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Prevention of Internal Erosion by Cut-Off Walls in River Embankments on the Upper Rhine

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Prevention of Internal Erosion by Cut-Off Walls in River Embankments on the Upper Rhine

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Between 1928 and 1971, a total of 10 barrages including river embankments with a height of up to approx. 10 m were erected on the Upper Rhine between Basel and Karlsruhe. The river embankments were constructed using local building materials: the shells consists of sandy gravel, and the cores of a silty material (alluvial loam). The in-situ sandy gravels in the Upper Rhine region show a pronounced grain-size gap for coarse-grained sand and fine gravel which is why they are not resistant to suffosion. This lack of suffosion resistance affects both the ground below the river embankments and their shells. Furthermore, the filter stability of the silty soil material used in the cores is not sufficient to filter the sandy gravels of the ground below the embankments and/or their shells. Immediately after flooding of the impoundments, the exit of seepage water was observed on the downstream embankment slopes. Due to the embankment material's lack of suffosion resistance and filter stability this caused a loss of soil in certain areas. To improve the situation, and working from the crest downwards, cut-off walls (diaphragm walls, injection walls and sheet pile walls) were subsequently driven into the river embankments over long stretches. These increase the length of the seepage path, thus reducing the hydraulic gradients in the embankment and the ground. The resulting reduction of the seepage forces reduces the risk of internal erosion. The efficiency of the cut-off walls embedded in the embankments subject to seepage depends on the overall ground situation and the groundwater flow characteristics on the one hand, and on the walls' resistance to geohydraulic load on the other hand.

Keywords: Internal erosion, suffosion, river embankment, rehabilitation, cut-off wall

Prévention de l'érosion interne par des murs parafoilles dans les digues du Rhin supérieur

Entre 1928 et 1971, dix barrages ont été construits dans le Rhin supérieur entre Bâle et Karlsruhe avec des digues latérales d'hauteurs allant jusqu'à 10 mètres environ. Ces digues ont été réalisées avec des matériaux du sol local : les flancs avec des graviers sableux et le cœur des digues avec des matériaux silteux (limon alluvial). Dans le Rhin supérieur, les graviers sableux en place ont une granulométrie discontinue marquée en ce qui concerne les sables grossiers et les graviers fins et ne

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résistent pas à la suffosion. Ce manque de résistance à la suffosion affecte aussi bien le sous-sol des digues que leurs flancs. De plus, les graviers sableux du sous-sol et/ou des flancs des digues ne garantissent pas une stabilité du filtre suffisante par rapport au sol silteux au coeur des digues. Immédiatement après la mise en eau, des sorties d'eau ont été observées sur les pentes aval des digues. Etant donné le manque de résistance à la suffosion et de stabilité de filtre du matériau des digues, ceci a entraîné des pertes de sol dans certaines zones. Pour améliorer la situation, des murs parafoilles (parois moulées, parois d'injection et murs de palplanches) ont donc été introduits dans les digues, a posteriori et depuis les crêtes, sur de larges sections. Ceux-ci prolongent le trajet d'infiltration et permettent une réduction des gradients hydrauliques dans la digue et dans le sous-sol. L'affaiblissement des forces d'écoulement qui en résulte contribue, de plus, à réduire les risques de transport de matériaux. L'efficacité des murs parafoilles placés dans les digues soumises à infiltration dépend, d'un côté, des conditions du sous-sol et de celles de l'écoulement des eaux souterraines, et de l'autre, de la stabilité des murs par rapport aux contraintes géohydrauliques.

Mots-clefs : Erosion interne, suffosion, digue, réhabilitation, mur parafoille

1 History of the development of the upper rhine

Up until the early 19th century the stretch of the river Rhine between Basel and Mannheim consisted of numerous shallow branches that permanently changed. The surrounding low-lying land had a width of 2-3 km. Between 1817 and 1880, the first river training measures were implemented according to the plans of Johan Gotthilf Tulla, engineer and lieutenant colonel in the duchy of Baden, to protect existing settlement areas from flooding and to develop a larger area for land use. In the period from 1907 to 1956, groins, guide walls and rock sills were built to create a stable navigation channel with the same minimum depth everywhere. These river training measures, which were named after the general superintendent Honsell, created an uninterrupted stretch of the river which could be navigated by large ships.

