Storm Surge Barrier Ramspol

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ABSTRACT: To protect West Overijssel against flooding due to high water at the IJsselmeer and Ketelmeer an inflatable rubber dam has been designed and is at this moment under construction. This dam will then be the largest barrier of its kind ever built. Since the size of this project is unique, 3D hydraulic model studies have been carried out to verify the dynamic behaviour of the rubber dam during inflation, operation and deflation.

For the strength of the barrier, a rubber body reinforced with an aramid fabric has been developed. Due to the size, new material and unique application it has been concluded that the applicable design standards could not be used. To verify the capacity of the reinforced rubber body a large number of tests were conducted, supported by complex finite element calculations.

From a hydraulic point of view it is concluded that the application of a rubber dam as a storm surge barrier under extreme hydraulic conditions is feasible. After modifications of the geometry, it is also concluded that the capacity of the aramid reinforced rubber body is sufficient to withstand the stresses, introduced by the hydraulic load and local stress concentrations.

1 INTRODUCTION

To protect West Overijssel, a province in The Netherlands, against flooding due to high water at the IJsselmeer and Ketelmeer a storm surge barrier has been designed and is at this moment under construction. The barrier consists of three inflatable rubber dams, which are connected by dikes. (see Figure 1).

The Local Water Authority 'Waterschap Salland' granted the design and construction of the barrier to the Dutch contractor 'Hollandsche Beton- en Waterbouw' (HBW). The design and fabrication of the rubber bodies is subcontracted to Bridgestone, Japan. During the design and construction the Local Water Authority is represented by the Dutch Public Works Department (RWS).

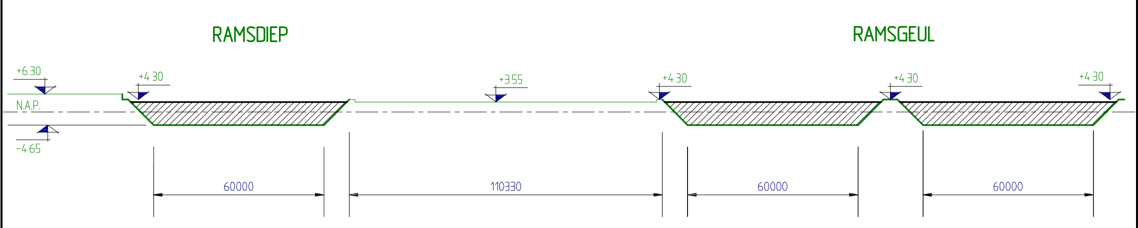

Figure 1. Longitudinal cross-section of the barrier

The size and application of a rubber dam as storm surge barrier is unique. The hydraulic conditions and required safety level are severe compared to existing rubber dams. Therefore the feasibility of the project has been verified with 3D physical model studies and tests to determine the capacity of the applied material.

In chapter 2 first a general description is given regarding the design of the barrier. In the same chapter a brief explanation is given about the performance of the barrier during the different stages of operation based on the above mentioned hydraulic model studies.

Due to the increased forces in the rubber body, as a result of the size and extreme conditions, the design could not revert to proven materials applied for existing dams. A rubber body reinforced with aramid fibres has been developed for this purpose. In chapter 3 an overview is given of all relevant aspects related to the design of such a rubber body.

2 DESIGN OF THE INFLATABLE STORM SURGE BARRIER RAMSPOL

For the total closure three identical dams will be installed with dimensions of 75 m long, 13 m wide and a design height of 8.35 m. The design height has been based on extreme hydraulic circumstances with a probability of occurrence of once every 10,000 years. With these dimensions it will be the largest barrier of its kind ever built.

