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Comparing field data with numerical simulations of ice loads on dams

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Ice loads are core design criteria for hydropower dams in northern regions. They are responsible for a significant proportion of the design load of small dams that are typically used in Norway. In spite of their importance, the magnitude and regional variability of ice loads are still poorly understood and current regulations rely on limited amounts of field measurements. In order to develop tools and procedures for ice load predictions, numerical simulations have been compared with field measurements. This study presents preliminary results from 3-D numerical simulations of thermal ice loads in a small reservoir. Simulations are driven by measured air temperature data. The impact of inhomogenous boundary conditions is investigated with respect to snow depth distribution, ice cover thickness, and confinement. Simulations are compared with temperature and stress measurements in the ice. The results show that 5-week period of stresses can be simulated without periodic re-initiation of the model, that periods of disagreement between model and observations coincide with extreme events due to mechanical forcing or melting temperatures, that snow cover and boundaries have a significant but manageable influence on ice stress, and that agreement between thermal stresses modeled with a thermoelastic model and measurements is promising.

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1 Introduction

Thermal expansion and water level changes have been identified as key processes leading to static stresses in the ice cover of reservoirs (e.g., Carter et al., 1998; Comfort et al., 2003; Stander, 2006; Petrich et al., 2015). However, in spite of a number of analytical and numerical studies of ice loads (e.g., Bergdahl, 1978; Azarnejad and Hrudey, 1996; 1998; Ekström, 2006), Gebre et al. (2013) recently asserted that general models for the estimation of ice loads are still not fully verified and accepted and concluded that there is a need for research to develop and validate numerical ice load models. Such models could be used to improve dam design.

Based on ice stress measurements during the winter of 2013/14 (Petrich et al., 2014), this study investigates numerically the influence of boundary conditions on stresses within the ice cover of a small reservoir. For this purpose, results are based on a thermoelastic model that does not account for fracture or creep of the ice cover. It had previously been shown that a thermoelastic model can reproduce transient features of stress distribution in this reservoir (Petrich et al., 2015).

2 Methods

Thermal stresses were simulated with the LS-DYNA general purpose finite element code (Hallquist, 2006). The temperature field in the ice was determined from 1-dimensional heat transfer with phase change, driven by air temperature in 2014. Absorption of solar radiation in the ice was not considered. Based on the simulated temperature field, 3-dimensional thermoelastic stresses were calculated in ice and dam using solid elements. The numerical domain included a vertical, elastic concrete dam of 1 m thickness, 6 m height (z-direction) and 30 m length (y-direction), and a 30 x 30 m^2 ice cover. The dam was fixed at its base and otherwise free to move (i.e., bend). The square-shaped ice cover is a simplification of the real shape of the reservoir (Petrich et al., 2014). The thickness of the simulated ice cover was 0.8 m except near the dam, where it increased slightly (Figure 1). Ice thickness near the dam was derived from the temperature profiles measured by the stress cells.

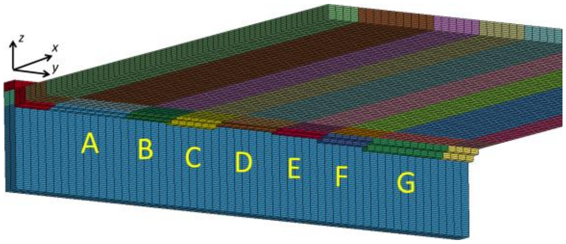

Figure 1. Illustration of the numerical domain with the ice cover seen from below. Note the non-uniform ice thickness at the dam. Colored stripes highlight the respective lateral positions of stress sensor stations A through G at the dam.

The air–ice heat transfer coefficient was set to 50 W/m^{2}K based on air temperatures measured 5 cm above the ice surface. Ice was allowed to melt with a latent heat of $L=3.34\times10^5$ J/kg, and density, heat capacity and thermal conductivity were 910 and 1000 kgm^{-3}, 2100 and 4200 Jkg^{-1}K^{-1}, and 2.2 and 0.58 Wm^{-1}K^{-1} for ice and water, respectively. The dam had an elastic modulus of E=32 GPa and Poisson ratio ν=0.2 and the elastic modulus, Poisson ratio, and thermal expansion of the ice were E=6 GPa, ν=0.3 and $\alpha=50\times10^{-6}$ K^{-1}, respectively. Gravity and buoyancy forces were not included in the simulations and as a result, water level fluctuations in the reservoir were not considered. The finite element mesh was rectangular with 0.5 x 0.5 m^2 cross-sectional area and 0.1 m thickness. The numerical time step was Δt=60 s and solutions were obtained through implicit time integration.

