REHABILITATIONS OF DAM FACINGS MONITORED BY AN ANDVANCED TECHNOLOGY FOR LEKAGE DETECTION

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1 INTRODUCTION

In the recent past the rehabilitation of hydraulic structures' sealing systems has been gaining importance. Bituminous and synthetic geomembranes have become a serious alternative to conventional sealing systems because of improved materials and new possibilities concerning the fixing and seaming techniques. Cost pressure due to the drop in prices for electric power and shorter concession periods in Europe lead partly to a reduction of the planning horizon. Operators think about solutions with reduced investments but with a smaller durability. For some special applications on open canals, a rehabilitation of the facing by geomembranes is the only alternative to a complete reconstruction. A special technical focus of the applicability of synthetic membranes is on the fixation, as it decisively affects the construction costs.

The monitoring of the water tightness of geomembranes is of particular importance. The distributed fibre optic temperature measurement offers the possibility to perform an effective leakage detection even for facing constructions which until now could hardly be monitored in detail.

2 REHABILITATION OF FACINGS WITH GEOMEMBRANES

2.1 General

2.1.1 Field of Application

Bituminous and synthetic geomembranes have been gaining importance as a sealing technique in the last decades. In geotechnical engineering geomembranes are frequently used as a subsurface sealing. For instance landfills are encapsulated in geomembranes to protect the groundwater from pollution. For these underground applications the membranes are needed for sealing purposes only and are not strained by loads, except as a result of settlements. In hydraulic engineering synthetic geomembranes are mainly used as facings, especially for rehabilitation.

2.1.2 Materials

Polyethylene of high density (PEHD), flexible polypropylene (FPP) and polyvinylchloride (PVC) are used as geomembrane materials for hydraulic structures. A fleece is used underneath the membrane to prevent it from getting punctured by rough edges in the surface below, to enable drainage below the membrane and to improve friction to the underground. All Materials are resistant to UV-radiation and are expected to achieve a service life of more than 30 years.

PVC is very flexible, can easily be aligned to difficult geometries and has a large seaming window. FPP is also a flexible material, but its seaming window is small and thus requires precise workmanship on the site. PEHD has the largest seaming window but is very stiff. FPP and PEHD both manage without chemical additives. Joints can be covered trouble-free because the geomembranes' break elongations range from ε_{PVC} = 250% to ε_{PEHD}=700% [3] [4].

2.1.3 Design

When a concrete facing of a dam becomes permeable due to aging, the water pressure increases inside and below the dam, affecting the stability. The most effective method to reduce the uplift pressure is to install a drained surface sealing system connected to the sub surface sealing. In case of a rupture of the surface sealing, the drainage system has to cope with large amounts of seepage water. Therefore it has to provide an adequate hydraulic transmissivity. Submerged perimeters of geomembrane facings usually are executed as watertight compressive perimeters.

During operation of dams the highest load onto the geomembrane facing is the water pressure occurring behind the membrane as a result of rapid draw-down. In water conveyance systems like open canals or tunnels with high flow velocities higher loads can occur as well.

The fixation onto the surface is realized by anchors in combination with steel profiles (Fig. 1). First, the anchors are installed. Then the fleece (drainage geotextile) and the geomembrane are placed onto the surface. They are clamped by steel bars which are placed and fixed to the anchors. Optionally a strip of membrane can be welded over the line of fixation. The fixation bar at the perimeters additionally can be sealed with epoxy resin.

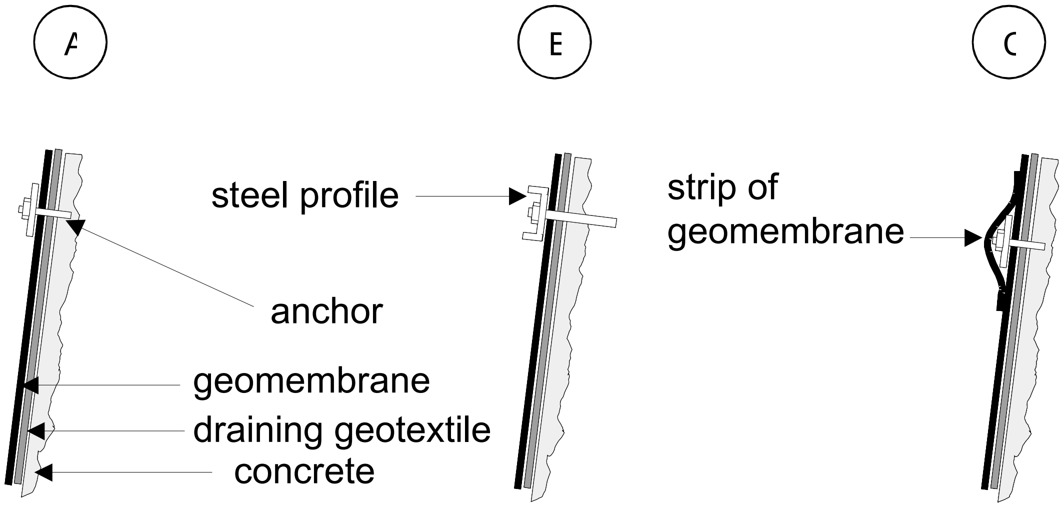


Fig. 1

Examples for different fixing systems for geomembranes

Exemples des systèmes différentes de fixation des géomembranes

(A) flat profile fixed with small anchors at small distances

(B) U-shaped profile with strong anchors at bigger distances

(C) flat profile – fixation secured with strip of membrane welded over the line of fixation

(A) fixation avec un profile plat

(B) fixation avec un U-profile

(C) fixation avec un profile plat, couverte avec une pièce de géomembrane

Ideally, these fixations transmit the forces from the membrane linearly. However, if the anchors are placed at a too great distance the membrane will be held only point wise and might tear out. Reducing the distance of the anchors will prevent this, but as a high percentage of the rehabilitation costs are due to the fixation, the spacing requires optimisation.

