kg/dm³	w_d kg/m²	w_w kg/m²	t (m)	ρ kg/dm³	w_d kg/m²	w_w kg/m²
chipping-drainage layer (n = 0,40)	0,10	2,65	159	99	0,10	2,65	159	99
armour stone (n = 0,40)	0,25	2,5	375	225	--	--	--	--
grouting mortar (ca. 40 l/m²)		2,2	88	48	--	--	--	--
ferro-concrete slabs	--	--	--	--	0,22	2,5	550	330
revetment total weight per unit area	toe bench row (horizontal)		622	372	toe bench row (horizontal)		709	429
	slope 1 : 3		590	353	slope 1 : 3		673	407

where:
t = layer thickness
ρ = dry density
w_d = weight per unit area in the dry
w_w = weight per unit area under water (wet)
n = porosity of bulk material

1.2 *Appearance of first damage in 1992*

In March 1992 at some few drainage openings (grouted armourstone) in the toe section of the slope were broken up by the pressure of a large geotextile bubble filled with water and thus acting like a hydraulic jack (Fig. 3).

At the beginning, this damage concerned only the toe bench and the adjacent first slab row of the slope, i.e. the zone of the highest tidally influenced gradients. Later on a few drainage openings situated a little higher were affected too. It was apparent that in all cases the geotextile filter layer had become nearly impermeable and geotextile and seepage water not flowing off were discoloured rusty brown.

Furthermore the grouted armourstone cover of the adjacent drainage openings at the same level, one to the right and one to the left, also already showed some signs of uplifting and slight mortar damage, while the contiguous ferro-concrete slabs were lying without any visible change.

The damage appeared concentrated at two revetment sections near km 29.7 and km 32.2, but had an extent of less than 50 m.

Figure 3. Geotextile/water bubble in a damaged drainage opening

2 INVESTIGATION PROGRAMME OF THE BAW

2.1 *Sampling from the geotextile and from the groundwater*

In one of the totally damaged drainage openings with significant signs of geotextile colmation, the overlapping geotextile was exposed. Both the geotextile and the overlying drainage chippings were discoloured rusty brown (Fig. 4). When lifting the geotextile, a rusty brown slime became visible, which had accumulated on the underside of the fabric. The surrounding seepage water emerging from the subgrade was discoloured rusty brown as well.

For comparison purposes an intact non-ochreous drainage opening two rows above was opened (Fig. 5). Neither the drainage chippings nor the geotextile showed any marks of slime accumulation or discoloration.

Figure 4. Ochreous drainage opening prepared for sampling

Figure 5. Non-ochreous drainage opening prepared for sampling

Samples were taken from the nonwoven and the seepage water from both drainage openings. Afterwards the holes left by sampling were closed again with an appropriate piece of a brand-new geotextile, the drainage chippings were re-installed and the drainage opening was closed with a special provisional concrete slab prepared for this purpose, allowing drainage of seepage water through the surrounding gap of 2 – 3 cm width. To enhance stability against uplift, the slab was wedged to the adjacent ferro-concrete slabs.

Two month later these 2 drainage openings were inspected. While the toe situated geotextile piece had become nearly impermeable and highly discoloured rusty brown, the piece of geotextile two rows above did not show any particular signs.

2.2 *Subsoil exploration*

In each of the 2 damage sections, about 2.5 km from one another, 2 ram borings with open-sided tube (∅ 40 mm) were carried out to a depth of 9 m below ground surface and in each case at a distance of 4 m and about 35 m relative to the top of slope.

2.3 *Groundwater/ seepage water*

The 4 drill holes of subsoil exploration (see 2.2) were converted to piezometer tubes with a filter pipe at a depth of 7 – 8 m below ground surface. For control purposes an additional piezometer tube was installed to the side of each boring at a distance of 1 m, with a filter pipe at a depth of 3 – 4 m, because two independent aquifers could be assumed according to drill core inspection. Fluctuations in the groundwater were to be measured and its chemical properties determined.

3 TEST RESULTS AND DAMAGE ANALYSIS

3.1 *Subsoil*

The subsoil consists mainly of medium to coarse sands overlying the alluvial clay being present down from 8 m below ground surface. The mean permeability of sands was assessed on the basis of the grading curve to be $k_f \approx 1 \cdot 10^{-3}$ m/s.

According to results of the 4 borings (see 2.3) the overlying sands could be assumed to be divided into 2 hydraulically independent aquifers by an extended small clay interlayer present about 4 - 5 m below ground surface. At the 2 drill points situated close to the slope, a thin layer of coarse sand of the lower aquifer was discoloured rusty brown (ochre).

