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Sarvsfossen Dam

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After 2,5 years construction time, in September 2014 the 50 meter high double curvature Sarvsfossen dam was completed in Bykle in the Aust-Agder province as part of the 'Brokke Nord/Sør' project. It is the largest concrete dam built in Norway since the 1980s. The structure dams the river Otra that flows south through the valley of Setesdalen. The annual energy output of this hydropower-project is 69 GWh. Together with additional energy from existing stations downstream, a total of 175 GWh of renewable energy has been added to the regional grid. Along the 145 m long dam crest a concrete bridge is built, connecting the Bykle community center in the west to the rural district Stavnes in the east.

Design

Sarvsfossen (photo 1) is the largest concrete arch dam built in Norway since the Alta dam built in the 1980s. In this respect, it is a unique structure in Norwegian context. The dam thickness tapers from 6.5 m at the bottom to 2.3 m at an elevation of 43 m higher. The total concrete volume is approximately 19 000 m^3. The dam is not anchored to the bedrock by bolts, but relies on its selfweight and the double curvature shape to transfer loads into the abutments. In simple terms the water pushes the arch structure towards the abutments.

The general purpose finite element (FE) software Ansys, and a post-processor software performing non-linear concrete design of reinforced shell elements, MultiCon (Brekke et al. 1994, Multiconsult n.d.), was used for the design of Sarvsfossen dam. This has been the preferred tool for design of several large concrete structures in the offshore industry. This analysis package has been applied to model dam structures as they have many similar attributes to a typical gravity base concrete structure (GBS).

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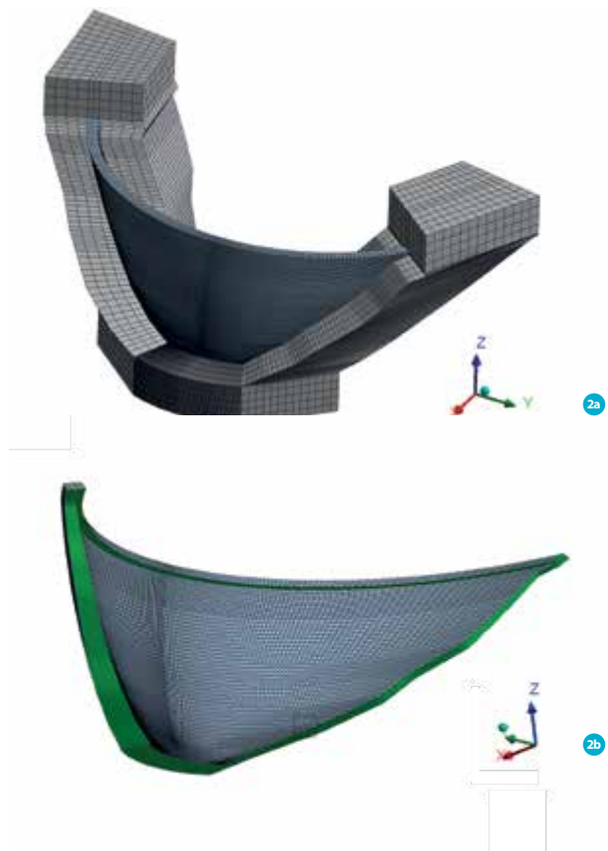
1 The Sarvsfossen dam and bridge from downstream side
credits: Multiconsult
2 FE model with solid element mesh: (a) dam and bedrock (view upstream), (b) dam (view downstream)
3 Deformation of dam with full reservoir (deformation scale 400:1): (a) Vector sum of displacement [m], (b) vertical deformation [m]