3 STUDIES OF GEOMEMBRANES IN OPEN CANALS

3.1 General

In the course of a rehabilitation measure of an open canal in Bavaria questions on the fixation of the geomembranes onto existing concrete emerged. There are two factors which need to be understood to engineer the fixation. For once there is the loading onto the membrane, which develops in the case of a damage of the membrane and water passing underneath. Due to the velocity of the water inside the canal a dynamic water pressure p_{dyn} may develop underneath the ruptured membrane

$$p_{dyn} = \rho\, g \frac{v^2}{2g} = \frac{1}{2} \rho\, v^2 ,$$

where ρ is the density of water and v is the mean flow velocity in the canal. The water pressure may cause tensile stresses inside the membrane according to

$$N = p_{dyn}\, r ,$$

with r being the radius of the deformed membrane. The second factor needed to be known is the transmission of the occurring forces in the membrane into the existing concrete [5].

To investigate the described factors, pull-out tests have been carried out in 2001 and further tests are being carried out at the laboratory of the Institute of Hydraulic and Water Resources Engineering of the Technische Universität München in 2002.

3.2 Fixation Test at the Alz Canal

During the draw off of the Alz Canal in the year 2001, the facing of the canal was rehabilitated using geomembranes. For the rehabilitation a big part of the entire costs were estimated to be caused by the fixation. To investigate the efficiency of different fixation techniques pull-out tests have been carried out with FPP and PEHD geomembranes used in this project.

Samples of geomembranes have been fixed to the upper part of the canal’s old concrete facing and with the help of a winch defined loadings at defined angles have been applied (Fig. 2).

The experiments with an anchor spacing of 10 cm were satisfactory, as a load greater than 120% of the design load could be applied without any deformation in the fixation line. A spacing between the anchors of 100 cm showed to be too high for transferring the loads linearly. The membrane was held only point wise and thus was pulled out (Fig. 3).

3.3 Investigation of the Loads of Geomembranes in Canals

The loads, which can occur in case of a damage of the membrane can be calculated as described above. So far these loads have not been verified. Therefore an investigation in a trapezoid canal is carried out at the laboratory of the Institute of Hydraulic and Water Resources Engineering of the TU München in 2002. The canal will be lined with geomembranes and equipped with sensors. A prepared cut in the membrane will be opened. During the test the parameters water velocity, water level, water pressure developing underneath the membrane, deformation of the membrane and the forces acting onto the fixation will be monitored. Different types of geomembranes are tested. The aim is to determine, respectively to verify, the correlations between the velocities of the water, the water pressure actually developing underneath the membrane and the forces, which need to be held by the fixation.

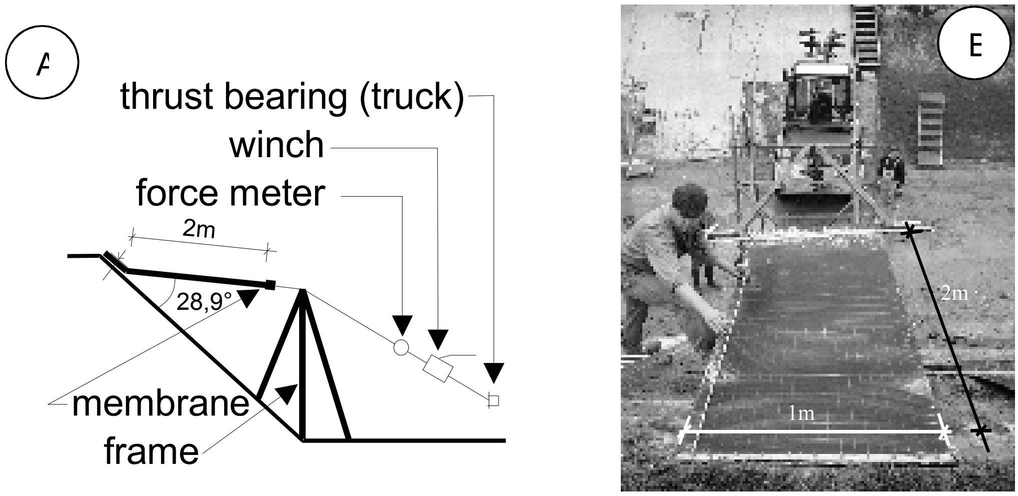


Fig. 2
Alz Canal, set-up of the experiment to test different fixations
Alz Canal, l'expérience pour tester la fixation

(A) sketch of the experiment set-up *(A) esquisse de l'expérience*

(B) image of the experiment set-up *(B) photo de l'expérience*

3.4 Testing of Fixation Systems

Until now the design of the fixation is based on experiences and has not yet been thoroughly been investigated. Therefore, another test is carried out. A geomembrane will be attached on sample concrete blocks with different fixations and can be strained by a system of cables and weights. The actual load onto the fixation is being registered by a force meter and the behaviour of the fixation will be observed. The parameters to be investigated are the distances of the anchors, the diameter of the anchors, the stiffness of the steel profiles, the stiffness of the different geomembrane materials, the angle at which the membrane is being lifted and the surface of the sample concrete blocks. The main aim is to find the ratio between the amount of force transmitted linearly by friction with the concrete and the amount transmitted point wise by the anchors.

