Computation of fluid and/or gas filled inflatable dams

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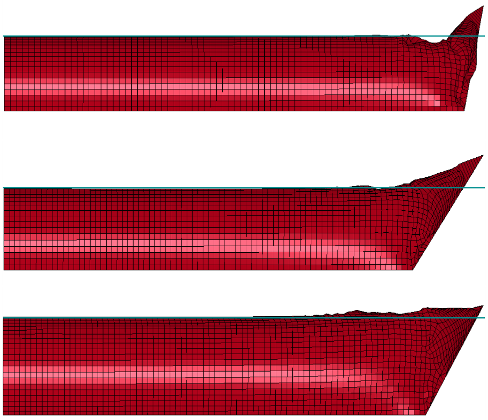
Summary:

Inflatable dams are used worldwide as diversion structures, lock systems, tidal barriers and to rise the height of water reservoirs. At the moment there are very few and limited guidelines for dimensioning an inflatable dam. As a part of a research project to define new and more complete guidelines at the Bundesanstalt für Wasserbau the Institut für Mechanik is working on simulations of inflatable dams.

Figure 1: Water filled inflatable dam near Marklendorf

The varying geometry in dam design is based on several independent parameters which describe an inflatable dam. An example for a geometric parameter is the length of the weir field or the angle of the side flanges. Non-geometric parameters like the internal medium and its state, the height of head and bottom water change the appearance due to fairly large deformations as well. The general equations to describe the correct pressure also in complex deformation processes are following the proposal given by [8], [6], [4], [7], [5] and an algorithm allowing the simulation of multiple water/air filled chambers of a structure was recently implemented in LS-DYNA. With a newly programmed input card *AIRBAG_FLUID_AND_GAS fluid and/or gas filled structures in quasi-static fluid-structure interaction can be simulated. Even multi chamber systems with different fluid/gas loading in each chamber can be treated. Inflatable dams and their different chambers are then first filled and afterwards loaded in a quasi-static process and can so be simulated by this theory.

Inflatable dams tend to have major folds near the side flange. Near the folds the stresses are very high and in most cases head water can drain through the fold. In case of dimensioning a dam, geometric parameters have to be found which result in inflatable dams with only small folds and wrinkles. To analyze the dependency between geometric parameters and the folds 200 different inflatable dams have been simulated. In a filled state all dams have been classified if they have a major fold near the side flange, no major fold or only small folds and wrinkles. Figure 2 shows three different classified inflatable dams.



Inacceptable inflatable dam

Unclassified inflatable dam (small folds and wrinkles)

Acceptable inflatable dam

Figure 2: Influence of geometric parameter variation on folds and wrinkles

After the classification the geometric parameters which are important for the appearance of the folds and/or wrinkles have been identified. If e. g. the angle of the flange is near $90°$, there will be a deep fold. On the contrary if this angle is close to $45°$, there will be only a small fold (depending on all other geometric parameters). For further details we refer to the long version of our contribution and to forthcoming publications and reports.

Keywords:

Fluid-structure interaction, quasi-static, inflatable dam, fluid/gas filling

1 Motivation

The first inflatable dam was built in the Los Angeles River in 1957 [1]. Since then more than 2500 (as in 2006) inflatable dams have been built worldwide, in Germany more than 70 [2]. Applications are numerous, e. g. as diversion structures, lock systems, tidal barriers and rising the height of water reservoirs. Compared to other dam systems inflatable dams have various advantages like a long lifetime, no corrosion protection required, robustness against vandalism and low maintenance and replacement costs.
Figure 3 shows an inflatable dam built 2006 in the river Aller near Marklendorf, Germany. In this case the weir field is 23.60 m long and the height amounts to 2.20 m. This specific dam is filled with water, however there are also many gas filled as well as fluid and gas filled dams in Germany.

