Conference Paper, Published Version

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# Inflatable dams - Prospects for the use of flexible gates Advantages and application range - Hydraulic and structural design - Requirements for materials - Initial experience on Federal waterways

# INFLATABLE DAMS - PROSPECTS FOR THE USE OF FLEXIBLE GATES. ADVANTAGES AND APPLICATION RANGE - HYDRAULIC AND STRUCTURAL DESIGN - INITIAL EXPERIENCE ON FEDERAL WATERWAYS

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## ABSTRACT

In addition to the potential savings on capital spending as well as during the operation and maintenance of impoundments, environmental compatibility is becoming more and more important. Lubricants and paints are no longer permitted to contain substances that are hazardous to water and there are strict requirements for the renewal of existing anti-corrosive coatings, which may contain asbestos. It is against this background that inflatable dams have become increasingly important in the past two decades. The savings due to the use of flexible gates are significant so that a growing number of private and public operators are opting for this relatively new technology.

Construction of the first inflatable dam on a federal waterway in Germany began at the end of 2004. The dam will replace the existing structure at Bahnitz on the lower River Havel. The existing barrage at another impoundment, at Marklendorf on the River Aller, is also being replaced with an inflatable dam of similar dimensions. The Hydraulic Engineering and Structural Engineering Departments of the Federal Waterways Engineering and Research Institute (BAW) have been studying the new type of gate in parallel to these projects for the past four years.

The presentation covers the results of the investigations conducted during the interdisciplinary Research & Development (R&D) project, the principles of hydraulic and structural design and initial experience with planning, construction and operation. For example, the investigation of the influence of different hydraulic boundary conditions, internal pressures and types of clamping systems on the discharge capacity as well as on the shape and stability of the rubber body are dealt with. Investigations using physical models were supplemented by numerical calculations to clarify hydraulic and structural-mechanical problems. The long-term behaviour of rubber membranes was observed using special test equipment in order to gather information on the retardation of the materials in the clamping system. In addition, numerous investigations of the materials used in commercially available membranes have been conducted and requirements for rubber membranes have been drawn up to enable material specifications to be written. Finally, bullet-resistance tests at various distances using various commercially available calibres and tests to determine the resistance to puncturing by sharp objects have been commissioned owing to the possible risk of vandalism.

The results of the investigations are presented against the background of the two dams being constructed by the German Federal Waterways and Shipping Administration (WSV) and outlines the prospects for the use of flexible gates in future.

## SOMMAIRE

Two projects at German waterways, in which inflatable dams are being installed for the first time, provided the BAW with an opportunity to initiate an R&D project which is being conducted jointly by the Hydraulic Engineering and Structural Engineering Departments. The aim of the project is to bring together the latest findings in engineering, determine the application range of water- and air-filled types and to establish principles for hydraulic and structural design of flexible gates.

- In comparison with numerical methods (finite-element model with ABAQUS) and measured geometries in physical models it becomes obvious, that geometry and membrane force can be calculated for many applications with analytical methods as a function of the internal pressure, the circumference, the headwater and tailwater levels and the spacing of the clamping lines. Design diagrams are therefore provided.

- Vibrations must be avoided during operation. Owing to their relatively low mass, the air-filled type has a greater tendency to vibrate than the water-filled type. Two frequency ranges were detected for the water-filled type where the greatest amplitudes occur when the tailwater level is around 70% of the headwater level. A series of breakers, which were investigated systematically for the first time in a physical model, was shown to be an effective alternative to deflectors.

- On the basis of material tests and relevant standards requirements were specified for the first time in the call for tenders for the inflatable dams at Marklendorf and Bahnitz. Compliance with the requirements was monitored during production by means of regular control tests.

- In response to the frequently expressed concerns about vandalism bullet-resistance and puncture tests were carried out. Due to the elasticity of the elastomer, the bullet holes caused by relatively large calibres close again so that only very small leaks are to be expected. No subsequent tearing was detected either.

- The experience with the operation of the existing inflatable dams in Germany at non-navigable rivers has been very positive. In all of the barrages, the water level is controlled automatically within a top water level tolerance of only a few centimeters. The oldest weir operates with the original membrane since 1981.

The first rubber membrane at weir Marklendorf on the River Aller was installed in October 2005 (Figure 1). The Waterways and Shipping Authority at Verden plans to start operating the weir at the end of 2006.