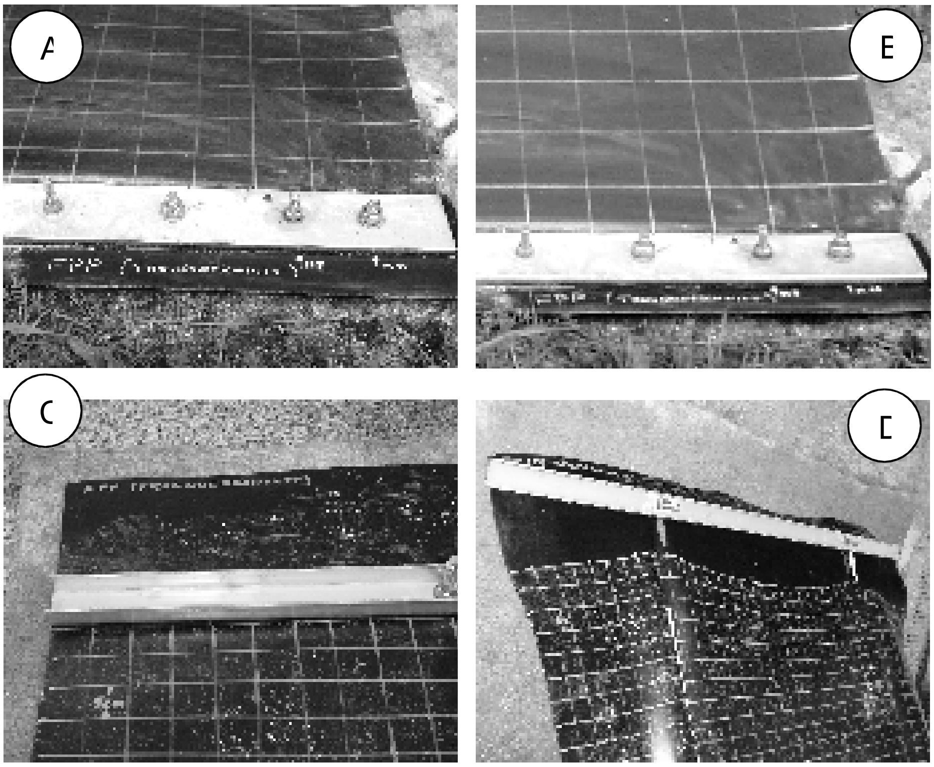


Fig. 3

Fixation test Alz Canal, images of the fixation with different spacing of anchors

Test au Alz Canal, photos de la fixation avec différentes distances des ancres

(A)	before applying the load, anchor spacing 10 cm	*(A)*	*avant le chargement, distance des ancres 10 cm*
(B)	applying 120% of design load, anchor spacing 10 cm	*(B)*	*120% du chargement dessein, distance des ancres 10 cm*
(C)	before applying the load, anchor spacing 100 cm	*(C)*	*avant le chargement, distance des ancres 100 cm*
(D)	applying 100% of design load, anchor spacing 100 cm	*(D)*	*100% du chargement dessein, distance des ancres 100 cm*

4 LEAKAGE DETECTION BY MEANS OF DISTRIBUTED FIBRE OPTIC TEMPERATURE MEASUREMENT

4.1 General

The distributed fibre optic temperature measurements are based on the optical properties of the fibre. The system can measure temperatures with a spatial resolution up to 0,25 m and a temperature accuracy of up to ±0,2°C along optical fibre cables with a length up to several kilometres. The *Gradient Method* requires a difference in temperature between the seeping water from the reservoir and the direct surrounding of the cable, which only appears reliable if the cable has an adequate distance from the reservoir's water. For leakage detection under membrane facings the *Heat-up Method* must be used, because the cable is located close to the water [1]. For heating up the cable an electric voltage is applied to the integrated copper wires. The temperature increase in the cable especially depends on the thermal properties and on heat transport mechanisms in the surrounding of the cable. In case of seepage water flow the conductive heat transport will be superposed by the more effective advective heat transport. The heat input in the cable is transported away by the seepage water flow. The resulting anomalies in temperature increase indicate leakages. For a proper functionality of the leakage detection system a draining geocomposite has to lay under the membrane.

4.2 Example of the Functionality, Leakage Test under a Membrane Facing

One part of the Alz Canal rehabilitated in the year 2001 has a trapezoid cross section (see Fig. 4 / A). Only the slab of the right embankment was sealed with a drained geomembrane system. The left slab was solely locally improved. The bottom of the canal was rehabilitated with a new layer of asphaltic concrete. The joint between the asphaltic concrete and the geomembrane needed special design to avoid a harming of the membrane by the high temperatures of the asphaltic concrete placement. To observe the water tightness of the new facing and the joint, fibre optic cables were installed under the membrane (see Fig. 4 / B). The temperature increase measured using the *Heat-up Method* ranged from 2 to 10 K.