Figure 3: Water filled inflatable dam near Marklendorf

2 Theory

The filling process with water and/or gas is a quasi-static process. Thus waves, turbulence and other dynamic behavior of an inflatable dam are not expected. As a result the effect of gas or water inside a chamber can be described by an energetically equivalent pressure load vector and also the standard water loading is quasi static. Even when water is flowing over the dam as shown in Figure 3 the dynamic loading is prevented to a very large extend by using deflectors.
An important aspect is that the water/gas loading is defined via given initial volumes and gas or fluid deformation relations. This is predominantly important for structures undergoing large deformations or in stability prone problems.
Of course this idea can not only be applied to inflatable dams. Other structures including quasi static fluid structure interaction are e. g. hydro-forming, buoyancy simulation of ships and inflatable beams and tents.
In the following subsections all three different load-cases (pure gas loading, incompressible fluid loading and incompressible fluid with compressible gas loading) are discussed. A complete derivation and further load cases considering also compressible fluid can be found in [5] and [6].

2.1 Gas

In case of gas loading the whole internal boundary of a gas filled chamber is loaded with a constant gas pressure p^g. As shown in Figure 4 p^g is the gas pressure, $\partial\Omega^g$ the boundary and $\mathbf{n}^g$ the normal directed towards the outside of the wetted structure. The virtual work term resulting in a load vector due to gas loading, which has to be subtracted from the structural load vector, reads as

$$\delta\Pi^g_{ext} = \int_{\Omega^g} p^g \mathbf{n}^g \cdot \delta\mathbf{u}^g \mathrm{d}\Omega^g \tag{1}$$

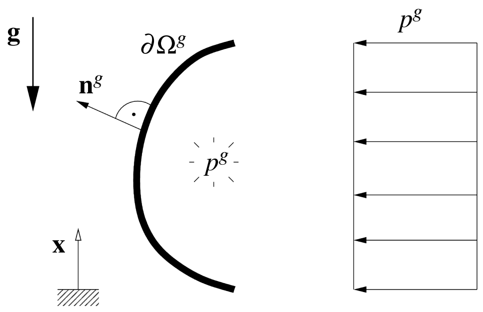


Figure 4: Pressure in a gas filled chamber

with the variation of the displacement $\delta\mathbf{u}^g$.
After each time step the gas pressure has to be updated considering a simple gas law with the adiabatic exponent κ and the gas volume v^g:

$$p^g = p^g_{old} - \kappa p^g_{old} \frac{v^g - v^g_{old}}{v^g_{old}}. \tag{2}$$

The pressure is hereby as in the following load cases controlled by volume modifications.

2.2 Incompressible Fluid

Without an additional gas loading there is a free fluid surface and the following load case is achieved considering only incompressible fluid as the compressibility of the fluid plays no role in the rather soft structure considered in this contribution.

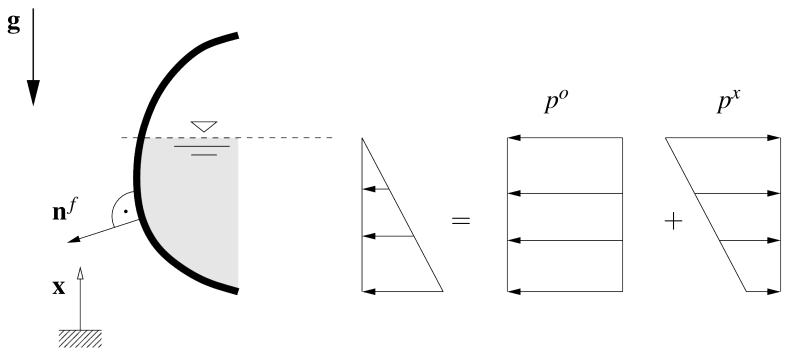


Figure 5: Hydrostatic pressure in a partially filled chamber

With the gravity vector $\mathbf{g}$, the outward directed normal of the wetted surface $\mathbf{n}^f$, the density of the fluid ρ and the coordinate to the fluid surface $\mathbf{x}^o$ the pressure at water level is computed by

$$p^o = \rho\mathbf{g}\cdot\mathbf{x}^o \tag{3}$$

and the pressure at any point of the wetted surface is

$$p^x = \rho\mathbf{g}\cdot\mathbf{x} \qquad\qquad \mathbf{x} = \mathbf{0}\ldots\mathbf{x}^o. \tag{4}$$

This leads to the virtual work of a load vector consisting of p^x and p^o:

$$\delta\Pi^f_{ext} = \int_{\Omega^f} (p^x - p^o)\mathbf{n}^f \cdot \delta\mathbf{u}\, \mathrm{d}\Omega^f. \tag{5}$$

2.3 Incompressible Fluid combined with Gas

The last regarded load case is the combination of the two previous load cases.