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When at the end of the 19th century electricity generation and especially transmission over long distances became possible, the utilization of the Upper Rhine's hydropower potential became an issue. The first power station was the Rheinfelden plant which was built upstream of Basel in 1898. Under the Treaty of Versailles signed in 1919 after World War I, France was granted the right to use the Upper Rhine between Basel and Lauterburg to generate hydroelectricity. Figure 1 provides an overview of the development of the Rhine between Basel and Karlsruhe which will be briefly explained in the following.

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In the years between 1928 and 1977, 10 barrages were built in three development sections. In a first stage, the Grand Canal d'Alsace (a waterway along the river Rhine) between the towns of Märkt and Breisach was built. It includes barrages in Kembs, Ottmarsheim, Fessenheim and Vogelgruen on the French side west of the Rhine. The Grand Canal d'Alsace is used for power generation at its four barrages and as a navigation channel. The water level in the lateral canal is significantly higher than that of the Old Rhine to the east. A minimum discharge is maintained for the Rhine ; otherwise the river is only used for discharging floods that exceed the maximum discharge specified for the lateral canal. This has resulted in considerable groundwater abstraction due to the lower water level of the Rhine, the receiving stream of the groundwater, and this in turn has lead to numerous counter-measures.

From 1959 to 1970 the Upper Rhine was further developed and four short lateral canals, the Rheinschlingen (loops), were built between Breisach and Strasbourg. These lateral canals, which are all on the western side of the Rhine, are equipped with barrages at Marckolsheim, Rhinau, Gerstheim and Strasbourg and also serve for navigation. As the lateral canals are rather short, their impact on the groundwater is clearly reduced in comparison to the influence of the Grand Canal d'Alsace. The river embankments on the Rheinschlingen canals are located both, west and east between the lateral canal and the Rhine, on French territory. In the reaches between the lateral canals, the Rhine is used for navigation. The impoundments extend to these reaches of the Rhine, which is why river embankments were built also in these reaches, both on the French and the German sides of the Rhine.

Joint Franco-German studies confirmed the necessity of erecting at least two additional barrages downstream of Strasbourg. To prevent erosion of the bottom of the Rhine downstream of the last barrage, the structure was built in an area with a low bottom gradient where the river shows less erosion tendency. In 1977, the Gamsheim and Iffezheim barrages were completed ; they are located in the river. These impoundments do not extend beyond the Rhine and include river embankments with a height of up to 10 m on the French and the German sides [Hager, 1982].

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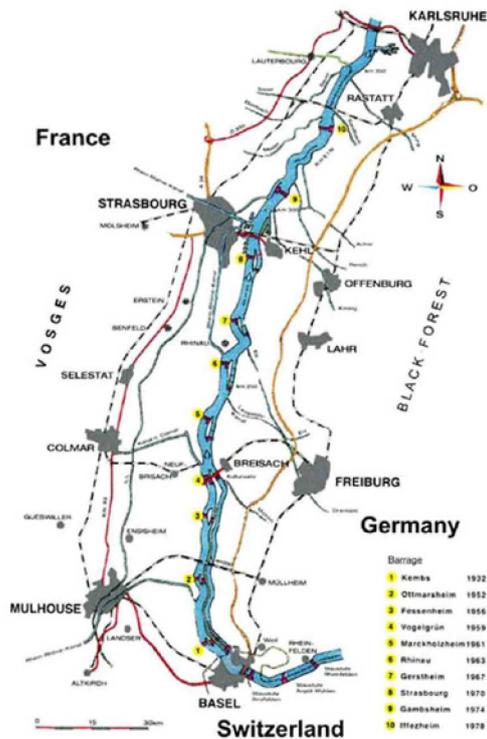


Figure 1: Development of the Upper Rhine between Basel and Karlsruhe

2 Structure of the river embankments

For the river embankments on the Upper Rhine, in-place soil has been used as construction material, i.e. the shells of the embankments consist of sandy gravel, and the cores of silty - partly also gravelly - sand (alluvial loam). The shape of the embankment core varies, depending on the supply of in-place soil material. The alluvial loam soil layer was cleared from some areas before the embankments were built. At the Gamsheim and Iffezheim impoundments, a cut-off wall was driven into the ground before raising the embankments and connected with the embankment core. Downstream of the river embankments there is a berm and a toe ditch in almost every area.