To improve the possibilities of the evaluation of the measurements several leakage simulation tests were carried out. To create defined leakages, tubes were laid on the old concrete facing during the rehabilitation through which water was pumped under the membrane at constant flow rates (see Fig. 4 / C) after the re-impoundment of the canal. The simulated leakages caused anomalies in the temperature increase and helped to associate the measured values to typical conditions of the cable surrounding like "dry", "wet" or "seepage water passing".

The leakage simulation tests were performed at two different leakage tubes, which ended one meter above the toe of the embankment slope. The distributions of the temperature increase without leakage and with leakages at different flow rates are shown in Fig. 5 / A and B. The flow rates varied from 0,1 l/s to 0,4 l/s (Fig. 5 / C). The leakage flow was applied at a constant rate before starting *Heat-up* measurements consisting of a reverence measurement and a heated up measurement after one hour.

The results show that the leakage detection system can locate the leakages correctly. Furthermore for small flow rates the minimum of the temperature increase depends on the flow rate. For higher flow rates no further decrease of the minimum can be observed but the spread of the anomaly increases rapidly. For instance the anomaly at the leakage tube 2 after 3,5 hours with a flow rate of 0,1 l/s and additional 2,5 hours with a flow rate of 0,3 l/s spreads over 50 meters. The temperature differences do not notably fall below

2 K which is due to the cable itself. Even heating up the cable in the flowing water of the canal at the same heating power caused comparable temperature increases of 2 K.

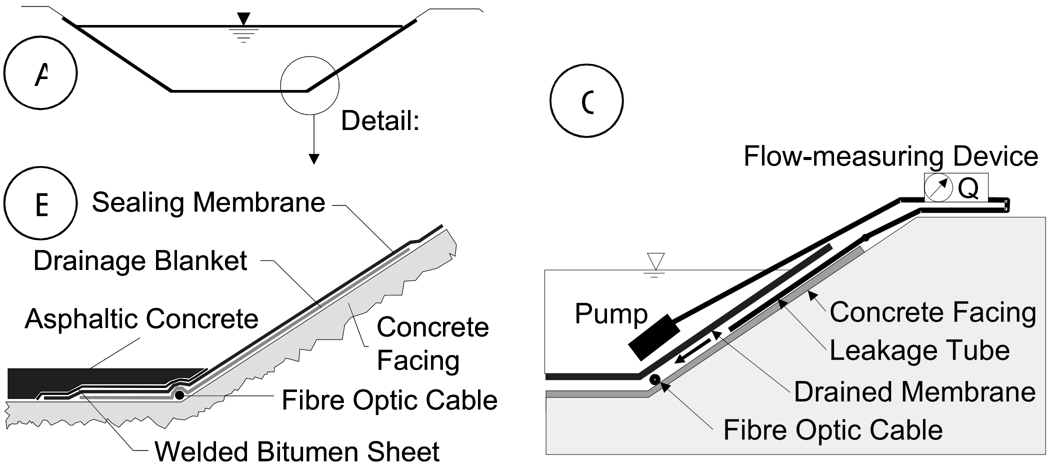


Fig. 4
Schematic cross section of the rehabilitated Alz Canal and the simulation test
Profil en travers schématique du Alz Canal et de la simulation

(A)	Schematic cross section of the canal	*(A)*	*Profil en travers schématique du canal*
(B)	Detail of the toe of the right slope	*(B)*	*Détail du pied du talus*
(C)	Schematic cross section of the simulation test installation	*(C)*	*Profil en travers schématique de la simulation*

The variability of the measured values in the complete section is only at a small part caused by impreciseness of the temperature measurement and mainly shows the variability of the cable's boundary conditions like the porosity of the old concrete slab and the width of the gap between the membrane and the slab. Furthermore the thickness of the asphaltic concrete over the cable varies due to unevenness of the old bottom of the canal. These uncertain material properties of the cable's surrounding have an influence on the heat transport mechanisms and the temperature increase, so that a precise estimation of leakage water run offs under the membrane can not be done. Nevertheless, the monitoring system can precisely locate a failure of the water tightness of the membrane. The project showed also that the leakage observation of the joint using the *Heat-up Method* can only offer trustworthy results if the cable is not in reach of possible other seepage water flows, which in this case could come from the relatively permeable left embankment. Generally the *Heat-up Method* works best on completely sealed and drained systems.