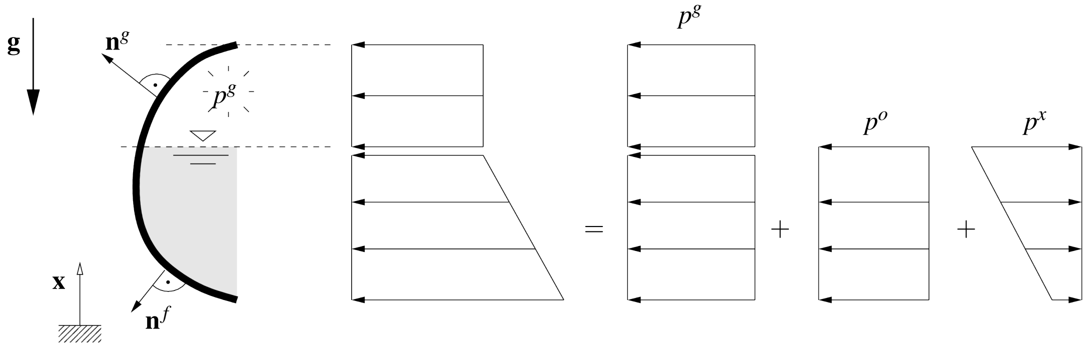


Figure 6: Hydrostatic pressure of a fluid and gas filled chamber

The virtual work of the load vector is a combination of equation (1) and (5):

$$\delta\Pi^f_{ext} + \delta\Pi^g_{ext} = \int_{\Omega^f} (p^g + p^x - p^o)\mathbf{n}^f \cdot \delta\mathbf{u}\, \mathrm{d}\Omega^f + \int_{\Omega^g} p^g \mathbf{n}^g \cdot \delta\mathbf{u}\, \mathrm{d}\Omega^g \tag{6}$$

The update of the gas pressure is performed in analogy to equation (2) in the case of only gas loading. The last two cases and an extension to multiple chambers have been implemented into LS-DYNA following a previous implementation in FEAP-MeKa [9], [7], [5]. For the further theoretical background and its implications for implicit algorithms as well as stability problems we refer to [7], [5], [4].

3 Using LS-DYNA for quasi-static fluid-structure interaction

The first case of only gas pressure in a chamber has already been implemented in LS-DYNA for a long time. With the card *AIRBAG_SINGLE_PRESSURE_VOLUME the described load vector in Section 2.1 is added to the right hand side.
In a current test version of LS-DYNA the additional algorithms for all three load cases presented above have been implemented and the control of the various algorithms is merged to one input card. While using this card, LS-DYNA recognizes by itself which load case is appropriate. The presented equations are for quasi-static loads which are now used in a quasi dynamic simulation. This implies almost zero kinetic energy which can be achieved by applying the load like the gas pressure in Figure 7 fairly slowly.