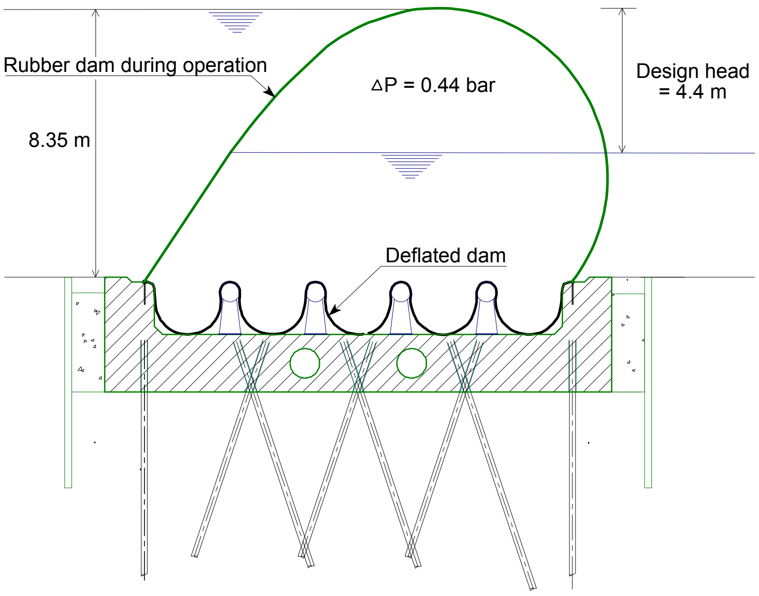

Figure 2. Cross-section of the inflatable dam

Traditionally, most inflatable dams are filled completely with air or completely with water. For the Ramspol Barrier a combination of air and water as an inflation medium is applied. This has been done to minimise the dimensions of the rubber body and the concrete sill and at the same time to optimise the inflation and deflation system of the dam.

2.1 *Inflation of the barrier*

When the water level has reached the alarm level (NAP+0.5 m; NAP = datum) the water pipes, which connect the inner side of the barrier with the upstream water level, are opened. At the same time the air valves on both sides of the barrier are opened and air is blown in by the compressors. As a result the air pressure inside the dam increases to 0.1~0.2 bar. The increase in pressure causes the parts above the abutments to rise above the water level like pillows.

At the same time the water flows in freely due to the water head difference and increased volume. Due to the inflow of the water the sheet comes slowly out of the recess and moves to the downstream side where it rests on the bottom and forms a broad crested weir. This in combination with the pillows causes a contraction of the flow behind the dam.

Meanwhile the dam is further filled with air and water and a so-called V-notch is formed in the middle. Eventually the dam rises above the water level, which causes the volume of the dam to increase. At that moment the barrier has closed off the stream and the hinterland is protected from the storm surge. From that moment the filling with air continues for a while until the air pressure has reached the required level (0.2~0.3 bar).

2.2 *Behaviour of the dam during operation*

Directly after inflation the water head difference will be relatively low (< 1 m). In that case also a low air pressure of 0.2~0.3 bar is required. When the water level is rising to the level as shown in Figure 2, the barrier deforms more to the downstream side. Due to the decreased volume the air pressure will increase automatically to the required level of 0.44 bar.

The inflated barrier also has to withstand dynamic wave loads on top of the static load caused by the water head difference and internal air pressure. Due to the wave loading the barrier responds by variation of its shape, while the internal air pressure fluctuates correspondingly. In addition, and this is a complicating factor, the water inside the dam responds in a sloshing mode.

In order to examine this dynamic response, 3D physical model studies were conducted at Delft Hydraulics. It was found that the barrier responded passively on the waves in a ‘swaying’ mode with frequency equal to the wave frequency (≈ 0.25 Hz). No real dynamic amplifications were observed (Jongeling, 1997).

Other conclusions were that the wave induced forces in the membrane, measured at the clamping line, were different at both sides of the dam. This is contradiction to the static situation where the forces are almost equal over the circumference of the membrane. Another remarkable aspect was the significant effect of the tension stiffness of the applied sheet. The dynamic amplitude of the upstream membrane force more than doubled when the tension stiffness EA was increased from 19,000 to 89,000 kN/m^1 (prototype values).

2.3 *Deflation of the barrier*

When after a storm the water level is reduced, the barrier will be opened again by means of deflation. To ensure complete deflation and safe storage when not in use, a corrugated floor configuration with rotating bars has been designed. In the hydraulic model the process of putting away the sheet in the bottom recess has been studied.

At the beginning of the deflation process the air valves are opened immediately after the start of the water pumps. The pillows on the abutments shrink slowly and in the centre of the dam a notch is formed, where water starts overflowing. The barrier settles further and the mid section sinks below the water surface until it lays on the bottom at the downstream side. From this moment the sheet has to be redistributed over the five troughs.

In first instance the sheet is for the greater part sucked into the first trough seen from the downstream side (see Figure 3). Subsequently redistribution of the sheet across the recess takes place, but in the final situation only the first two troughs are fully filled, while the sheet in the last three has no contact with the floor. During the model tests sometimes a large fold remained in the first trough, but in all cases the fold stayed well below the top of the concrete sill.

