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ON THE HYDRAULIC AND STRUCTURAL DESIGN OF FLUID AND GAS FILLED INFLATABLE DAMS TO CONTROL WATER FLOW IN RIVERS

M. GEBHARDT *, A. MAURER† AND K. SCHWEIZERHOF†

* Federal Waterways Engineering and Research Institute,
76187 Karlsruhe, Germany
e-mail: michael.gebhardt@baw.de

† Institute of Mechanics, Karlsruhe Institute of Technology,
76131 Karlsruhe, Germany
e-mail: anne.maurer@kit.edu, karl.schweizerhof@kit.edu

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1 INTRODUCTION

The German Federal Waterways and Shipping Administration operates about 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. An inflatable dam is a relatively new gate type, which enables savings to be made on the capital spending and maintenance costs. It consists of a multi-ply rubber membrane (Figure 1), is filled with air or water and clamped to the weir body with one or two fixing bars (Figure 2). Inflatable dams have a number of advantages when compared with steel gates [2]:

- 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 used, which might be harmful to the environment. Inflatable dams are not affected by settlements or earthquakes.
- Drive mechanisms, such as hydraulic cylinders, electrical actuators or chains, which require a great amount of maintenance are not needed. Inflatable dams are controlled by inflating or deflating by injecting and discharging air or water.
- The cost of recesses and reinforcement is low and the transfer of forces into the weir sill 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 and can always be deflated to prevent blocking. The 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 inflatable dams. This is partly due to the damage that has occurred in the past and partly due to the lack of design principles.

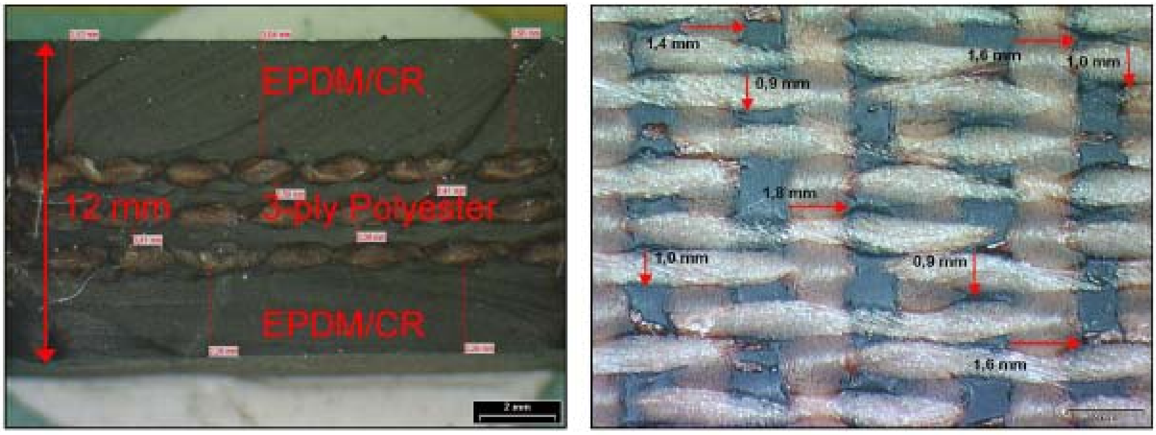

Figure 1: Micrograph of a three-layer, 12 mm thick rubber membrane:
cross section (left) and plan view (right) [3].