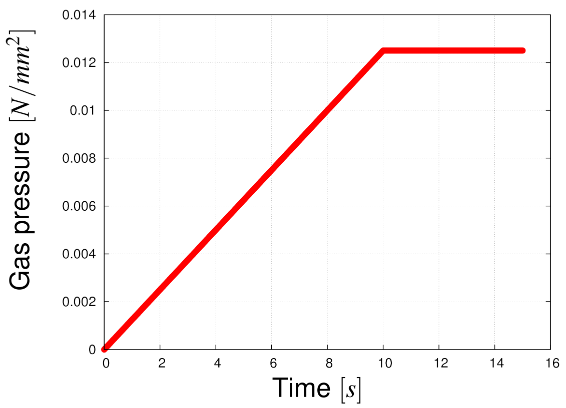


Figure 7: Increasing the gas pressure

The LS-DYNA input has then the following layout for a single chamber:

```
*AIRBAG_FLUID_AND_GAS_ID
$#      id                                                                 title
         1Kammer1
$#     sid    sidtyp      rbid      vsca      psca      vini       mwd      spsf
         2         0         0     0.000     0.000     0.000 150.00000     0.000
$#      xw     xwadd     xwini      pini      tend       rho
       5.0       0.2       6.0       0.0       0.2       0.1
$#    gdir     nproj      idir     iidir     kappa       kbm
        -3         3         0         0       1.0     2080.
```

The input parameters can be subdivided into global and local variables, see Table 1. Global variables apply to all chambers (like gravitation) - if there is more than one -, in contrast local variables like gas pressures belong to a specific chamber.

Parameter	Explanation	Effect
gdir	Direction of gravitation	global
proj	Number of projection directions	global
Idir	If proj $\neq 3$: First direction of projection	global
IIdir	If proj $= 2$: Second direction of projection	global
kappa	Adiabatic exponent (in general 1.4)	global
xwini	Water level at time $t = 0$	local
xwadd	Value of increasing the water level	local
xw	Maximum water level	local
pini	Maximum gas pressure	local
tende	Time, at which pini is reached	local
rho	Density	local

Table 1: Parameters in the LS-DYNA input card

4 Simulation of inflatable dams

An inflatable dam consists of a rubber-fiber-membrane, which is screwed to a concrete bottom plate. The setting can be described by seven independent parameters. Five of them are shown in Figure 8. In addition the two further variables are the length l of the dam and the circumference of the membrane B.

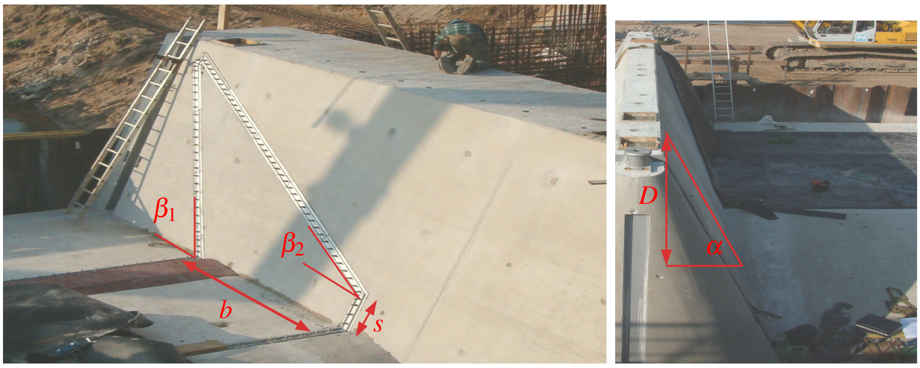


Figure 8: Side dam with a sketch of the rubber fixation

The variable β_1 depends on D, b, s, α and β_2. In the FE model for reasons of symmetry only half of the weir is discretized with shell elements. The thickness of the weir material has been set constant to 14 mm. To simplify the material model first a linear elastic material has been chosen. In doing so numerical problems arise near the wrinkles which can be avoided by e. g. an elastoplastic material model with hardening; in LS-DYNA Material 24 was used.

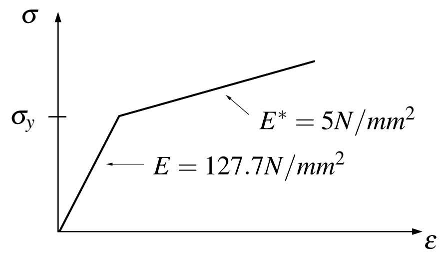


Figure 9: Stress-strain-curve

The concrete is modeled by rigid walls. Since the full simulation model of an inflatable dam is a three chamber model in which all chambers have to be enclosed, the weir is in the simulation model a tub (see Figure 10) with three separate sections. The dam itself is forming naturally a chamber, the upper and lower parts of the tub are the other two chambers for head and bottom water in the simulation model. The walls of the tub allow the calculation of the fluid volume of head and bottom water. In summary the inflatable dam and the tub are discretized with more than 5000 shell elements in a rather coarse model.