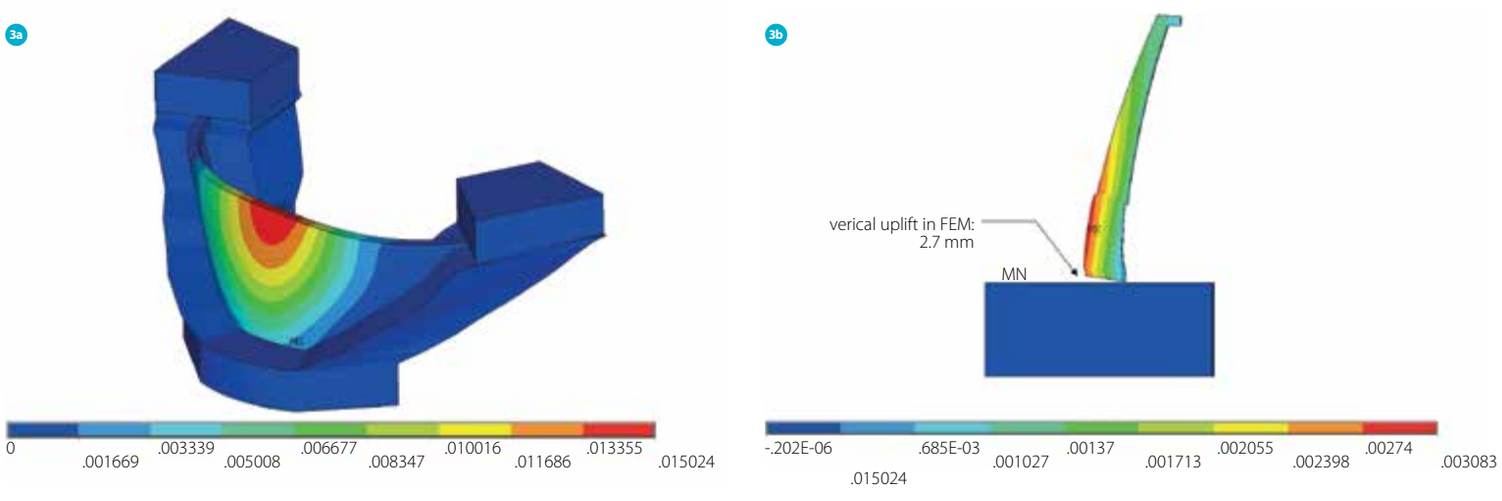


The FE model of the dam, which consist of solid elements, is illustrated in figure 2. The model includes a bedrock volume which provides an elastic foundation for the dam. Between the concrete and bedrock elements, there are contact elements that can simulate sliding and/or uplift in the contact interface. The contact introduces non-linearities in the FE model (NLFEA). The contact region is illustrated in green in figure 2b.

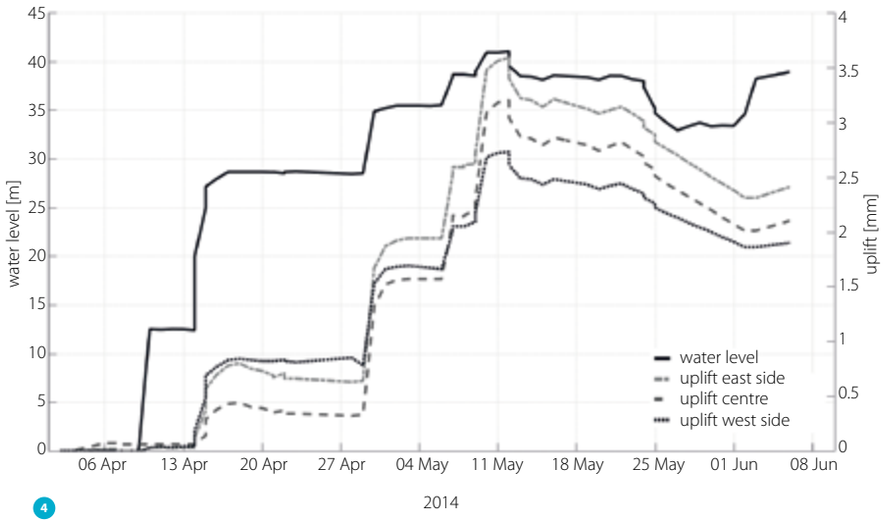
In addition to several water level configurations, ice, temperature and earthquake loads are simulated in the FE analysis (FEA). The rules for combination of loads, including applicable load factors, follow Norwegian Water Resources and Energy Directorate's guidelines for concrete dams (NVE 2005). This document states that the currently applicable Norwegian design code for concrete structures should be used, but with some special rules on e.g. load factors. The Norwegian Dam Regulations refer to general use of Eurocode 2: Design of concrete structures (Norwegian Standard 2008). This standard was initially used as a basis for design in agreement with the Norwegian Water Resources and Energy Directorate. However, due to its good track record for concrete structures with large shell thickness in a marine environment it was later decided to use the previous general concrete standard NS 3473 (Norwegian Standard 2003) as design framework. This standard has a good reputation from design of offshore concrete structures, including Concrete Gravity Base Structures (GBSes) in the North Sea. It is still used for this type of application. Through the process, it was also found that the shear tension capacity for concrete sections with large thickness is significantly higher in NS 3473 compared to Eurocode 2.

Simulation vs. on-site measurements

It was considered important to introduce contact interface elements in the FEA since no anchoring of the reinforced concrete to bedrock was part of the design of the dam. If the dam was modelled fixed to the bedrock, this would lead to very high reinforcement intensities in the vertical direction in the lower part of the dam on the water side due to clamping of the three-dimensional shell structure. This was found unfeasible since it would require a large amount of anchors/bolts and consequently it would increase the construction cost substantially. Modelling the dam



4 Relation between the water level and uplift of the upstream dam toe
5 Construction of the dam
credits: Multiconsult
6 Section of transition between foundation block and bottom of dam
7 Overview of dam site
credits: Otra Kraft



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as fixed to bedrock would also underestimate lateral deformations. Lateral deformations of the dam were important in the design of the bridge structure.