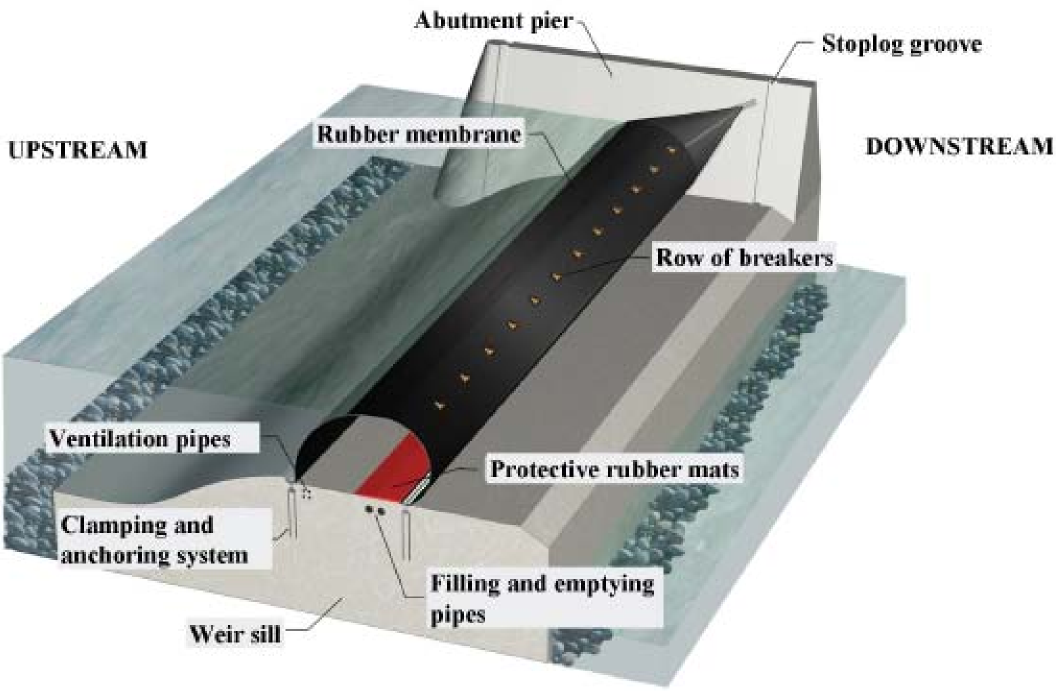

Figure 2: Water-filled inflatable dam – Isometric drawing

2 HYDRAULIC DESIGN ASPECTS

2.1 Overflow characteristics

Physical models were used to investigate the hydraulic engineering problems (Figure 3). 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 countermeasures, such as the installation of deflectors and breakers, were investigated in numerous series of tests.

Figure 3: Physical Model in the laboratory

One of the characteristics of air-filled inflatable dams is that the water flow over the dam 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. This is due to the fact that 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 overflow depth. As membranes are very thin two-dimensional load-bearing structures with relatively low bending stiffness, the system will become unstable and the membrane will be folded or dented. The resulting V-shaped "dent" will cause the inflatable dam to be loaded on one side only and the downstream riverbed to be subjected to locally higher loads. Stationary vortexes can develop in the tailwater which may result in sloped banks being subjected to higher loads. Practical experience has shown that this does not adversely affect the regulation of the headwater level. Air-filled types used to control water levels will collapse in this way even if the overflow depths are low [1].

2.2 Causes of vibrations and the effects of countermeasures

Due to their elasticity, inflatable dams change their geometry in dependence of the pressure distribution along the surface, so that the occurrence of vibrations can be very different in their characteristics (mode shape, amplitudes and frequencies). Generally four types can be distinguished: vibrations of the nappe, vibrations due to pressure fluctuations, vibrations due to uplift forces and vibrations of the deflated membrane [5].

In order to reach a dynamic similarity of the vibration behavior in experimental models, the bending stiffness EI must be taken into account. Tensile tests were carried out on samples, to estimate the Young´s modulus in model and nature. In order to examine the range of vibrations, the vertical amplitudes at the crest of the rubber body were measured, using a laser distance measuring device which works according to the triangulation principle. A further evaluation took place with the help of a Fast Fourier Transform (FFT) [1].