**KEYWORDS**: Movable weir, inflatable dam, rubber dam, hydraulic and structural design, application range, vibrations, material requirements, vandalism


Figure 1: Weir Marklendorf on the River Aller: a) Membrane after calendering b) Joining the sheets
c) to e) Installing the rubber membrane in October 2005 e) Pressure test

## 1. PROSPECTS FOR THE USE OF FLEXIBLE GATES

The German Federal Waterways and Shipping Administration (WSV) operates 280 weirs, half of which are more than 50 years old. Many of these weirs will therefore need to be refurbished in the near future even though budget resources are shrinking. Although steel gates have a long life-span of up to 70 years, they must be refurbished every 15 to 20 years on average. On the River Neckar, which has 27 weirs and locks, between 4 and 6 gates are refurbished every year for example, with each refurbishment taking an average of six months. Besides the potential for making savings on capital spending, operation and maintenance by using flexible gates, environmental compatibility is also becoming more and more important. Lubricants and paints are no longer permitted to contain substances that are hazardous to water and there are strict requirements for the renewal of existing anti-corrosive coatings, some of which contain asbestos. In many cases, it is necessary to fully enclose the gate.

It is against this background that inflatable dams have become increasingly important in the past two decades. The savings due to installing flexible gates are significant so that a growing number of both private and public operators are opting to use this relatively new technology. For example, it was possible to reduce the capital outlay costs for the refurbishment of the hydropower plant at Kiebingen on the River Neckar in the amount of EUR 0.5 million by using flexible gates instead of conventional gates made of steel [ITTEL & HEIMERL 2001]. When replacing the existing structures at Marklendorf on the River Aller and at Bahnitz on the lower River Havel, the use of inflatable dams instead of flap gates will enable savings of between 20 % to 25% to be made on the capital spending and maintenance costs. In addition to the economic aspects, inflatable dams have a number of advantages when compared with steel gates (GEBHARDT 2006):

- The design is simple and does not include any moving parts (hinges, bearings); there are no problems due to corrosion or sealing and no lubricants that are harmful to the environment are used. Inflatable dams are not affected by settlements or earthquakes.

- The drive mechanisms, such as hydraulic cylinders, electrical actuators or chains, that form part of conventional steel gates and require a great deal of maintenance are not needed. Inflatable dams are controlled solely by pumping air or water into the rubber body and by emptying it.

- The cost of recesses and reinforcement is low and the transfer of forces into the weir is evenly distributed. Major refurbishments are thus facilitated considerably, especially if the existing concrete structure has to be included.

- Inflatable dams can be operated safely at high water levels as the rubber body can always be deflated or emptied to prevent blocking. Some authorizing bodies have therefore waived the need for compliance with the (n-1) condition in accordance with DIN 19700 at some weirs.

- The rubber membranes can be installed or replaced within a few weeks so that the construction times and periods for inspection and refurbishment are considerably reduced.

In spite of their advantages, there is still much scepticism regarding the use of flexible gates, especially at water-retaining structures, the operators of which demand a high level of safety for the people living in the vicinity and for users, such as shipping. This is partly due to the damage that has occurred in the past and on the other hand to the lack of design principles. Guidance and recommendations for planning are usually limited to the information supplied by the manufacturer. Two projects by the WSV at Marklendorf on the River Aller and at Bahnitz on the lower River Havel respectively, in which inflatable dams are being installed as part of a major refurbishment, provided the BAW with an opportunity to initiate an R&D project, which is being conducted jointly by the Hydraulic Engineering and Structural Engineering Departments. The aim of the project is to bring together the latest findings in engineering, determine the application range of water- and air-filled inflatable dams and to establish principles for design and construction.