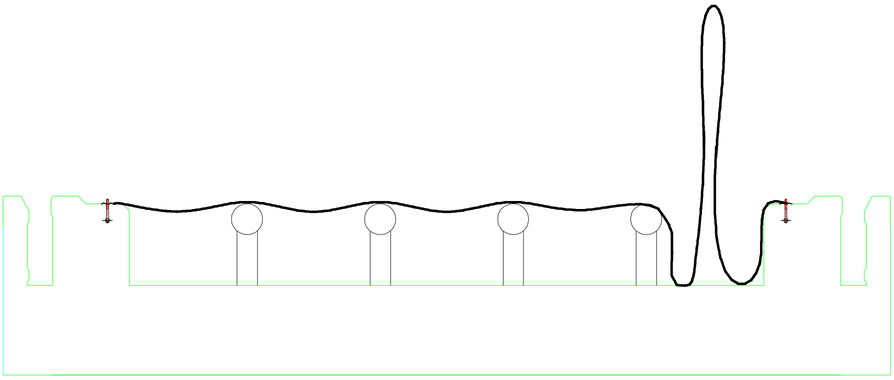

Figure 3. Position of the rubber sheet during deflation

Besides the hydraulic model tests a calculation method was developed for the deflation phase. The distribution of the rubber sheet over the five troughs could be calculated very well with the help of three equilibrium equations and the geometrical boundary conditions (dimensions, height and distance of the rollers). From this calculation model it was found that the bearing friction of the rollers determined *how* the sheet is redistributed and the friction between the sheet and the bottom *if* the sheet can be redistributed.

3 DESIGN OF THE RUBBER SHEET

In general an inflatable dam is made of rubber coated fabric. The fabric, which is normally made of nylon, gives the dam the strength to withstand the tensile force caused by the internal pressure of the dam and the external water pressure. The rubber plays the role of maintaining the air and water tightness of the rubber dam and of protecting the fabric.

Due to the increased forces in the rubber body the design for the Ramspol project could not revert to proven materials applied for existing dams. A rubber body reinforced with an aramid fabric has been developed for this purpose. The rubber body consists of one layer of aramid fabric and four layers of nylon fabric for the forces in warp and longitudinal direction respectively. On both sides, the inner and outside, the fabric is protected with a layer of rubber. The total thickness of the rubber body is 16 mm as can be seen in Figure 4.

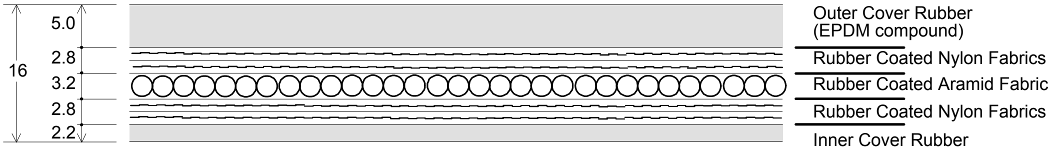

Figure 4. Rubber sheet reinforced with an aramid fabric

The average initial strength of this rubber sheet in the direction of the aramid is approximately 1,960 kN/m^1. Due to the different materials, the rubber body is an extremely orthotrope material. The material properties in warp and longitudinal direction differ quit a lot (all values apply to a width of one meter):

- Tension stiffness in warp (aramid) direction: EA_{warp} = 30,000 to 50,000 kN/m^1;
- Tension stiffness in longitudinal (nylon) direction: EA_{long} = 2,100 kN/m^1;
- Bending stiffness in all directions: EI = 10 Nm^2/m^1;
- Shear modules: G = 105 kN/m^1.

3.1 *Design practice for 'normal' inflatable rubber dams*

In 1995 it was reported that there are approximately 2,000 inflatable rubber dams constructed in the world (Dakshina, 1995). They are applied in the USA, Norway, Australia and other countries, the majority however, approximately 1,800, is installed in Japan. This is probably also the reason why only the Japanese have a design manual for this type of structure.

According to the Japanese Standard the initial design tensile strength should be 8 times the static load, calculated for a two dimensional cross-section. This general safety factor covers all material aspects like ageing, fatigue, etc. and additional loadings caused by earthquake, dynamic wave load, etc.