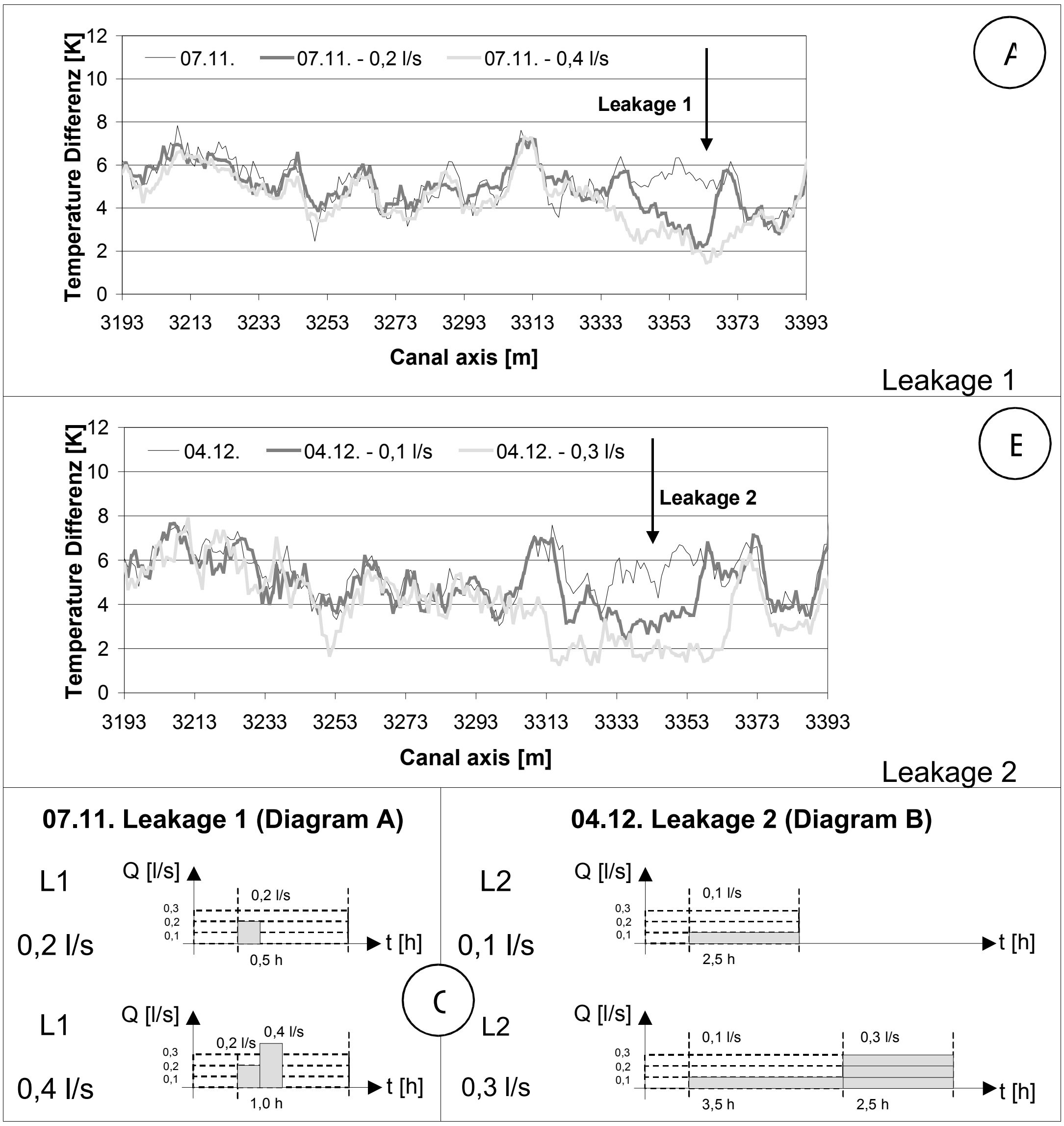


Fig. 5

Results and boundary conditions of the simulation test at the Alz Canal

Résultats et de la simulation au Alz Canal

(A) temperature distribution leakage 1

(B) temperature distribution leakage 2

(C) flow rates during the simulation tests

(A) Distribution de la température fuite 1

(B) Distribution de la température fuite 2

(C) Débit sortant pendent la simulation

5 APPLICATIONS

5.1 Rehabilitation of the Brändbach Dam

5.1.1 Project description

The Brändbach Dam is a 130 m long and 16 m high gravity-dam, which was built in 1921/22. It is located near Bräunlingen (Southern Black Forest, Germany) where it originally was operated only for hydropower production (0,7 GWh/a), but today it also takes flood protection tasks (0,35 Mio.m³ of flood storage) and provides wide recreation facilities.

The dam body consists of a stamped concrete core with originally rubble masonry facings. In the course of first rehabilitation works in 1955 the upstream facing was executed as an impermeable concrete shell. Further ageing of the structure and the lost efficiency of the drainage system made additional remedial works necessary, which were realized between July and December 2000. The investigations showed that the whole dam had to be sealed at its upstream face additionally to the service and bottom outlets having to be completely modernized [7]. The waterproofing of the upstream concrete face was designed as an exposed PVC-geocomposite on the upstream surface [6].

5.1.2 Leakage Detection by Distributed Fibre Optic Temperature Measurements (DFTM)

To prove the impermeability of the geocomposite facing the DFTM system was installed beneath the PVC membrane along its perimeter joint at the dam heel and at the spillway as designed by the Technische Universität München, Germany. According to Fig. 6 the fibre cables were installed directly on the facing concrete as loops, leading to connection boxes at the crest. The arrangement of the fibre cables at the membrane perimeters allows a definite detection of leakages in reference to the longitudinal dam stations and allows the correlation to leakages through the perimeter joints or the membrane itself.