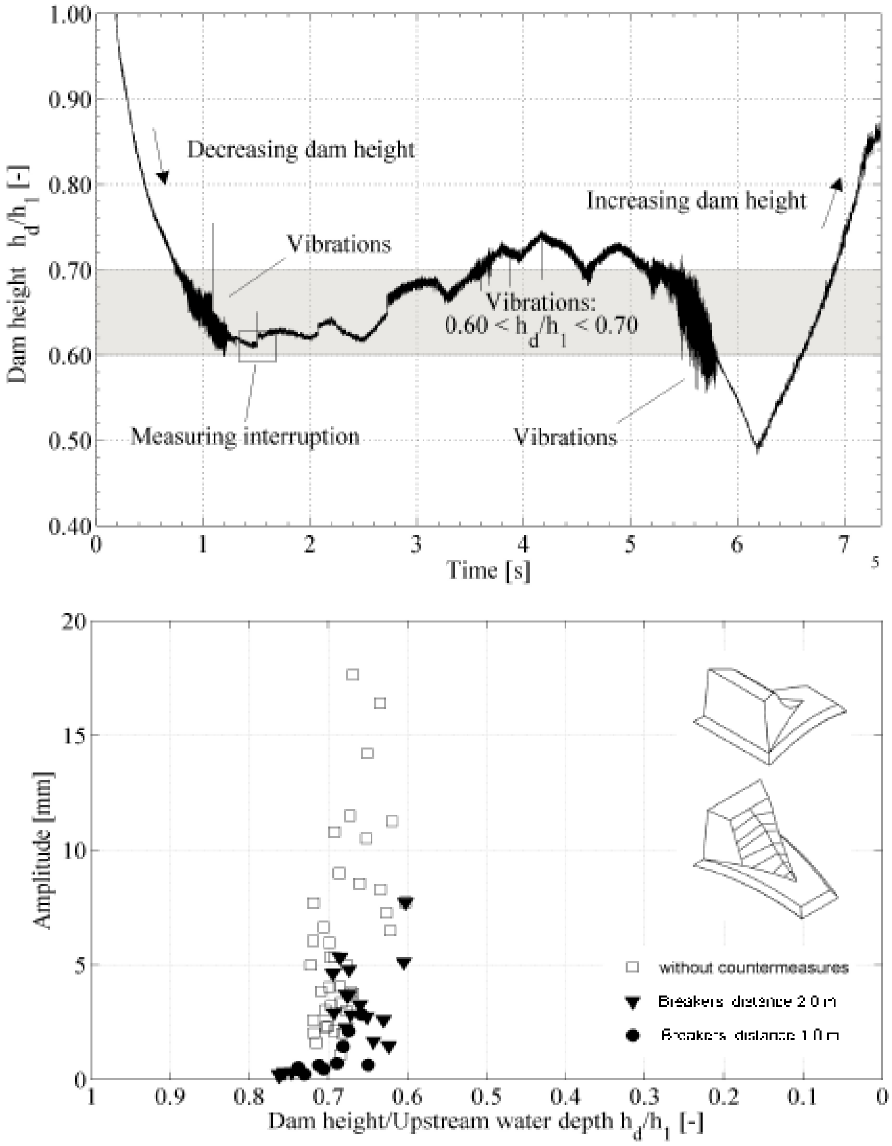

Figure 4: (a) Dam height vs. time during the in-situ investigations with range of vibrations, (b) amplitudes of the vibrations depending on the distance of the breakers [4]

As a result of the above experiments, it can be shown that vibrations of the water-filled type can be observed only in a small range of dam heights when no countermeasures are provided and a constant upstream water level is considered. Then vibrations appear suddenly and disappear during further deflation of the dam. It is induced by an unstable separation point of the nappe and the resulting pressure fluctuations on the downstream side of the dam. Through the adaptation of a row of breakers vibrations can be avoided or can be at least significantly reduced. In order to improve the shape, the location and the separation distance of the breakers, several test series have been carried out at an existing water-filled dam with two spans of a width of 15.60 m each and a dam height of 0.84 m [5].

3 STRUCTURAL DESIGN ASPECTS

3.1 Geometry and membrane force

In the case of inflatable dams, the internal pressure should be taken as the control variable and the relationship between the internal pressure and the design dam height h_d is defined as the internal pressure coefficient α. In the design case for the components, i.e. with-out 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 5). Thus, for many applications, the geometry and membrane force can be computed as a function of the internal pressure coefficient α, the density of water ρ_w, the gravitational constant g and the dam height h_d, which corresponds to the upstream water depth when there is no overtopping. Analytical solutions allow developing design charts for all relevant parameters of a cross section [1,4].

Water-filled-type $$T = \frac{1}{4}\left(2\,\alpha - 1\right)\rho_w\, g\, h_d^2 \qquad (1)$$

Air-filled-type $$T = \frac{1}{2}\,\alpha\,\rho_w\, g\, h_d^2 \qquad (2)$$

By contrast, when designing inflatable dams with overflow, the differences between the results of numerical and analytical models 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 [2].

3.2 3D Finite-Element model of inflatable dams using quasi-static fluid-structure interaction

To optimize inflatable dams in terms of stresses, stability and impact of swimming structures a 3D finite element model was created. Provided that the filling of the inflatable dam proceeds quasi-statically and both top water and bottom water can be considered quasi-static and the water flow is relatively small, the fluid can be described by an energetically equivalent load vector [6] which can directly be correlated to certain water depths and water or gas volumes. The fluid parameters pressure and density describe completely the fluid filling and are input parameters of the finite element simulation.