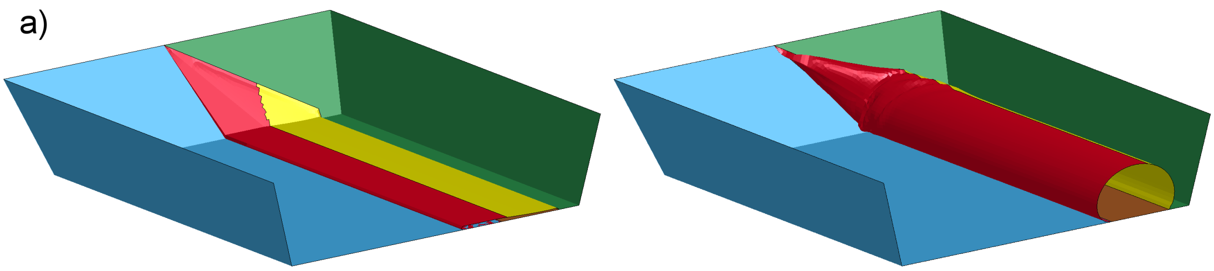


Figure 10: Model: a) initial state of uninflated tube and b) final state of the inflation with gas

4.1 Cooperation with BAW

The Bundesanstalt für Wasserbau (BAW) - Federal Institute for Water Engineering - works on a research project for the measurement and construction of inflatable dams in Germany. As a part of this project some sub-tasks are performed at the Institut für Mechanik at the Karlsruher Institut für Technologie. These sub-tasks are e. g.

- influence of geometry parameters on the large fold and wrinkles
- influence of geometry parameters on the stresses
- multi chamber systems.

Within the bounds of these sub-tasks the following results have been achieved.

4.2 Filling process with a single chamber system

In a first step the inflatable dam was considered without head and bottom water. Based on a geometry of the weir ($l = 30.3$ m, $b = 2.903$ m, $s = 0.4$ m, $R = 3.6$ m, $B = 7.1$ m, $\alpha = 60°$, $\beta_2 = 52°$) different loads lead to different characteristics of the folds and wrinkles. Three different filling types are shown in Figure 11. The different filling types are resulting obviously in different cross-section deformations and in very different folds/wrinkles at the flanges. The fairly high gas pressure results in one dominant fold and a maximum height of the cross-section (see Figure 12), whereas the internal lower water height $xw = 1.5$ m does not lead to a full filling of the complete dam volume in the side flanges and shows a deep fold. Further

Figure 11: Filled inflatable dams with different media and different internal water height

the cross-section looks fairly flat and remains in contact at the bottom water side. The higher internal water height with $xw = 3\ \mathrm{m}$ results in a complete filling of the dam volume and for the chosen geometry to several folds and wrinkles at the sides. The cross-section is wider and does not reach the height of the dam with gas filling but shows only little contact at the bottom water side.