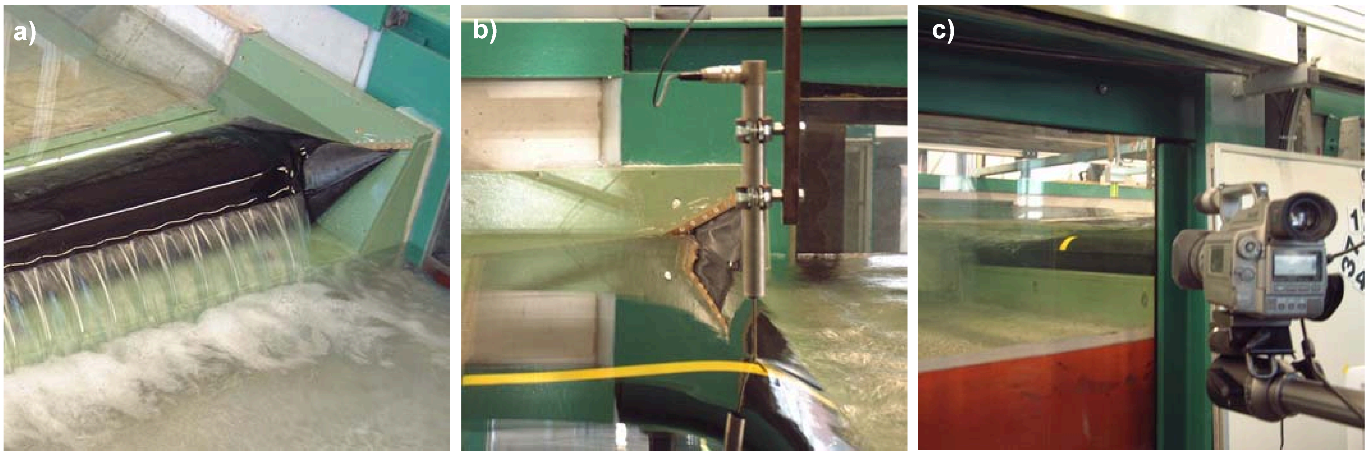


Figure 2: a) Water-filled model with deflector b) Measuring the height of the rubber body using an inductive displacement transducer c) Video documentation of the vibrations

## 2. PRINCIPLES OF HYDRAULIC AND STRUCTURAL DESIGN OF THE INFLATABLE DAMS

### 2.1 GEOMETRY, OVERFLOW CHARACTERISTICS AND SENSITIVITY TO VIBRATIONS

Two physical models - a model of a complete inflatable dam on a scale of 1:12.5 and a model of a section of an inflatable dam on a scale of 1:5 - were used to investigate the hydraulic engineering problems (Figure 2). The effect of various hydraulic boundary conditions, internal pressures and types of clamping systems on the discharge capacity, the geometry of the inflatable dam, the sensitivity of the rubber body to vibrations and the function of remedial measures, such as the installation of deflectors and breakers, were investigated in numerous series of tests.

In the case of inflatable dams, the internal pressure should be taken as the physical control variable and the relationship between the internal pressure and the shape described. In the design case for the components, i.e. without overflow, there is a good correlation between the results of the calculations performed with analytical and numerical methods (finite-element model with ABAQUS) and the geometries measured in the model test (Figure 3). Thus, for many applications, the geometry and membrane force can be calculated as a function of the internal pressure, the circumference of the rubber body, the headwater and tailwater levels and the spacing of the clamping lines. By contrast, when designing inflatable dams with overflow, the differences between the calculated results and the results of the model tests become greater as the overflow depth increases. This is due to the fact that the deviation from the hydrostatic pressure distribution increases with the overflow depth owing to the conversion of static to kinetic energy. Alternatively, the relationship between water level and discharge (stage-discharge relation) can be determined by the study of physical models, as in the past [GEBHARDT 2006].