The structural model is created using the geometric input parameters like the length of the inflatable dam or the angle of the flanges. In total the structural geometry and thus the model depend on eight independent geometric parameters. The concrete part of the structure is modeled by rigid walls.

Simulations have been done with various geometric parameter sets, with fluid and/or gas filling of the inflatable dam and different heights of top and bottom water using the currently implemented routines in LS-Dyna [7], which permits the use of different material models and contact formulations in combination with multi-chamber quasi-static fluid-structure interaction.

An empty and filled inflatable dam is shown in Figure 6. The internal volume of the inflatable dam is described by the red, yellow and brown part of the model, while the volume of the head water is calculated with the green and yellow part and the bottom water volume is described by the blue and red part. In total the inflatable dam and the tub are discretized with about 75000 shell elements. A fairly fine mesh is chosen for the locations where folding of the membrane is expected.

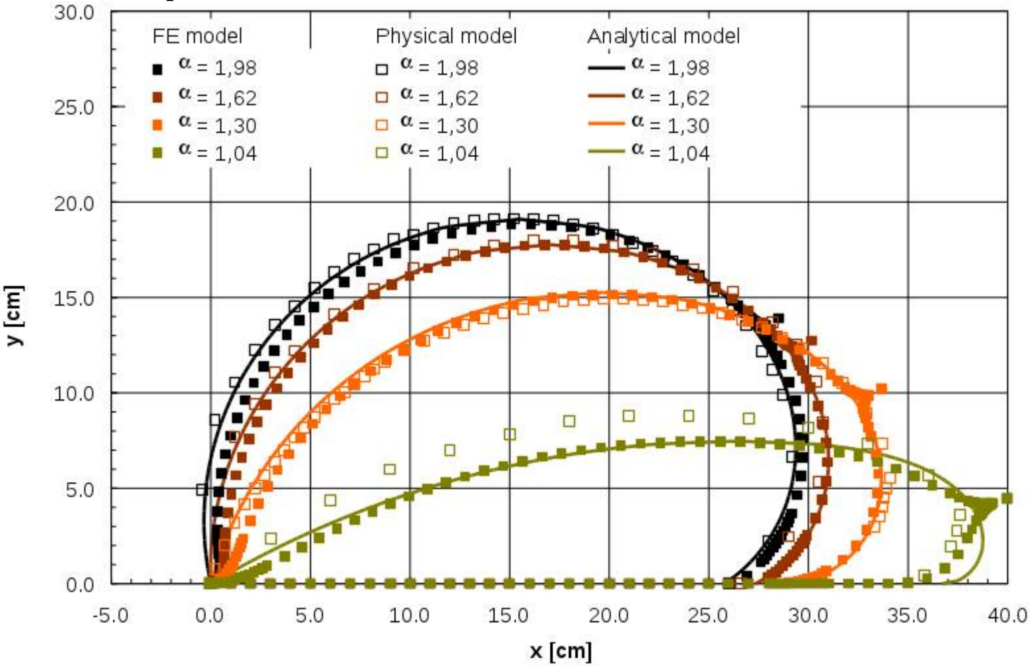

Figure 5: Comparison of the geometries of the rubber body determined with the FE model, the physical model and the analytical calculation [2]

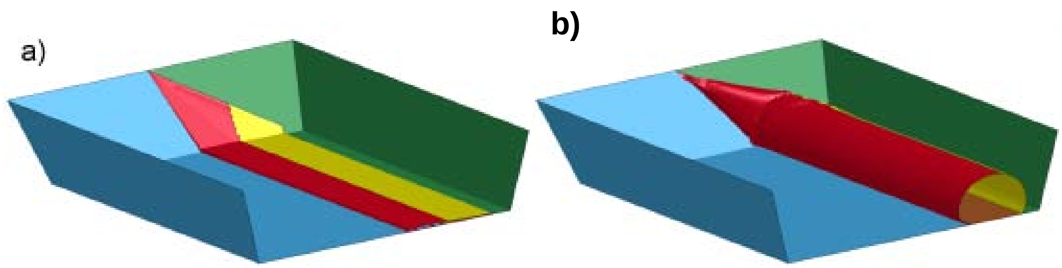

Figure 6: Model: a) initial state of uninflated tube and b) final state of inflation with gas

3.3 Impact of swimming trees and the effect on stresses

The standard loading of inflatable dams is by top and bottom water thus pressure. The top water however, can carry trees or sediment. The impact of a tree increases the stresses in the inflatable dam near the impact zone and for this reason affects the stress concentration factor.