3.2 *Geotextile filter layer*

The sample of geotextile, a needle-punched nonwoven, taken from the totally damaged drainage opening (see 2.1) with the dimensions 0.7 x 0.95 m was been examined in the laboratory of the BAW according to test procedures in force (RPG 1984) with regard to the following properties:

- permeability without load (falling-head method equal to EN ISO 11058)
- tensile strength
- determination of thickness at specified pressures
- determination of mass per unit area, including incorporated soil particles and ochre slime

Permeability was tested in the isolated state using 6 specimens. Due to incorporation of about 1080 g of slime and finest soil particles flow velocity had been reduced from originally

v = 0.2 m/s to
v = 0.001 m/s

i.e. a reduction of 99.5 %. In fact, the permeability reduction of the geotextile had surely been higher, because part of the slime accumulated on the reverse has been washed away when cutting out the sample. In contrast, the permeability of the nonwoven sample taken from the intact drainage opening was unchanged.

The tensile strength of originally 13.9 kN/m had enhanced in both cases up to about 25 kN/m due to incorporated particles. The thickness of filter layer was determined nearly unchanged at 5.2 mm.

3.3 *Groundwater/Seepage water*

3.3.1 *Aquifer*

When measuring the groundwater levels of the 8 piezometer tubes (see 2.3), it was noticed that their fluctuation during a tide was only slight, probably affected by the sheeting wall at the slope toe (see 1).

The difference of water levels between the deep and the flat adjacent groundwater monitoring points was 0.2 m up to 0.8 m, confirming that two independent aquifers exist.

3.3.2 *Analysis of the groundwater/seepage water*

Analysis of groundwater samples taken from the lower aquifer (deep piezometer tubes, see 2.3) yielded the following results:

- Fe_2O_3-content of solid matter was 7times higher than from the shallower adjacent piezometer tubes.
- both the pH-value of 7 ± 0.5 as well as the redox potential of about 185 ± 15 mV basically permit the oxidation of $Fe^{++} \rightarrow Fe^{+++} + e'$.

The visible result of this groundwater analysis were the precipitation products of insoluble $Fe(OH)_3$ from seepage water accumulated as flocks to a rusty brown slime at the reverse of the geotextile. This product was the so-called “iron ochre”.

3.3.3 *Iron-ochre/manganese-ochre formation*

As is well known “iron-/manganese-ochre formation” is a phenomenon which appears if groundwater/seepage water contains bivalent iron or manganese compounds and oxygen is present in sufficient quantity. The following modes of origin are possible:

- chemical process: oxidation of bivalent to trivalent iron/manganese due to presence of oxygen dissolved in the groundwater or dissolved by diffusion of oxygen at the air-water interface or in the case of sudden air contact (e.g. seepage water exit)
- hydraulic-chemical process: sudden change of flow velocity of groundwater/seepage water from laminar to a turbulent state (critical Reynolds number related to grain diameter $R_e > 10$) accelerates oxidation and thus flocculation of insoluble iron or manganese compounds.
- biological process: metabolic activity of iron or manganese microbes leads to excretion of insoluble iron/manganese compounds. This type of ochre formation is widespread. Iron or manganese microbes are found in many groundwaters.

In the present case probably all these processes coincided and caused ochre formation. With regard to the clear result of groundwater analysis more extensive investigations were not carried out.

3.4 *Analysis and extent of damages*

Damage to drainage openings was caused only by the extremely high reduction of nonwoven permeability of 99,5 % (see 3.2) due to blocking and clogging (colmation) of flocculated iron-ochre products from seepage water, accumulating on the underside of the geotextile and in its structure to a rusty brown slime. Because of this, the residual permeability of the geotextile has apparently become too low with regard to necessary drainage of seepage water during the ebb-tide phase, which is important for stability reasons (see 1.1).

According to results of groundwater analysis and of subsoil exploration only water of the lower aquifer was susceptible to ochre formation. This explains why damaged drainage openings concerned the lower section of the revetment only. Naturally the weakest areas of the revetment, the drainage openings, must fail by uplifting first (see table).

To date damages due to permeability reduction of the geotextile filter layer concerned drainage openings only.

4 POSSIBLE MEASURES AND FINAL SOLUTION

4.1 *General considerations*

Some measures known to retard ochre formation are the addition of organic filter matter rich in tannin, e.g. oak chips, rye straw (Karlen 1977). But the retarding effect ceases after 2 – 5 years. Thus ochre formation can be avoided essentially only if air access or turbulent flow of seepage water are excluded.