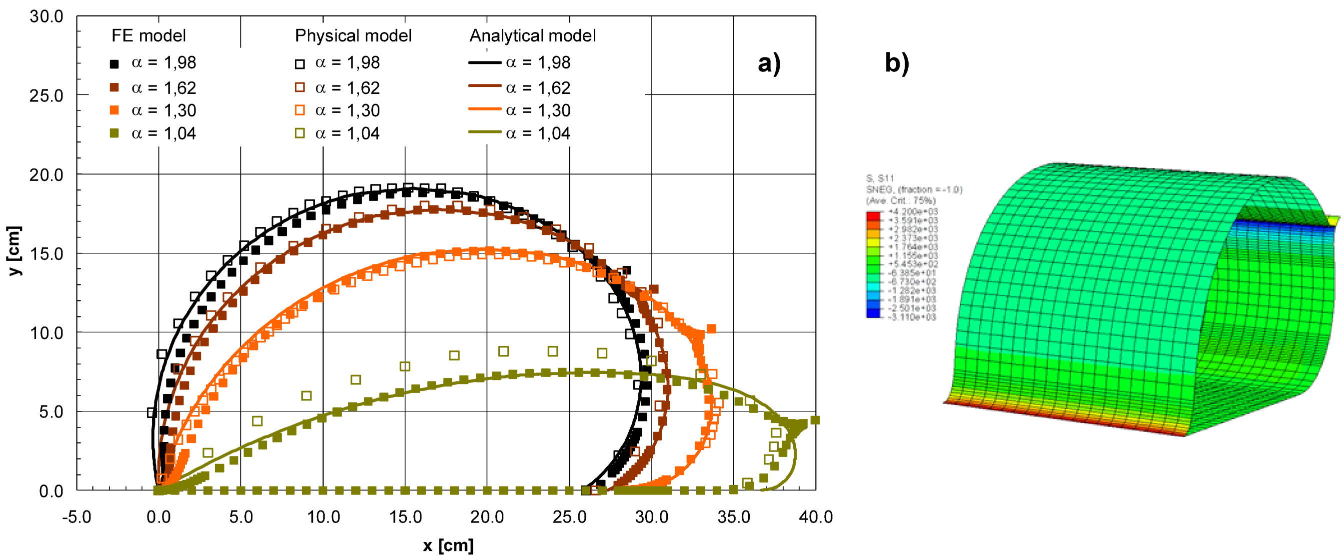


Figure 3: a) Comparison of the geometries of the rubber body determined with the FE model, the physical model and the analytical calculation b) Image of the normal stresses in the FE model [GEBHARDT 2006]

One of the characteristics of air-filled types is that the water flow over the rubber body ceases to be evenly distributed when the internal pressure drops. The inflatable dam will then collapse at one point, usually near one of the abutments (Figure 4a). That is because the pressure differential on the headwater side is not constant, as it is in the case of the water-filled type, but varies with the depth of the water. As membranes are very thin two-dimensional load-bearing structures with relatively low bending stiffness, the system will become unstable, buckling occurs and the membrane will be folded. The resulting v-notch will cause the inflatable dam to be overflown on one side only and the downstream riverbed to be subjected to local scouring. Stationary vortexes can develop in the tailwater which may result erosion at the sloped banks. Practical experience has shown that this does not adversely affect the regulation of the headwater level [ITTEL & HEIMERL 2001]. Air-filled types used to control water levels will collapse in this way even if the overflow depths are low ($h_ü/h_o$ = 0.10 to 0.15) [GEBHARDT 2006].

Vibrations can cause the rubber membrane to be abraded by the concrete surface, resulting in leaks, as cases of damage in the past have shown. Persistent vibrations must therefore be avoided during operation. Owing to their relatively low mass, air-filled inflatable dams have a greater tendency to vibrate than water-filled ones [GEBHARDT 2006]. Investigations of the vibration behaviour of water-filled inflatable dams as a function of the overflow depth, the tailwater level and the internal pressure were conducted with the aid of a triangulation laser and the results analysed by means of a fast Fourier transform (FFT) algorithm. Two frequency ranges were established —

a low-frequency fundamental vibration and a higher frequency harmonic component. The tailwater level has a significant effect on the occurrence of vibrations. The greatest amplitudes occur when the tailwater level is around 70% of the headwater level. However, vibrations can also be avoided or considerably reduced by remedial measures such as installing deflectors and breakers (Figure 4b+c). A series of breakers, which were investigated systematically for the first time in the model test, was shown to be an effective alternative to deflectors.