DFTM were performed according to the *Heat-up Method* after the completed re-impoundment of the reservoir. The heating power was 2,4 W/m for the cable at the lower perimeter and 2,0 W/m for the spillway cable, resulting in temperature increases of 3 K and 8 K respectively (Fig. 7).

The application and results of the DFTM system at Brändbach Dam show the definite suitability of this system for the leakage monitoring of a subsequent upstream facing with geocomposites. The *Heat-up Method* allows to distinguish between real leakages and ordinary phenomena behind such modern facing systems. The experiences with the DFTM system in terms of high accuracy and long-term durability as well as the low costs for the fibre cable (~ 4 €/m) lead to the ideal application as a “sleeping” monitoring system, which even can be activated after many years.

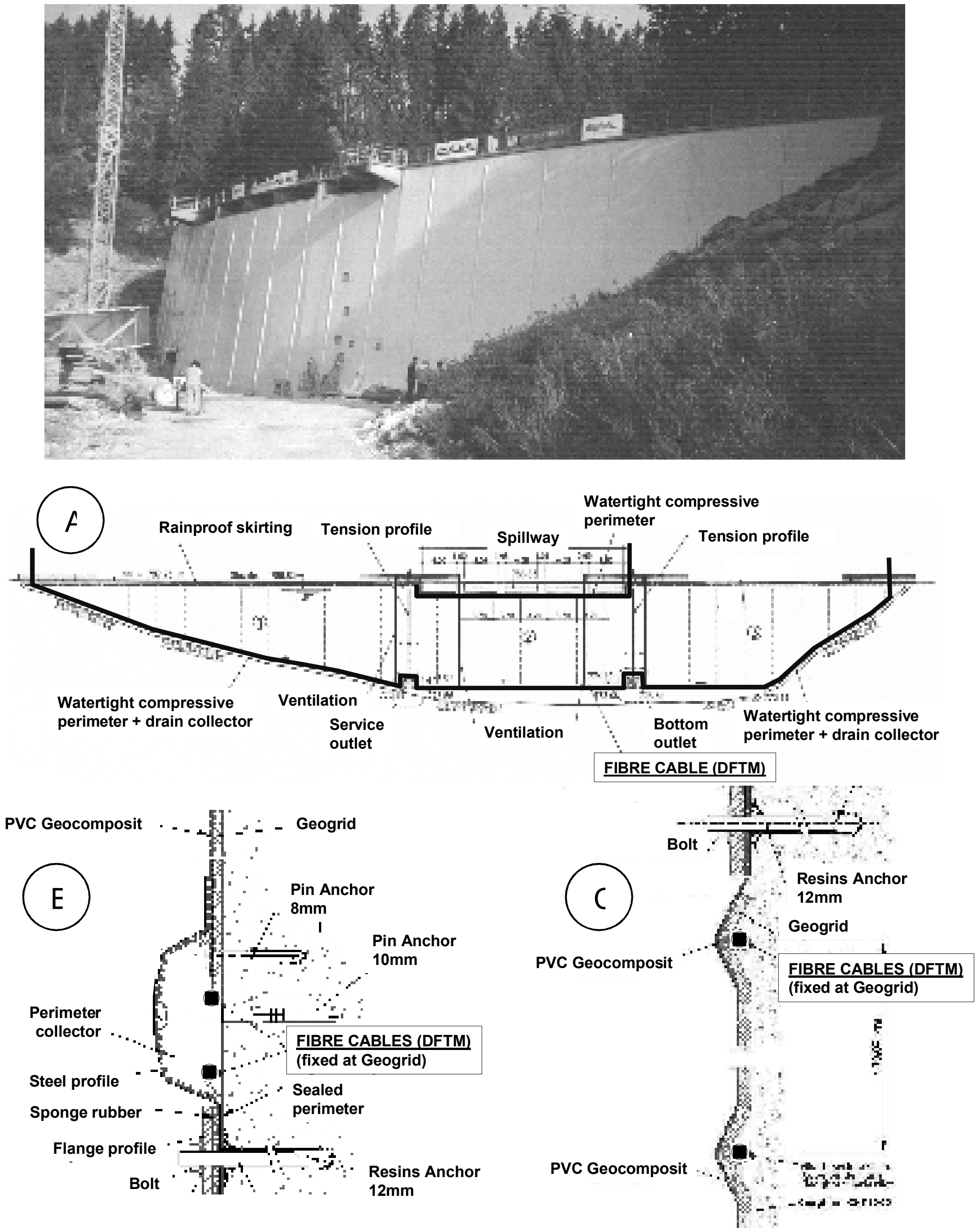
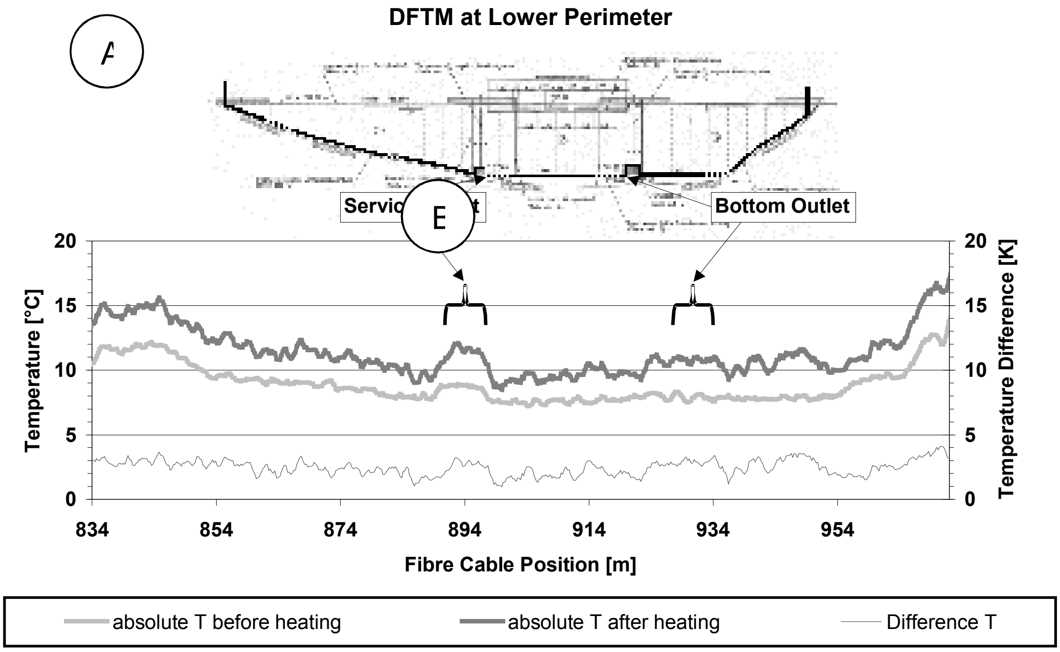