As a consequence, it was decided to simulate the global response due to various load conditions in terms of non-linear contact analyses and rely on the dam's curvature vault shape to transfer forces to the abutments where uplift and sliding were permitted. The deformation of the structure for a typical load combination including water pressure is presented in figure 3. The plot to the left shows the vector sum, i.e. a combination of the three translational deformation components, in an isometric view, while the plot to the right shows the vertical deformation component in a section through the dam center. An uplift effect is observed at the bottom of the dam on the water side. Note that water pressure in the interface between bedrock and concrete was included with a linear distribution from the upstream side to the downstream side to simulate the effect of water intrusion.

In order to monitor the uplift during execution and operation of the dam, it was decided to install extensometers on three locations on the water side of the base of the dam before water filling was initiated. These extensometers measured separation between bedrock and the concrete structure above. Data from the extensometers are presented in figure 4. The measured uplift values are given together with the water level.

The measurements were conducted continuously through the first filling sequence of the dam after construction completion in April 2014. Good agreement with the predicted uplift in the FEA was observed. Both the water level for which uplift was initiated and the final uplift value for a full dam reservoir, were predicted with good accuracy. For the full dam reservoir a maximum vertical uplift of 3.5 mm was measured (fig. 4), while the maximum uplift was estimated to 2.7 mm in the FEA (fig. 3).

Construction

Initially the contractor investigated the use of sliding formwork for construction of the major part of the dam. The complex, double curvature shape combined with the asymmetrical layout proved this technique to be neither technically nor economically feasible. It was concluded to construct the dam in 5 m lifts divided horizontally in sections approximately 9 m wide resulting in 128 blocks to be cast. A Doka formwork system was used (photo 5). Towards the eastern abutment, the rock excavation on the upstream face was carried out as smooth excavation including stitch drilling. As a result, this face of the rock acted as the formwork for the twisting dam and the connection was improved by anchoring reinforcement in the rock.

Shear keys with upstream and downstream water stops were designed for both horizontal and vertical joints. A double set of injection hoses was installed, one for use before and one for use after impoundment. The reinforcement is continuous over both vertical and horizontal joints. There are wedges in the vertical edges of the separate casting phases to improve the interaction, especially on shear.

The predicted uplift of the upstream dam toe required careful considerations concerning water tightness of the foundation. The FE model showed the contact area to be relatively small in the bottom part of the dam while the contact area was larger in the sloping parts of the foundation. Due to poor quality of

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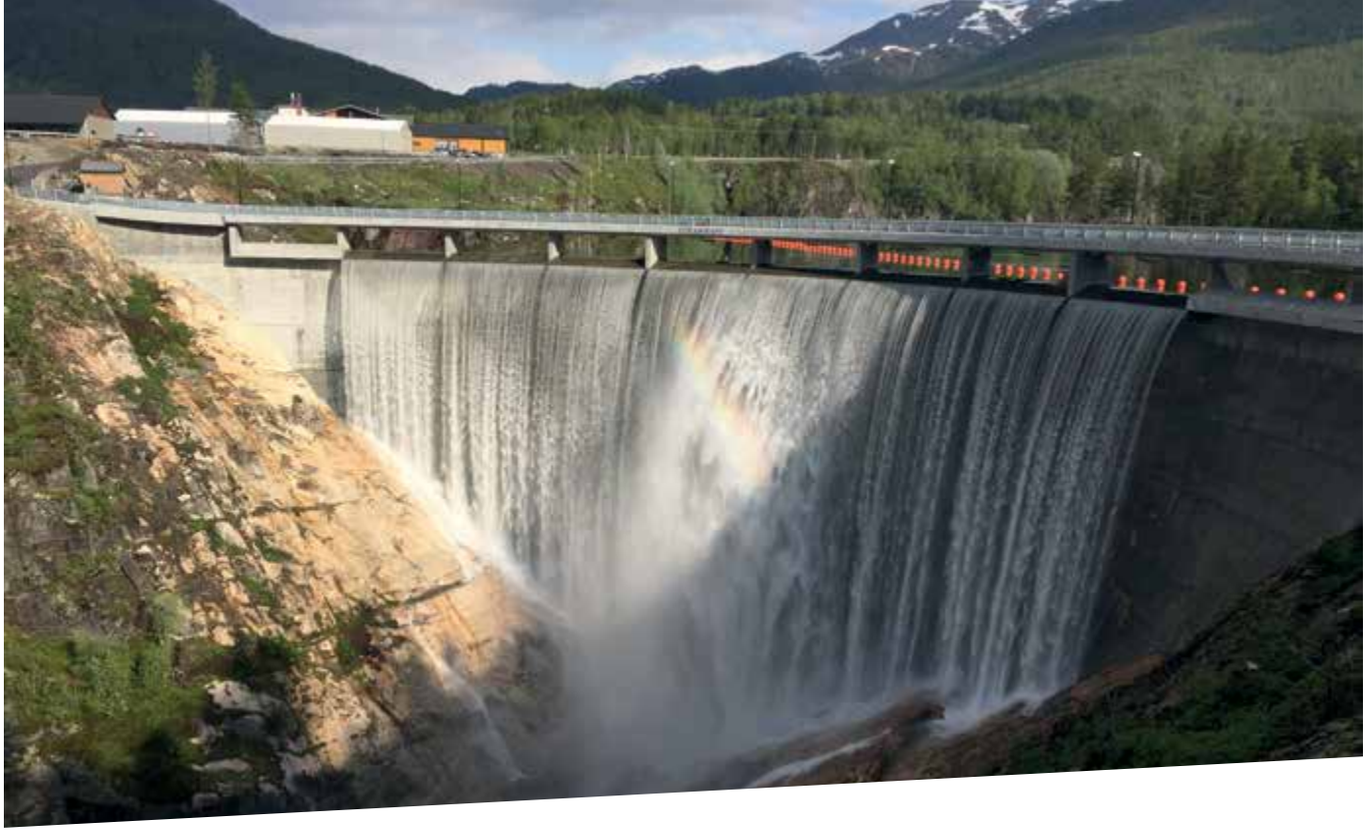