An impervious lining has been provided for each of the beds of the lateral canals (Grand Canal d'Alsace, Rheinschlingen). However, no artificial lining was planned for the Rhine in the impoundment areas between the Rheinschlingen and in the Iffezheim and Gamsheim impoundments. Here, a hydraulic barrier has been created due to clogging of the bottom of the water body. The river embankments in these impoundment areas have no artificial lining. This means that the embankments are subject to seeping, which is limited by the low-conductivity embankment core, as well as to an underflow in relation to the development of the clogged layer. Figure 2 provides an example of the composition of the embankments at the German side of the river at the Iffezheim impoundment.

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The in-situ sandy gravels in the Upper Rhine region show a pronounced grain size gap for coarse-grained sand and fine gravel. On the left-hand side, Figure 3 illustrates the size range of the sand-gravel mix as determined by core samples taken from the ground of the German-side embankment of the Iffezheim impoundment.

As the shell around the embankment core consists of in-place gravels, the size range shown corresponds more or less to that of the shell. As described above, the embankments along the Upper Rhine have a core which is made of compacted fine soil. It consists of the soils of the in-place alluvial loam layer and its conductivity is clearly lower than that of the shell and the ground. On the right-hand side, Figure 3 illustrates

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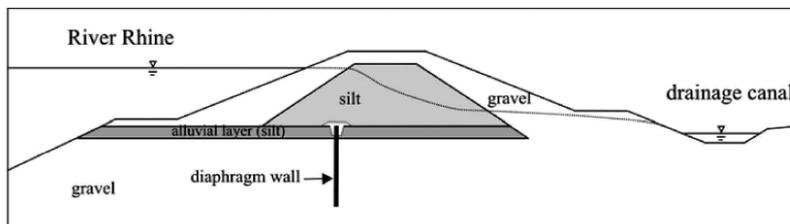


Figure 2: Cross section of the river embankment in the Iffezheim impoundment area

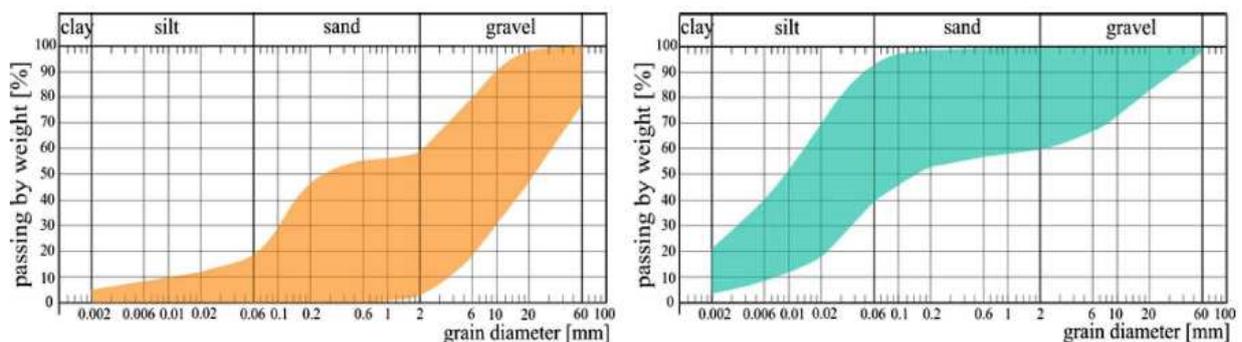


Figure 3: Size ranges of the ground (sandy gravels, left) and of the core (alluvial loam, right)

the size range of the embankment core material, again for the Iffezheim embankment situated on the German side.

3 Internal erosion caused by groundwater flow

The grain size distribution in the layers of the embankment and ground subject to seepage as well as the maximum flow velocities and the direction of flow have a significant impact on the development of internal erosion. It is necessary, therefore, to examine whether in the soils of these embankment and ground layers internal erosion can generally occur due to the soil structure, and, taking account of the direction of flow, whether the maximum flow velocities can cause soil displacements.

Owing to the soils found in the Upper Rhine region, in principle two types of material transport are possible, provided that certain geohydraulic boundary conditions are met: first, contact erosion can occur on the embankment core's contact area with the ground and the shell and second, suffosion can occur in the ground and/or the shell.

3.1 Contact erosion

Contact erosion means the migration and transport of almost all particles of a fine-grained soil occurring at the interface between the fined grained soil layer and a coarsegrained layer. This is only possible if the soil particles of the fined-grained material can be transported into the pore space of the soil particles of the adjacent coarse-grained soil material (geometric criterion). In addition, the flow velocity must be sufficiently high for a material transport to be caused by the seepage forces (hydraulic criterion). If the fine soil particles are cohesive, i.e. if they form aggregates and do not exist as individual grains, the cohesion of the fine-grained material to be transported has a significant impact on the critical flow velocity required for the soil movement.