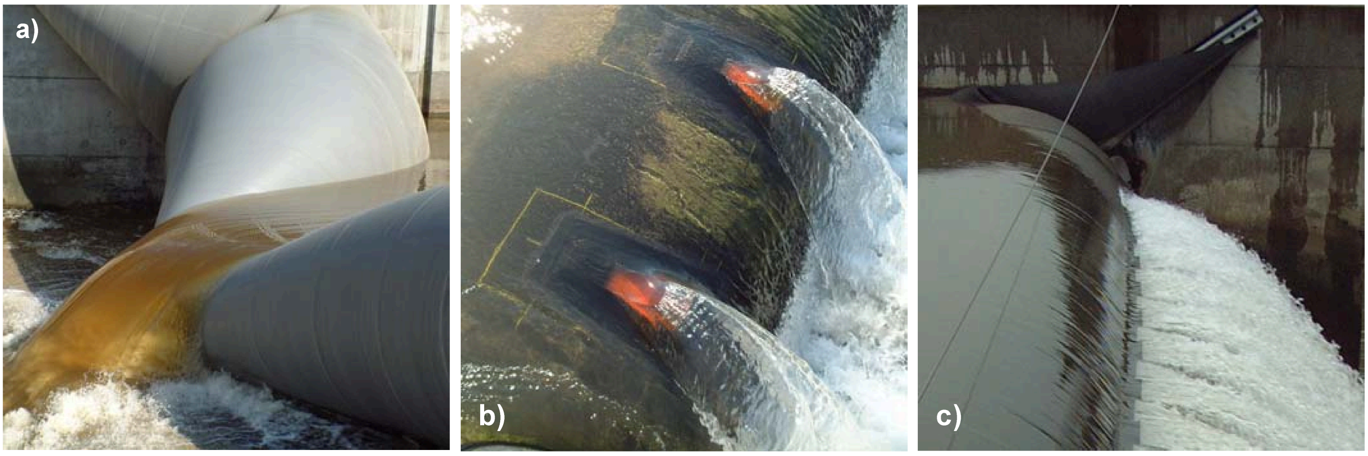


Figure 4: a) V-notch of an air-filled inflatable dam b) Prototype of a series of breakers c) Deflector

**2.2 MATERIAL TESTS, CLAMPING SYSTEMS AND DAMAGE DUE TO VANDALISM**

Extensive testing of the materials used in commercially available membranes was conducted to enable material specifications to be drawn up. The chemical analyses revealed that the manufacturers use special types of rubber such as chloroprene rubber (CR) and ethylene-propylene diene monomer rubber (EPDM) although polymer blends of natural rubber (NR) and styrene-butadiene rubber (SBR) are also used. High-strength woven material made of polyamide or polyester is used as a backing to provide strength (Figure 5a). Tensile specimens were made for component tests based on the tests usually conducted on the textile belts used for conveying material in mines and their tensile strength in the longitudinal and transverse directions was tested. On the basis of the material tests and the relevant standards, limiting values for the elastomer such as the Shore A hardness, tensile strength, elongation at rupture and abrasion were established. These requirements were specified in the call for tenders for the inflatable dams and compliance with the requirements was monitored during production by means of regular control tests.


Figure 5: a) Micrograph of a three-layer, 12 mm thick tubular membrane b) Long-term behaviour test rig
c) FE model and stresses in the steel rails

The BAW put into operation a test rig designed to test the long-term behaviour of rubber membranes after installation (Figure 5b) and determine the retardation (creep) of the materials used in the clamping systems. It was shown that no significant creep occurred, even after a two-year observation period. In addition, finite element calculations for an anchorage for inflatable dams, in which two steel bars (S235JRG2) are anchored in the concrete by means of pretensioned bolts, were commissioned. The rubber membrane is clamped between the two steel bars. The calculations have been verified on a section of the membrane with the aid of the ANSYS FE programme using the symmetry conditions. A line load of 85 kN/m was applied to the rubber membrane and the bolts were pretensioned with 75 kN. An analysis of the results of the calculations showed that, although a maximum equivalent stress of 226 N/mm² (which is only slightly below the yield stress of the steel) was reached in the steel bars, it was only caused locally by the unfavourable geometry of the components in that section of the dam (Figure 5c).

In response to the frequently expressed concerns about vandalism, the Firearms Testing and Certification Authority in Ulm carried out bullet-resistance tests on selected membrane samples. Several commercially available calibres were used and the membranes were fired at from various distances. In addition, puncture tests were conducted with the standardised drop apparatus as specified in the Technical Directive for Protective Vests. As expected, the membrane samples under investigation did not pass the test for bullet-resistance conducted with the calibres commonly used in shooting clubs, for example. However, the strength of the samples was sufficient to withstand attack by air rifles (4.5 mm calibre), which are very common. The membranes did not suffer serious damage either when attacked with lead shot from a distance of 15 m. Thanks to the elasticity of the elastomer, the bullet holes caused by relatively large calibres close again so that only very small leaks are to be expected. No subsequent tearing was detected either [MAISNER, GEBHARDT & GABRYS 2003]. In the case of water-filled inflatable dams, the energy of the bullets or shot is reduced to such an extent that it is highly unlikely that a bullet would penetrate the rubber body a second time, i.e. at the back.

## 2. EXPERIENCE IN PLANNING, CONSTRUCTION AND OPERATION

Although inflatable dam technology dates back nearly 50 years [IMBERTSON 1960], the majority of the flexible gates in Germany have been constructed in the past two decades. Experience with inflatable dams used as gates therefore covers a relatively short period of time. The survey included the oldest weir in operation, which is the hydropower station on the River Regnitz in Erlangen (Figure 6a). The water-filled dam is 1.20 m high and 22.40 m wide and has been in operation with the original membrane since 1981. The experience with the operation of the structure in Erlangen, as well as with other structures of this type, has been very positive. In all of the weirs, the water level is controlled automatically within a top water level tolerance of only a few centimetres, regardless of whether the inflatable dams are water- or air-filled. Although extremely high water levels have been discharged, the membranes are still generally in very good condition, without any major damage which would impair operation. Minor damage to the membrane has been caused mainly by broken glass or nails. There have also been rare cases of vandalism. Such damage was repaired simply by applying repair patches by cold vulcanisation. Even on rivers with high bed-load rates, for instance at the hydropower plant at Tullau on the River Kocher (Figure 6b) no major damage has occurred, nor has any abrasion been detected. A weir section has even been used for the routine removal of bed material from the reservoir at the hydropower plant at Lechbruck on the River Lech (Figure 6c) (GEBHARDT 2006).