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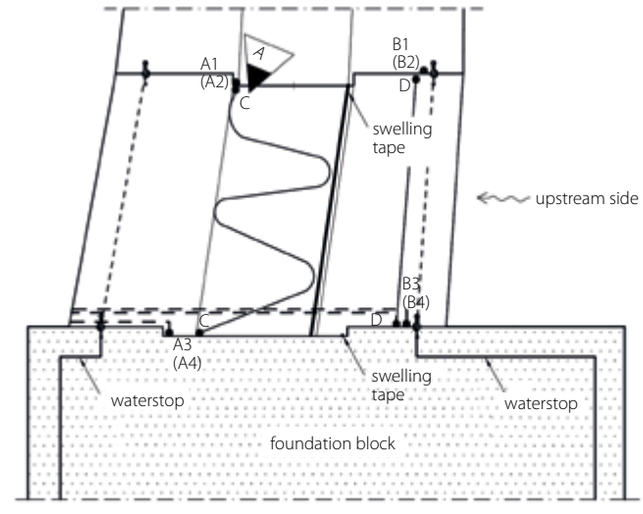
the bedrock, it was decided that a horizontal 30 m wide foundation block in the middle, underneath the dam required deeper excavation, i.e. 5-8 m. This block was cast with an expansion joint towards the dam (fig. 6). A shear key with an upstream and downstream water-stop and a swelling tape in the middle was installed. This measure should prevent leakage in the joint between the bedrock and the concrete caused by uplift of the dam toe. The completed dam structure is illustrated in photo 1 and 7.



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Conclusion

In the Sarvsfossen project it has been favorable to establish a 3D finite element model with solid elements for concrete design purposes. This allows for estimations of the structural response without the need for (costly) conservative approximations. Using specialized design software for concrete shell structures, the necessary reinforcement amounts where efficiently calculated, satisfying relevant requirements in the ultimate and serviceability limit state. In particular, it was important to represent the complex geometric shape of the large concrete shell structure and its boundary conditions appropriately. After completion of the dam, this has been confirmed by on-site measurements that show satisfactory agreement with simulated data. It was concluded that one could solely rely on the geometric shape of the structure and its selfweight to transfer loads to the abutments. This facilitated a faster construction schedule and economic savings. ☒

Acknowledgements

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REFERENCES

1 Lindemark, J., Aasheim, E. E., Mork, R. O., & Bjønnes, T. (2015). Sarvsfossen Dam – Design of a Norwegian Concrete Arch Dam, ICOLD 25th Congress / ICOLD 83rd Annual Meeting, Symposium Hydropower'15.

2 Brekke, D.-E., Åldstedt, E., & Grosch, H. (1994). Design of Offsore Concrete Structures Based on Postprocessing of Results from Finite Element Analysis (FEA): Methods, Limititations and Accuracy, Proc. Of 4th Intl. Offshore & Polar Engineering Conference.

3 Guidelines for concrete dams (2005). Oslo: Norwegian Water Resources and Energy Directorate (NVE). Multiconsult. (n.d.). MultiCon - Concrete shell design post-processing program (developed by Dan Evert Brekke).

4 Ansys. (n.d.). www.ansys.com.

5 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. NS-EN 1992-1-1:2004+NA:2008. Norwegian Standard (2008).

6 NS3473: Concrete structures - Design and detailing rules (6th edition). Norwegian Standard. (2003).