For the interface between the material of the embankment core (cohesive, fine-grained mixed soil) on the one hand and the material of the shell and the ground on the other hand (sandy gravels and/or gravelly sand) which is examined in the present case, it is not possible to generally exclude that contact erosion due to the grain size distribution (geometric criterion) may cause material transport. Hence, it is necessary to analyse the degree of cohesion of the core's soil material and whether the maximum flow velocities are high enough to cause a material transport.

3.2 Suffosion

Suffosion refers to the transport of soil particles of the fine grain size fractions of a soil material in the pore space of the granular skeleton formed by the coarse fractions. Suffosion, too, only occurs if the transport of the finer soil particles within the granular skeleton of coarse fractions is possible due to the size of the pore channels (geometric criterion). Again, a sufficient flow velocity is the additional precondition for soil material transport to be caused by the seepage forces (hydraulic criterion).

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The coarse sands and fine gravels found in the ground in the Upper Rhine region as well as in the shells of the river embankments which consist of a similar material are characterized by grain-size gaps. The ground and the shells are therefore not generally resistant to suffosion. Hence, if the necessary geohydraulic boundary conditions that trigger a material transport are met, the migration of a certain percentage of fine fractions (< coarse-grained sand) within the supporting granular skeleton of the coarse fractions (> fine gravel) is possible.

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4 Damage due to internal erosion

Immediately after flooding of the impoundments, seepage water was observed on the downstream embankment slopes. Due to the embankment material's lack of suffosion resistance and filter stability this caused a loss of soil in certain areas. In particular, fine soil particles - in some places considerable quantities - were carried into the ditches at the toe of the downstream slope (Figure 4, left). As in many cases a water body is discharged into the toe ditches it was often not possible to determine the loss of soil occurring in the embankment body with accuracy, because of the flow velocity in the toe ditch.

5 Embankment rehabilitation with cut-off walls

To reduce the risk of internal erosion, especially where soils are susceptible to suffosion, rehabilitation should include the subsequent installation of cut-off walls to prevent and/or diminish seepage in the embankment and ground. Due to the soil characteristics of the ground in the area of the river embankments on the Upper Rhine, it is necessary in most cases to ensure that the cut-off walls extend well below the contact area of the embankment core. Because the ground in the Upper Rhine region is an aquifer consisting of quaternary sediments with a thickness of several hundred meters, it is not possible to embed the cut-off walls in the aquiclude. They can therefore not completely prevent seepage in the ground but rather have the effect of lengthen the seepage path.

5.1 Effects of cut-off walls

In a homogeneous, isotropic aquifer, a cut-off wall which is embedded only to a small degree in a thick aquifer has only limited impact on seepage. In this case, a cut-off wall extending below the contact area of an embankment with a low-conductivity core (see Figure 2) reduces the flow velocities along the contact area only locally, near to the cut-off wall; in the lower area where water flows

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around the wall, the flow velocities are increased. This is clearly shown by the results of a numerical calculation of groundwater flow which was performed for a simplified embankment cross section with a homogeneous, isotropic aquifer with a thickness of approx. 50 m and with a cut-off wall that is embedded over a length of 10 m in the aquifer below the embankment core (Figure 5, left). The Figure illustrates the changed flow velocity (filter velocity in m/d) resulting from the installation of the cut-off wall as compared to the flow velocity observed under the same hydraulic boundary condition but without a wall. Without a cut-off wall, the mean filter velocity below the embankment contact area is approx. 0.4 m/d.

However, the quaternary sediments constituting the ground of the Upper Rhine embankments are neither homogeneous nor isotropic. Due to alternating depositions of more fine-grained and more coarse-grained sediments, the ground is anisotropic in most areas, with a horizontal conductivity