Fig. 6

Upstream view of Brändbach Dam and DFTM details (courtesy of CARPI Spa.).

Vue de la barrage de Brändbach avec des détails de DTFM

(A)	upstream view of the dam layout of the DFTM cable	*(A)*	*vue de tête avec location des câbles de* DTFM
(B)	cross section fixation bar, cable at lower perimeter and collector	*(B)*	*profil en travers de la fixation, câble au périmètre au-dessous*
(C)	cross section fixation bar, cable at spillway perimeter	*(C)*	*profil en travers de la fixation, câble au périmètre au-dessus*



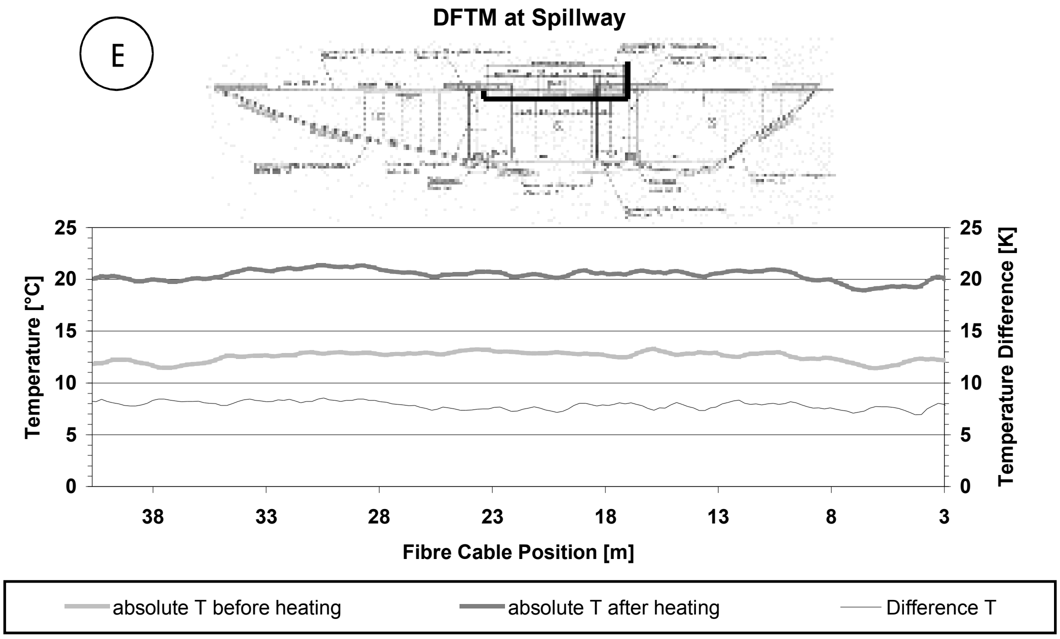


Fig. 7

Temperature distribution at the new upstream sealing of Brändbach Dam

Distribution de la température à l'étanchéité superficiel nouvelle

(A)	DFTM at lower perimeter	*(A)*	*DTFM au périmètre au-dessous*
(B)	DFTM at spillway perimeter	*(B)*	*DTFM au périmètre en 'haut*

5.2 Leakage Detection at the Ohra Dam

The asphaltic concrete facing of the 60 m high Ohra Dam (Thyrigna) was rehabilitated in 1997. On the existing facing a new, double layered asphaltic concrete facing was applied. Besides the conventional monitoring of the seepage water from the drainage layer a very defective part of the facing close to the right abutment was additionally observed by means of the *Heat-up Method*. The installed measuring system was tested with simulated leakage run offs in the drainage layers from the crest of the dam. The test showed, that the leakage monitoring in the drainage layer of the dam works well. Besides the exact localisation of leakages the system can furthermore estimate different seepage water run offs [1].