Stresses under different boundary configurations were investigated (Figure 2). In all cases, LS-DYNA surface–surface contact elements were used to couple the elastic dam with the ice. In the reference scenario (MAIN, Figure 2) ice was free to move in vertical (*z*) direction at boundaries perpendicular to the dam while being fixed and prevented from moving opposite the dam. In one scenario (RAND2), ice was free to move in direction perpendicular to the dam (*x*-direction) opposite the dam, while two scenarios contained completely unconstrained sections (RAND). One scenario simulated a temperature differential due to increased snow cover in one quadrant (CONV), assuming a reduced heat transfer coefficient of 10 W/m^2K in this area.

All simulations started on 29 January 2014, 06:00 and were run for at least 5 simulated weeks. The start point was chosen for convenience of model initiation as the measured ice temperature profile was linear at that time.

Compressive stresses are positive in this study, consistent with the way stresses were measured. Stress measurements were performed with arrays of three custom-modified GEOKON stress cells, 200x100 mm^2, vertically spaced 150 mm. The cells register stress normal to their plane. A detailed description of the measurement set-up has been given by Petrich et al. (2014). In this study, comparisons are made with cell “D-top”, which was located at the center of the dam, 0.55 m from the ice–air interface beneath 0.4 m of superimposed ice.

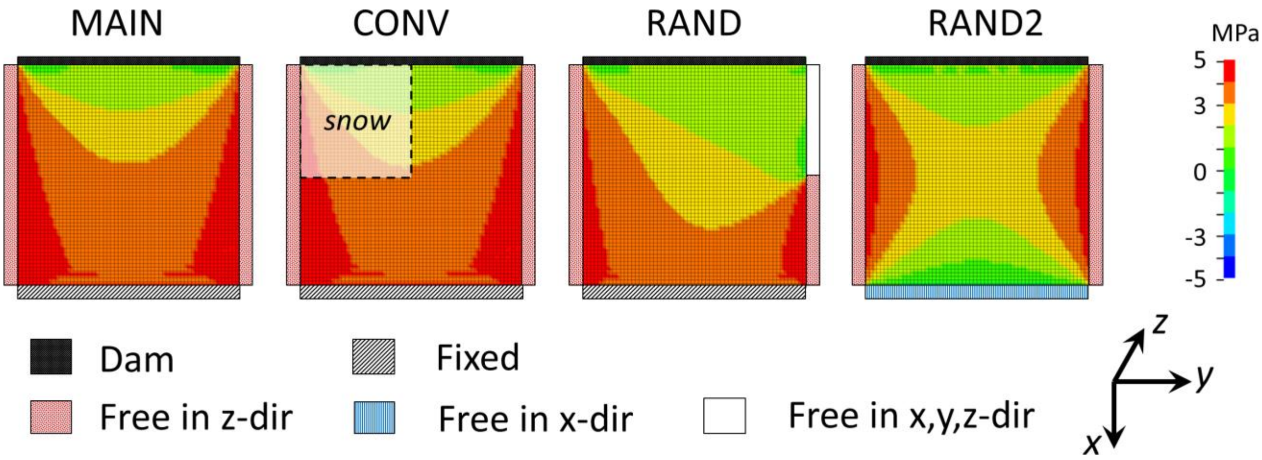

Figure 2. Illustration of boundary configurations with simulated magnitude of the surface stress field in *x*-direction (i.e., normal to the dam) at the end of an exteded warm spell on 12 Feb 2014. Note that compressive stresses are positive.