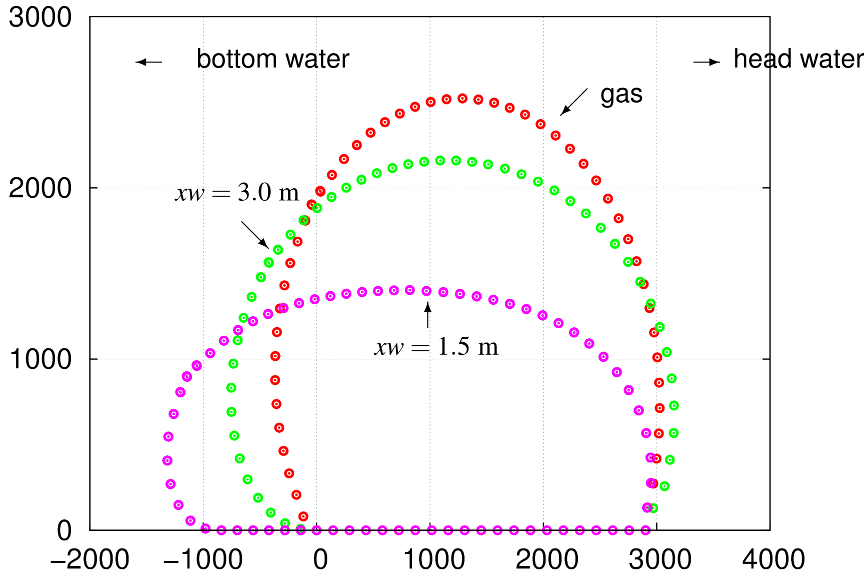


Figure 12: Cross-section deformation for different fillings

4.3 Inflatable dams with head and/or bottom water

In addition to a fluid and/or gas filling of the inflatable dam head and bottom water can be added. For this case three different chambers (implies three different AIRBAG-cards in LS-DYNA) have to be defined. In Figure 10 the first chamber is the inflatable dam (red, yellow and brown section as enclosure), the second chamber is needed for head water (green and yellow sections as enclosure) and the third chamber contains the bottom water (blue and red sections as enclosure). Depending on the filling of the weir, head and bottom water have different effects on the cross-section.

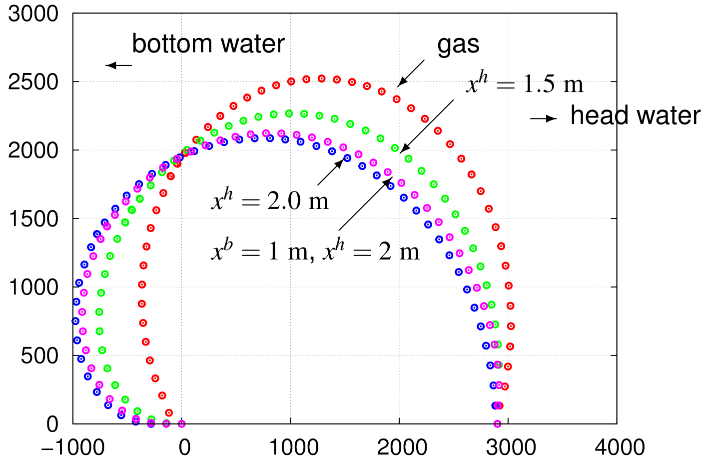


Figure 13: Red: Dam filled with gas ($p = 0.0125\ \mathrm{N/mm^2}$), Green: additional head water ($x^h = 1.5$ m), Blue: additional head water ($x^h = 2$ m), Pink: additional head and bottom water ($x^b = 1$ m,$x^h = 2$ m)

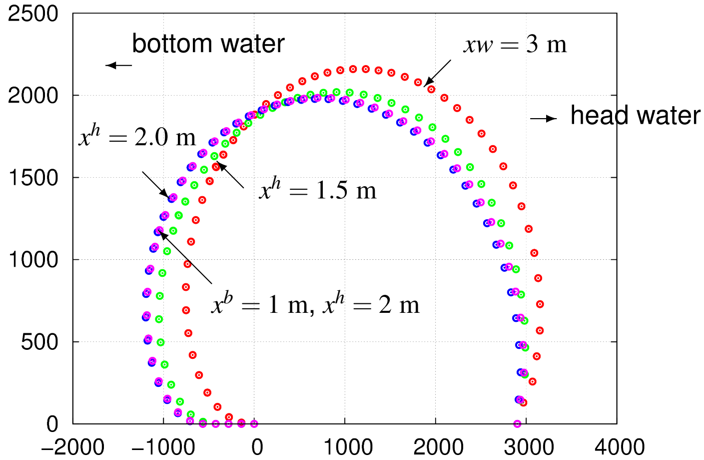


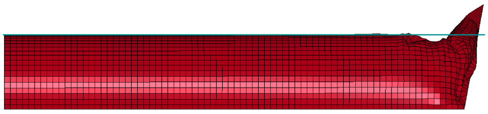
Figure 14: Red: Dam filled with fluid ($xw = 3$ m), Green: additional head water ($x^h = 1.5$ m), Blue: additional head water ($x^h = 2$ m), Pink: additional head and bottom water ($x^b = 1$ m, $x^h = 2$ m)