Figure 4: Damages due to internal erosion

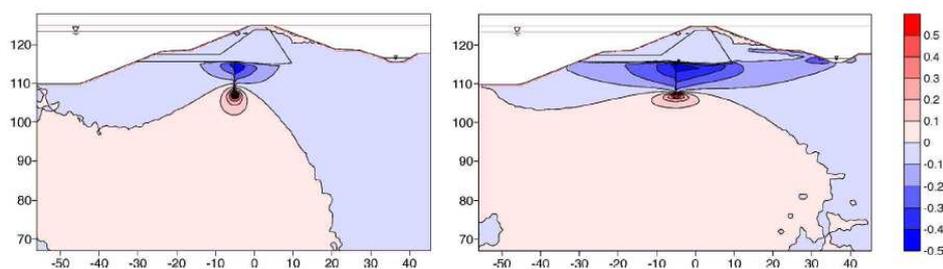


Figure 5: Changed flow velocity due to installation of a cut-off wall, isotropic ground (left) and anisotropic ground (right)

that is significantly higher than the vertical. In such circumstances, the embedment of a cut-off wall in the aquifer helps to significantly reduce flow velocity along the embankment contact area. This is shown by the results of the model calculation, assuming an anisotropic aquifer with a vertical conductivity that is lower than the horizontal conductivity by the factor 10 (Figure 5, right). As flow velocities along the contact area are markedly reduced due to the installation of the cut-off wall, there is a lower risk of internal erosion in the embankment core caused by contact erosion and of further soil loss due to suffosion.

The quaternary ground in the area of the Upper Rhine embankments is in its deeper layers partly characterized by originally horizontal, fine-grained layers with a significantly lower conductivity. If cut-off walls are embedded over long reaches in these layers, they are an effective means of reducing flow velocity in the ground below the embankments and thus of preventing internal erosion.

Before the river training measures according to the engineer Tulla's plans were adopted, the Upper Rhine meandered across a large area, permanently creating new discharge channels. Therefore branches of the former Old Rhine can be found in many places in the ground of the Upper Rhine embankments, mostly filled with coarse grained soil material. If these channels, which have a significantly higher conductivity than the other quaternary sediments, are located below the embankments' contact areas, the risk of internal erosion will be increased in these areas. Here, the installation of a cut-off wall to prevent water flowing through the channels under the embankments would be an effective rehabilitation measure and reduce the risk of internal erosion.

5.2 Types of cut-off walls

There are a wide variety of types and engineering procedures for making vertical cut-off walls, e.g. : sheet pile walls, diaphragm walls ; or jet grouting and soil mixing walls (mixed-in-place or cutter-soil-mixing). Which type of cut-off wall is appropriate depends, inter alia, on economic aspects, durability requirements, the wall length required or local boundary conditions such as composition of the ground, and in particular the flow characteristics found in the ground. Bridges and other structures which can, for example, minimize the working height or require sealing of the bridge/wall junction also influence the type of cut-off wall to be chosen.

5.3 Causes of defects in cut-off walls

Defects in a cut-off wall lead to concentrated, increased seepage which reduces the wall's effectiveness as a protection against internal erosion. The risk and cause of the formation of defects in the cut-off wall differ according to the above-mentioned types of cut-off walls. Defects in sheet pile

walls can be caused by declutching. If pile driving problems occur, this may mean that the sheet piles cannot be driven as deep as originally estimated. However, sheet pile walls are less sensitive to mechanical and hydraulic stresses and are therefore particularly suitable for cutting off a groundwater flow in areas with increased flow velocity.

If impervious materials installed into the ground serve as cut-off wall, the composition of the material (e.g. bentonite-cement-suspension for diaphragm walls) has a great impact on the effectiveness and the durability of the hydraulic barrier. Since the first diaphragm walls were installed at the Upper Rhine, significant progress has been made in diaphragm wall technology. For instance, unsuitable suspension compositions can cause the penetration lengths of the suspension to extend into the pore space of the granular skeleton, reduce resistance to internal and external erosion, favor filtration at the interface between the in-situ soil and the suspension or cause sedimentation within the suspension. Beside the properties diaphragm wall materials, external boundary conditions like the composition of the in-situ soil and flow characteristics found in the ground may also influence the quality of the cut-off wall. Depending on the composition of the suspension, the soil layers and the flow characteristics, the effectiveness of the diaphragm wall varies along the length of the wall due to the migration of sediments, e.g. sedimentation, filtration or penetration. If such erosion processes occur over a long period, this can continuously weaken the cut-off wall and also lead to damages. The chemistry of the groundwater can also have an adverse effect on the wall's quality. However, problems can also result from defects caused during construction (e.g. pulling speed, vibration energy, suspension pressure).

If cut-off walls are to be embedded in a ground subject to seeping, flow velocity is the relevant factor that determines which type of cut-off wall and construction procedure are suitable. The hydraulic gradient has no relevance in this context because in some areas (e.g. in permeable channels in the ground) high flow velocities may occur even if the hydraulic gradients are relatively low. As a rule, cut-off walls which are installed by using a suspension only offer sufficient hydraulic barrier performance in areas where flow velocities are low.