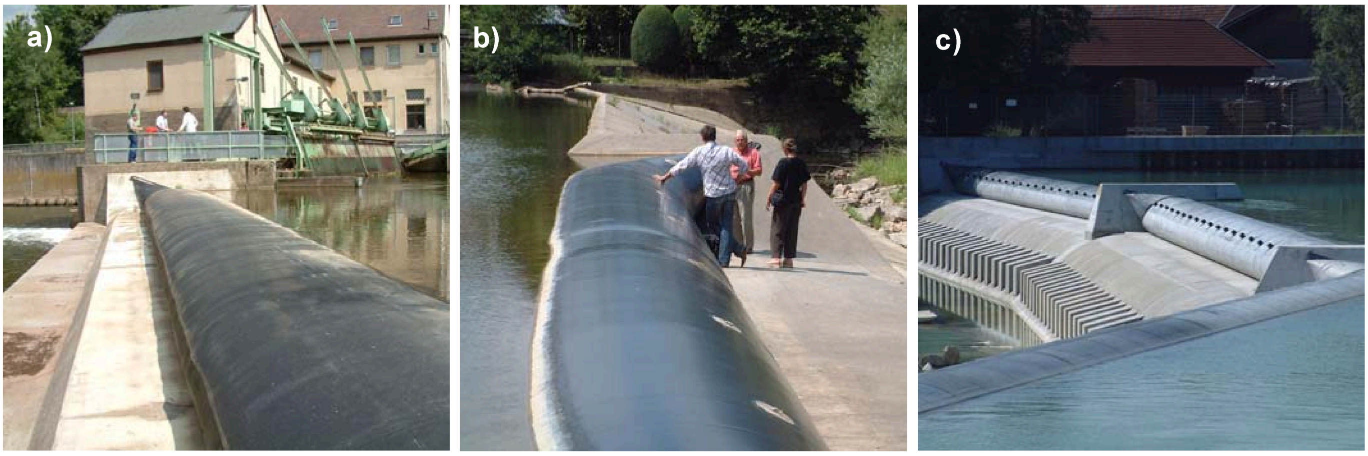


Figure 6: a) Erlangen/River Regnitz (Bavaria), b) Tullau/River Kocher (Baden-Wuerttemberg), c) Lechbruck/River Lech (Bavaria)

The first rubber membrane at weir Marklendorf on the River Aller was installed in October 2005 (Figure 1). The Waterways and Shipping Authority at Verden plans to start operating the weir at the end of 2006. The existing weir at Bahnitz on the lower River Havel is also currently being replaced by an inflatable dam. The Waterway Construction Authority in Berlin plans to install the first rubber membrane in May 2006. The water-filled inflatable dam is part of "Project 17", one of the infrastructure projects being carried out following German Unification, in which it is planned to upgrade the existing waterway connecting Hanover, Magdeburg and Berlin to an efficient European waterway.

The two weirs each consist of two weir sections with a width of 23.60 m (Marklendorf) and 36.50 m (Bahnitz) and a height of approx. 2.20 m and 2.40 m respectively. The BAW used model tests to optimise the width of the weir sections and the geometry of the weir sill and weir piers. In both cases, it was possible to reduce the height of the gates by around 1.00 m by means of a sill with a hydraulically favourable design [GEBHARDT & KEMNITZ 2003, KEMNITZ 2003]. Both of the weirs will be water-filled as the more uniform overflow enables the top water level to be maintained over the entire discharge spectrum, even at water levels that are above the part of the weir sill on which the rubber membrane rests. In the design case, the pressure head inside the rubber body exceeds the headwater level by a factor of 0.6. Two woven polyester plies were specified for the 12 mm thick chloroprene rubber (CR) tubular membrane. A series of polyurethane breakers, which are glued to the finished rubber body, has been used for the first time in the two inflatable dams.

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