In the present damage case the extent of groundwater containing bivalent iron (related to bank line) could be assumed to be confined, because of revetment sections without any signs of damage or discoloration. Thus it was decided to look for measures appropriate for local revetment repair.

Water pressure causing the damage of the drainage openings has been unknown and could not be assessed realistically in this case because the tidally influenced bank drainage is a very complex and unsteady hydraulic process. In addition, enhancing of revetment weight which would be necessary for the worst case, was excluded for economic reasons.

As it was not possible to prevent air access and turbulent flow, a technical solution could only be reached by using a large-pore filter with openings sufficient to allow passage of flocculated iron-ochre products. Filtration opening sizes necessary for this purpose were assessed to be in the range of 1.0 – 1.5 mm. The basis of deliberations were similar experiences with drainage systems and the known filter rules (MAG 1993.

It was clear that there was only a very small tolerance to move, because the sand present had to be restrained. Due to this uncertainty of success it was decided to start a pilot project containing a large-pore filter solution for a modified drainage opening, i.e. with greater risk of subgrade erosion than of colmation.

4.2 *Pilot project for a large-pore filter structure*

A nonwoven and a mineral grain filter of large pore size were to be applied as a pilot project to the totally damaged drainage openings. After cutting the existing nonwoven out of the area of the drainage opening the following variants were installed:

variant 1
- excavation of about 0.20 m of subgrade
- installation of chippings 8/32 mm for the required drainage and filtration function, layer thickness 0.30 m
- closure of the drainage opening with a specially fabricated permeable ferro-concrete slab, which could be relifted for filter-control purposes (Fig. 6). Depending on slab's opening size a geogrid can be placed upon the chippings for its erosion control if necessary.

variant 2
- installation of a nonwoven filter, $O_{90} = 1 - 1.5$ mm
- installation of chipping material 8/32 mm for the required drainage function, layer thickness 0.10 m
- closure of the drainage opening with a special permeable ferro-concrete slab as described in variant 1.

In variant 1, the ratio of mean grain diameter D_{50} of chippings to mean diameter d_{50} of present sand was $A_{50} = 50$, i.e. much greater than the admissible $A_{50} \leq 8$ according to filter rules (MAG 1993).

In variant 2 nonwovens with opening sizes $O_{90} \geq 0.25$ mm could not be obtained on the market. A special design was needed in this case. But production proved to be impossible. The largest opening size of a specially fabricated nonwoven-woven composite was only 0.5 mm (thickness 10 mm, weight 500 g/m^2) and was accepted with some reserve. When preparing the subgrade for variant 2, it became apparent that a plane subgrade could not be achieved due to heavy seepage water exit. Stabilization of the subgrade, inclined 1 : 3, was only reached after a coarse grain material had first been installed. Due to this, variant 2 was abandoned. Thus two drainage openings were restored in autumn 1992 according to variant 1 as a pilot project.

Figure 6. Closure of the pilot drainage opening with a specially fabricated permeable ferro-concrete slab

4.3 *Appraisal of the pilot project after 6 months*

A first inspection to assess the efficiency of the pilot filter project was carried out six month later in spring 1993. The following results were documented:
- the chippings were completely discoloured to a rusty brown.
- Seepage-water flow from the chipping layer seemed to be unchanged compared with installation state.
- the sand present in the subgrade did not significantly migrate into the chipping voids, if a very small mixed zone of the interface because of inevitable impacts caused by chippings installation was disregarded.
- flocculated ochreous products were found as a liquid slime in the inferior part of the chipping layer.

A second inspection to assess the efficiency of the pilot filter project was carried out after 6 years in autumn 1998. Drainage efficiency was unchanged. The surrounding ferro-concrete slabs lay without any significant heave or tilting. The further observations were the same as in 1993.

This appraisal was valid for other damaged drainage openings too which had been restored in the meantime according to the pilot project construction of variant 1.

5 CONCLUSIONS AND OUTLOOK

With respect to bank revetments no technical means exist to avoid flocculation of ochreous products if seepage water exits from the bank in connection with fluctuating water levels. The only possible technical solutions to stabilize the revetment are:
- increase of revetment unit weight per area taking account of possible maximum pressure of seepage water or
- using a large-pore filter structure allowing the passage of flocculated ochreous products

After a service time of now about 9 years the chosen large-pore grain filter seems to work in the desired sense. Observation will be continued.

6 REFERENCES

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