In Figure 13 the gas filled dam moves to the bottom water side and starts to lay down on the left side when head water is added. If the dam itself is filled with water it shows the same tendency in case of head and /or bottom water however with less deformation. As Figure 14 illustrates, some parts of the dam contact the ground in case of head water.

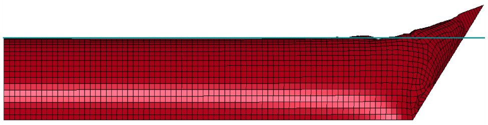
4.4 Reducing the folds and wrinkles

Changing the geometry parameters leads to extremely different distinctive folds and/or wrinkles. For example if the flange angle α is near 90°, there will be a deep fold close to the flange. In contrast if the angle is close to 45°, there will be - depending on also all other geometric parameters - only a small fold and little wrinkling.
To predict if or if not a distinct fold will be formed, a parameter study with about 200 geometric variations has been performed. All computed variations have been classified. An inacceptable dam has a distinct fold through which the head water could flow. An acceptable dam is a closed barrier between head and bottom water with no distinct fold and/or wrinkles. Weirs which can not be classified by these characteristics have been unassigned. Figure 15 shows examples of acceptable and inacceptabe inflatable

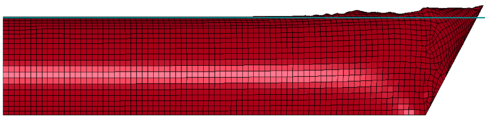
dams. The green line extends the height in the middle of the dam to the side plates to show the depth of the fold.



Inacceptable inflatable dam



Unclassified inflatable dam (small folds and wrinkles)



Acceptable inflatable dam

Figure 15: Influence of parameter variation on folds and wrinkles

After sorting all investigated inflatable dam geometries with respect to the development of the fold/wrinkles, the geometric parameters which are primarily responsible can be defined. One of these parameters is the angle α, which has been explained before. With the following formula (without units) the sorting can be described (lengths in m and angles in $^\circ$).

$$E = \frac{190}{\beta_2} + \frac{\alpha}{42} + \frac{10}{\alpha} + \frac{2.2}{h} + \frac{b}{5.5} + \frac{s}{0.002D} + \frac{B}{0.007b} + \frac{s}{3} + \frac{D}{0.01h} \tag{7}$$

For $E < 7.29$ the parameters result in an acceptable inflatable dam; for $E > 7.29$ an unacceptable inflatable dam is created.
The three most important parameters are α, β_2 and h. While α should be close to 45° to stretch the dam in the side flange, the angle β_2 should be large to have a steep increase of the rubber tube at the sides. The large circumference of the membrane - thus also a larger height h of the dam - leads to more volume which can be inflated at the sides avoiding folds/wrinkles.

5 Conclusions

In case of quasi-static fluid-structure interaction the gas and/or fluid effects as e.g. on inflatable dams can be described by an energetically equivalent loading described via given volumes of gas or fluid allowing a realistic simulation of fluid/gas loading for large deformation problems without discretizing the fluid. This method has been applied to inflatable dams. To investigate the occurrence of wrinkles a three chamber system of dam, head and bottom water has been simulated with LS-DYNA after implementing the corresponding algorithms. The input card in LS-DYNA had to be extended by the *AIRBAG_FLUID_AND_GAS card which can be used for fluid and/or gas filling. As a first result the cross-section of inflatable dams with several load cases has been examined to show that realistic results are achieved. A major result for further guidelines in dam design has been a formula which allows to judge if a constellation of geometric parameters is leading to an inflatable dam with or without major folds/wrinkles.

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