In the finite element simulations the tree is modeled by a cylinder of length 5m and weight 4t which swims with a constant velocity and hits the inflated dam under an angle between 0° and 90°. To show the effects of the filling the dams have been filled with different water heights and gas pressures.

Considerations show, that – not unexpected - a higher velocity of the tree or a completely gas filled dam with a low gas pressure would cause the longest deformations and highest stresses.

In Figure 7 the finite-element setting in an inflated state with the tree at initial position and the impact of the tree is shown. To show a case with a relatively large deformation of the dam the initial pressure has been set to a low pressure of 0,2bar and the velocity of the tree at time of impact 4 m/s.

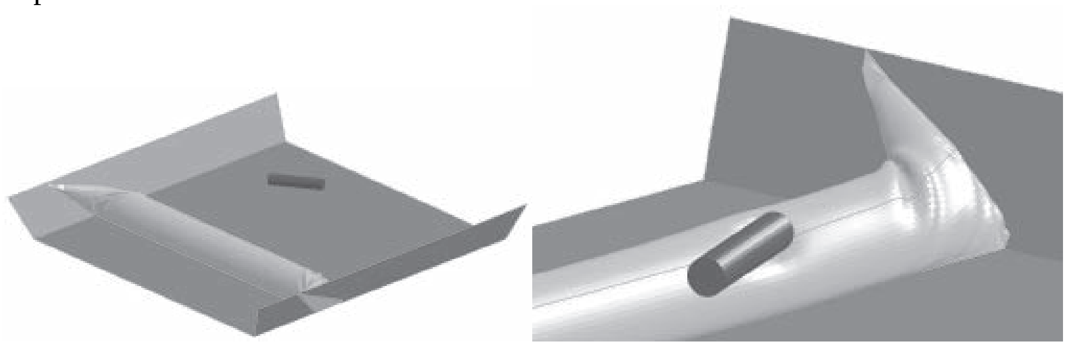

Figure 7: Inflated dam with idealized tree before and during impact

To compare stresses in this extreme example the stresses of the area of impact have been compared with the stresses of the complete dam. The stresses in the area of impact increase during the impact, but reduce shortly after the tree leaves the dam, see Figure 8. After a longer time period which is not included in the figure, the stresses and the geometry return to the state before the impact.

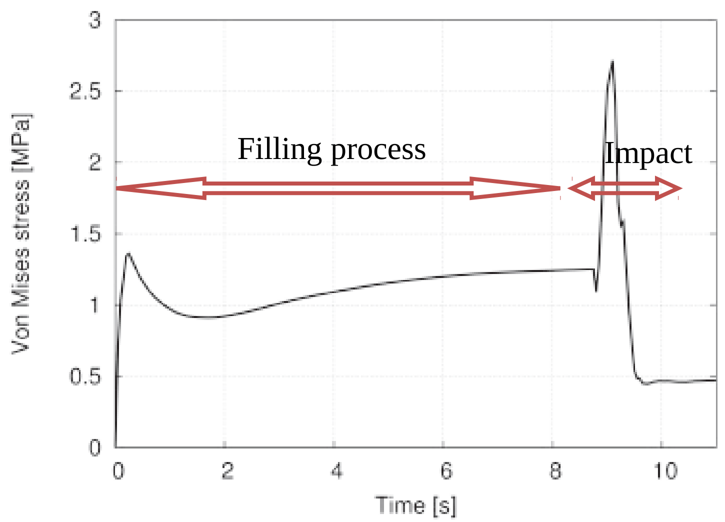

Figure 8: Von Mises stresses in area of impact

Comparing these maximum stresses in the area of impact with the maximum stresses near the flanges shows that these impact stresses do not change the stress concentration factor which is important for design. The maximum von Mises stresses in this particular inflatable dam are about 6 MPa, while the maximum stresses in the impact area do not exceed 2,9 MPa.

For lower velocities of the tree or dams filled with water the effect of the impact on the stresses is even smaller. So in general we can conclude that the impacts of object such as trees do not affect the maximum stresses of a dam. Further investigations will include the effect of sharp edges and the overrun of trees with sharper parts.