To what extend this standard could also be applied for the rubber sheet reinforced with aramid was questioned. Not only due to the application of a new material, but also due to the application of a rubber dam as storm surge barrier and the scale of the project. During the design of the barrier it was investigated what kind of factor is required for a rubber barrier reinforced with aramid.

3.2 *Design considerations for the aramid sheet*

During the tender design the strength of the rubber sheet was based on the above mentioned overall safety factor of 8. During the detailed engineering this was verified by means of model tests and additional calculations. The evaluated aspects can be more or less divided into three categories:

1. Material factors to take into account the deterioration of the aramid;
2. General partial safety factors to meet the required probability of failure;
3. Load factors like the dynamic loading and stress concentrations.

The last two categories are more or less related to the overall design and depend on the geometry, fill medium and required level of safety. The first category is related to the behaviour of the material aramid, embedded in the rubber body. Based on earlier studies (Breen, 1996) the following relevant material related aspects were selected and evaluated:

- Creep;
- Water absorption;
- Ageing;
- Fatigue;
- Clamping effect.

To take the combined effect of above aspects into account, a representative test has been conducted which included all aspects at the same time; A fully saturated sample of the rubber sheet was clamped in the clamping system (see Figure 5) and artificially aged in a water tank at 70°C during 500 hours to represent the design life of 25 years.

After the aging a fatigue load was applied, representative for 25 years, with the rubber sheet still in the clamp. In addition to this a fatigue load at a higher load level was applied to represent the extreme design storm conditions. At the end of the test the sample was taken out of the clamp and the remaining capacity was determined (during the last test series the remaining capacity was determined with the rubber sheet still in the clamp).

Since this test is performed many times with different load levels, clamping structures, sheet orientation, etc., it is difficult to give one general conclusion for the rubber sheet reinforced with aramid. Therefore first the load levels are discussed in the following section before in section 3.4 an overall conclusion is given.

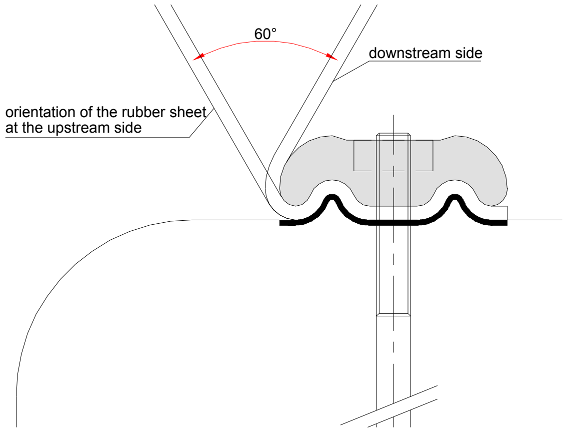

Figure 5. Applied clamp system to connect the rubber sheet to the foundation

3.3 *Design load for the rubber sheet*

By means of a semi-probabilistic design method (similar to the Eurocode) the design water levels have been determined given the required probability of failure of 10^{-5}/year for the rubber sheet. This resulted in an upstream water level of 7,65 m, with a corresponding head across the barrier of 3.25 m and an internal air pressure of 0.37 bar. With the help of a differential model the corresponding static membrane force F_{static} in a two dimensional cross-section has been calculated which is equal to 200 kN/m.

Due to extreme wave loading, as shortly discussed in section 2.2 , the total load is increased to 340 kN/m at the upstream side. At the downstream side the total load is limited to 230 kN/m. When the dynamic loading is expressed as a factor to the static load (similar to the Japanese standard), this does result in dynamic coefficient of 1.7 and 1.15, for the upstream and downstream side respectively.

The above loadings are applicable for the horizontal section. But as can be seen from Figure 1, the transition between the horizontal section and the dikes are formed by abutments on both sides with a slope of 1:1. Due to geometrical reasons (which are not further discussed in this paper) the sheet has to be folded on the abutment over a length of approximately 2 m as shown in Figure 6.