5.4 Cut-off walls in the river embankments on the Upper Rhine

The river embankments on the German side of the Upper Rhine were improved over long stretches by subsequently installing - working from the crest downwards - hydraulic barriers (e.g. sheet pile walls, diaphragm walls and injection walls). These barriers were installed in the embankment sections where seepage and internal erosion had been observed on the downstream slope. In total, cut-off walls with a length of approx. 19 km were installed, extending to a depth of 24 m below the embankment crest. Figure 6 shows the installation of a diaphragm wall (left) and a mixed-in-place wall (right) in the embankments in the Upper Rhine region. Most of the cut-off walls were installed relatively shortly after flooding of the impoundment. As at this time clogging of the river bottom in the impoundment areas had not progressed far, the inflow from the Rhine was not yet markedly reduced. Therefore, the ground was subject to more seepage and the cut-off walls in turn were exposed to a considerable flow already during installation. As described above, in soils that are subject to seepage cement-bonded cut-off walls can generally only serve effectively as hydraulic barriers if flow velocities are low, because the flowing groundwater can cause a loss of suspension

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material. The risk of defects developing is much higher in ground areas subject to seepage than in areas without seepage. This was particularly evident for the cut-off walls in the Upper Rhine embankments which were installed when flow velocities in the ground were still relatively high. The walls were not sufficiently effective in some areas (probably areas with increased seepage in the ground). An additional cut-off wall had therefore to be installed.

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Figure 6: Installation of a cut-off wall (left : diaphragm wall, right : mixed-in-place wall)

5.5 Inspection of cut-off walls

It is possible to perform spot checks in cement-bonded cut-off walls using boring methods to investigate the integrity and quality of the walls. In narrow diaphragm walls it is difficult to obtain one continuous core because of the higher strength of the wall which in most cases affects the accuracy of the boring operation. Moreover, these spot checks based on test borings only provide limited information on the wall's effectiveness over its entire length.

A reliable method for assessing the effectiveness of a cutoff wall is the measurement of the soil and/or groundwater temperature. This method is based on the different degrees of heat transport activity depending on whether there is heat transport with no groundwater flow (conduction) or whether there is a heat flow due to a groundwater flow (convection). The thermal conductivity of soils which are not subject to seepage is low, and consequently there is no significant heat transport. As a result, the soil and groundwater temperatures in an area without seepage in most cases clearly deviate from the temperature of the surface water. If there is an inflow from the sur-

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face water body, heat dissipation will be fast due to the heat flow (convection). The location and the intensity of the inflow can therefore be easily localized by temperature measurements if the temperature sensors are well placed.

To evaluate the effectiveness of a cut-off wall, temperature measurements must be performed before and after installation of the wall, with sensors placed at a relatively short distance from each other. By comparing the readings it is possible to demonstrate the impact of the cut-off wall on ground seepage and to identify defects. Areas with increased seepage flows can be detected as they cause temperature anomalies [Dornstädter, 1997]. The temperature measurement procedure was used several times to assess whether the cut-off walls effectively worked as hydraulic barriers in the Upper Rhine embankments. The measurements showed that while some walls were only subject to an underflow, others were also subject to seepage.

6 Conclusions

Due to the soil materials of the ground and the river embankments it is not possible to exclude the occurrence of contact erosion at the interfaces between the embankment cores which are made of fine-grained soil material and the ground and/or the shells of the embankments which consist of sandy gravels. Moreover, as there is a grain-size gap for coarse-grained sand and fine gravels the soil materials in the ground and the shells are not resistant to suffosion.

Installing cut-off walls in the embankments of the Upper Rhine which extend far into the ground beneath the embankment contact area can be a suitable means for preventing internal erosion resulting from contact erosion and suffosion. Which type of cut-off wall and which installation procedure and wall length are most suitable depend on local boundary conditions and, in particular, on the structure of ground and the groundwater flow characteristics. It is therefore essential to carry out detailed investigations regarding the ground and groundwater conditions if appropriate rehabilitation measures are to be implemented.

The temperature measurement is an effective method for assessing the effectiveness of cut-off walls. To evaluate effectiveness, it is advisable to perform temperature measurements downstream of the cut-off wall subject to flow, both before and after installation of the wall.

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