3.4 Comparing cross-section deformation of fluid and/or gas filled dams

At built gas filled inflatable dams it can be observed that these dams are prone to buckling, see Figure 9, while fluid filled dams do not develop such a V-notch.

Figure 9: V-notch in gas filled dam

To simulate the effects of top and bottom loading on the cross section of the inflatable dam, the dam was filled up to a water level of 3m. Three different states have been investigated: a head water level of 2m, a head water level of 1.5m and a head water level of 2m while the bottom water level was set to 1m. Figure 10 shows that the deformation of the cross section under head and bottom water is relatively small.

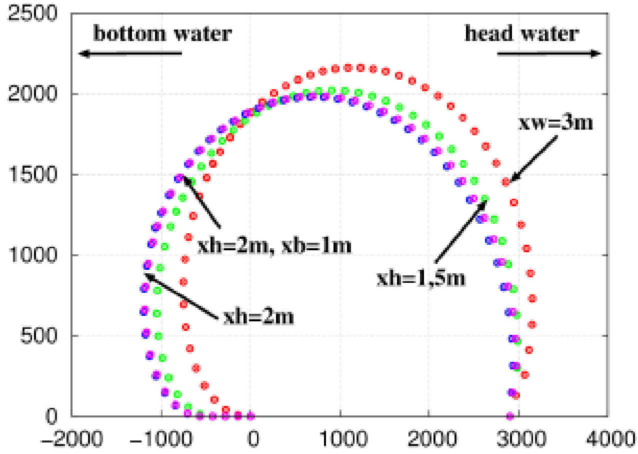

Figure 10: Cross-section deformation of water filled dam

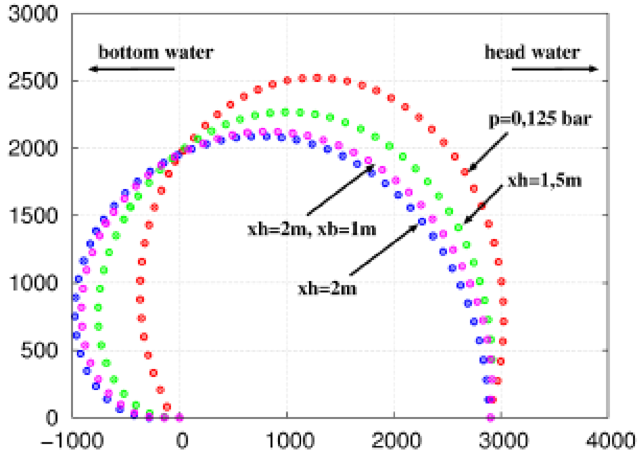

Figure 11: Cross-section deformation of gas filled dam

In comparison the dam is now filled with gas (gas pressure p=0.0125 N/mm²), see Figure 11. As a consequence the cross-sections show much larger deformations. In addition, gas filled inflatable dams are more prone to buckling.

4 CONCLUSIONS

The contribution covers some results of the investigations conducted during an interdisciplinary Research & Development project and gives an outline of first experiences varying design, construction and operation.

The results of extensive investigations with physical models form the basis for discussing the causes of vibrations and the effects of countermeasures. As a result of the experiments, it can be shown that vibrations can be observed in a small range of dam heights when no countermeasures are provided. Vibrations appear suddenly and disappear during further deflation of the dam. By the adaptation of a row of breakers vibrations can be avoided or at least significantly reduced. Information on the location and form of the breakers will be discussed.

The practical application of the results has been carried out on two inflatable dams within the area of responsibility of the WSV: Figure 12 shows the row of breakers in Bahnitz: the breakers were spaced by 1.0 m and located at 85 and 95 % of the deflated membrane length, alternately.


Figure 12: Weir Bahnitz east of Berlin: row of breakers (left), weir in operation (right)

In addition the important issues of cross-section deformation and impact of trees are investigated by an explicit finite element analysis. The filling is described by energetically equivalent loading which takes into account the considerable deformations and volume change during the filling phase and in the loading phase. In LS-DYNA such a feature was already included for gas and has within the project been enhanced for fluid filling and combinations of gas and fluid loading. With this new feature a numerical study on the cross-section deformation showed large deformations of gas filled dams while fluid filled dams are far less prone to buckling. Investigating the effect of trees hitting the dam showed that stresses in the area of impact are increased compared to the standard loading but remain still smaller than the maximum stresses in the complete dam which are usually in the region of folds at the flanges.

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