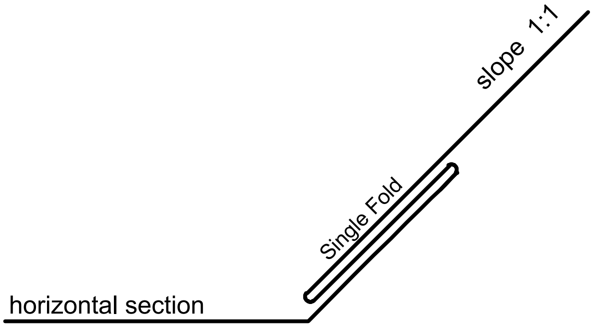

Figure 6. Sketch of clamping line at the lower corner of the abutment

Such a complex geometry could no longer be calculated with a two dimensional model. For this purpose the finite element program MARC was employed. Due to the applied geometry of the Single Fold and the material characteristics of the rubber sheet, this was quit a challenge. An example of such a calculation is given in Figure 7.

From these calculations it was found that in the area of the so-called Single Fold the load is not distributed equally over the three layers. In fact, some parts of the rubber sheet do not contribute at all. Other parts attract a lot of tension towards a relative small location. This result is mainly introduced by the relatively high tension stiffness of the aramid reinforced rubber sheet in warp direction in combination with the complex geometry.

Figure 7. Calculated geometry for the inflated condition

Preliminary calculations showed that the stresses along the clamping line could vary between 0 and 6 times the calculated stress at the horizontal section (i.e. from 0 to 1,200 kN/m for the static situation). Together with the dynamic load and material factors for ageing, etc., the rubber sheet would fail with such high stress concentrations.

On most locations, however, the stresses could be reduced considerable, by relatively small geometric modifications. Finally a geometry was found where the stress concentrations for the upstream side are not higher than 2.2 and 3.0 for the downstream side (where the stress concentration factor is defined as the local stress divided by the membrane force at the horizontal section). The tests, as described in the previous section, showed that these stress concentrations could be handled by the rubber sheet with aramid reinforcement.

3.4 *Conclusion on the capacity of the rubber sheet with aramid*

The relative simple approach with one general safety factor of 8, as prescribed in the Japanese Standard, is for the Ramspol Storm Surge Barrier not suitable. A better approach for this kind of constructions would be:

$$\frac{R_{init}}{\gamma_R \bullet \gamma_{mat}} > \gamma_{dyn} \bullet SCF \bullet F_{stat} \qquad (1)$$

Where:

F_{stat} = static membrane force for a two dimensional cross-section [N/m]

R_{init} = initial strength of the rubber sheet [N/m]

SCF = stress concentration factor [-]
γ_{dyn} = dynamic factor as defined in section 3.3 [-]
γ_{mat} = a factor which includes all material related aspects as mentioned in section 3.2 [-]
γ_R = partial safety factor (not discussed in this paper) [-]

For the Ramspol project, with a rubber sheet reinforced with aramid, it was found that the material factor γ_{mat} is in the order of 1.5 to 2.2, depending on the applied load level. The dynamic factor is equal to 1.7 and 1.15 for the upstream and downstream side respectively. With these factors there is still sufficient margin for the stress concentrations as calculated by MARC.

4 CONCLUSIONS

From a hydraulic point of view it is concluded that the application of a rubber dam as a storm surge barrier under extreme hydraulic conditions is feasible. During inflation, operation and deflation, the rubber sheet could be controlled very well and no unexpected or undesirable phenomena were observed.

Due to the unique size of the barrier, and the application of a new material, relatively high local stresses occurred in the rubber sheet. With the help of relatively small geometric modifications, these stress concentrations could be brought back to an acceptable level.

Based on the performed hydraulic model tests, finite element calculations and tests on the reinforced rubber sheet, it is also concluded that the application of aramid as reinforcement is feasible for the storm surge barrier Ramspol.

REFERENCES

Breen, J., 1996, *Sterktedoek voor balgstuw, phase 1 to 9*, BU3.96/xxxxx/JB, TNO Kunststoffen en Rubber Instituut, Delft

Dakshina, C.M., Reddy, J.N., Plaut, R.H., 1995, *Three-Dimensional Vibrations of Inflatable Dams*, Thin Walled Structures, Vol. 21, No. 4, p. 291-306

Jongeling, T.H.G., 1997, *Balgkering Ramspol - Functioneren van de kering in gebruiksomstandigheden*, Report on scale model study, WL | DELFT HYDRAULICS, Q2258-A, December 1997 (in Dutch)

The Japanese Institute of Irrigation and Drainage, 1989, *Engineering Manual for irrigation & Drainage*, Headworks