5.3 Leakage Detection at Concrete Faced Rock Fill Dams

Due to its economical and construction advantages CFRD are seriously considered as an option at most sites with rock foundations and will be used increasingly in the future. This type of dam will behave safely with large leakage and the concrete face can be repaired in a relatively easy, fast and economical way. Even though the shoulder of a CFRD is relatively insensitive to distinct seepage flow, a large number of design and construction efforts focus on improving the water tightness of the sealing element. Especially the joints will always imply an elevated risk of leakage. Empirically, due to settlement of the fill and the contraction of the concrete the perimetric joint will be burdened with tensile stress at the bottom of the valley, which can lead to an opening of the joint and raise seepage water flow. Besides that, all other joints of the concrete facing have a risk of leakage. In the past even cracking of the concrete slab has occurred in places due to contraction of the concrete and the settlement of the embankment fill. All these possible damage spots lead to an increase of seepage water flow and can not be tolerated unlimited. All rehabilitation steps aiming at minimizing leakage water flow can be done easier and more economic if any leakage can be located exactly.

As the cross section of a conventional CFRD does not include an effective drainage layer downstream the sealing element, which allows to allocate detected seepage water to certain sections of the facing, an alternative and effective monitoring system for leakage detection would improve the observation of an CFRD and simplify the handling of leakages in such dam constructions. The distributed fibre optic temperature measurement offers a well suited method for exact leakage detection and localization with a high spatial resolution. Due to leakage monitoring with fibre optic temperature measurement the functionality of the design can be proved explicitly and any leakage that appears even after a long time can be located precisely and effectively simplifies any intended rehabilitation.

As there is no drainage layer under the concrete slab seepage water can not be allocated to the facing. For the distributed fibre optic measurement this means, that the fibre optic cable can only observe the water tightness of its surrounding. For the observation of the whole slab or of all vertical concrete joints a cable layout as shown in the view of Fig. 8 / B or C has to be chosen, for the observation of the perimetric joint the cable has to be installed as shown in Fig. 8 / D. As the perimetric joint in a CFRD bears a certain risk of tensile stresses and the water tightness of that joint is one of the most important requirements for the successful outcome of such projects, the installation of fibre optic heat-up cables in that joint can be recommended as minimum installation for CFRDs.

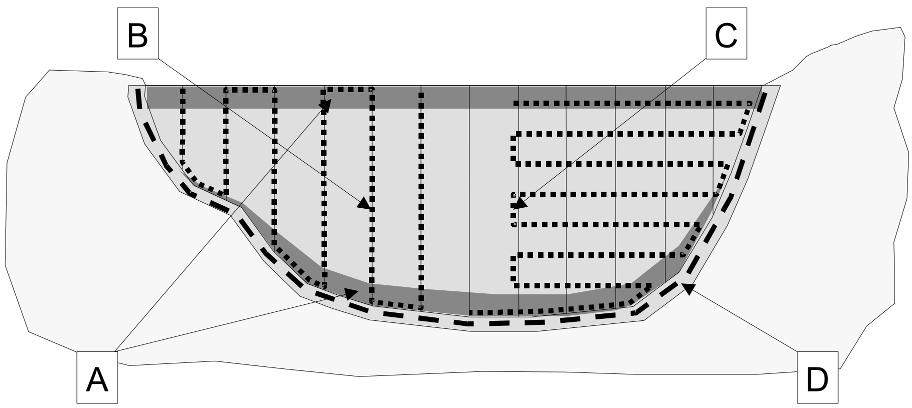


Fig. 8

Schematic view of a CFRD with possible cable layouts

Vue schématique du CFRD avec des locations possibles des câbles

(A)	areas of possible tensile stress	*(A)*	*section avec contrainte de traction*
(B)	observation of the vertical joints	*(B)*	*observation des joints verticaux*
(C)	observation of the slabs	*(C)*	*observation du talus complet*
(D)	observation of the perimeter joint	*(D)*	*observation du joint périmètre*

SUMMARY

The application of a new facing on an old permeable concrete dam can help to solve stability problems caused by interior uplift pressure. In the recent past sealing membranes have become a serious alternative for the rehabilitation of facings and occasionally geomembranes are part of the initial design for surface sealing systems of new concrete dams as seen on Roller Compacted Concrete gravity dams.

The paper reviews the applications of synthetic membranes on dams with a special focus on the fixation. A field test for the rehabilitation of an open canal in Bavaria and further investigations carried out at the Laboratory of Hydraulic and Water Resources Engineering of the TU München concerning the fixation of geomembranes on concrete are described.

Synthetic sealing membranes are mostly applied as drained systems. This allows an extensive monitoring of the water tightness. The distributed fibre optic temperature measurement offers an advanced technology for leakage detection in hydraulic engineering. The water tightness of drained membrane sealing systems can be observed using the *Heat-up Method*. The leakage detection system allows localising leaks with a high spatial resolution. The paper reports on a leakage simulation test carried out under a membrane facing, proving the functionality of the leakage monitoring. Additionally, applications of the fibre optic sensing for leakage detection under facings in dam engineering are described.

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