3 Results and Discussion

In order to verify the heat transfer model, Figure 3 compares measured and modeled temperature profiles during a 24-hour warming event. The thermal model traces the measurements well, indicating that heat transfer through the ice is implemented corrected. However, the long-term comparison with data in Figure 4 (discussed in more detail below) suggests that, in general, the model reacts to air temperature changes too strongly. This could result from a heat transfer coefficient that is too great. In addition, the LS-DYNA phase transition model had not be verified due to lack of controlled data and the variablility of the snow cover and snowmelt have not been accounted for. However, since ice stresses are more sensitive to changes in ice temperature than to absolute ice temperatures (e.g., Petrich et al., 2015), modeled stresses will be discussed next.

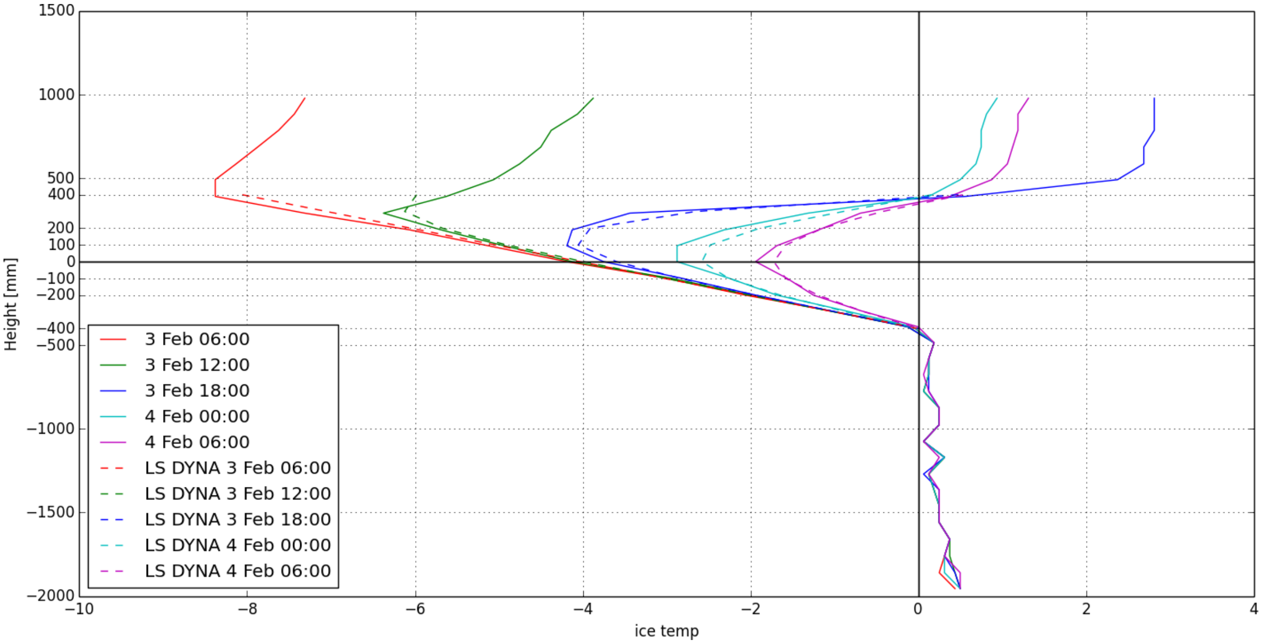

Figure 3. Comparion of modeled with measured temperature profiles. Ice extended from +400 to -400 mm with air and water above and below, respectively. The 0-level marks the equilibrium water level of the reservoir, i.e. ice above 0 is superimposed ice. Measured temperatures were not calibrated.

Figure 4 compares measured stresses of one particular cell ("D-top") with model output at two vertically adjacent nodes ("num_top-1" and "num_top-2"). The true location of the stress cell should correspond to a point between those two nodes. The discussion is divided into 7 periods as indicated in Figure 4. Correspondence between measurement and model is generally good with the measurements coinciding with numerical node "num_top2". Assuming a higher *E*-modulus for ice could have moved the measurements between "num_top-1" and "num_top-2". A systematic exception to the general good agreements occurred during Period I, when the water pressure dropped and rose again by 2 kPa (i.e., 0.2 m water column equivalent) on two occasions, i.e. over the course of 6 and 3 hours on 1 Feb and 4 Feb, respectively. The event on 4 Feb was recorded by a timelapse camera during daytime and showed that this corresponded to a vertical drop of the ice surface and subsequent rise. Measured ice stress dropped during the event on 4 Feb (cf. arrow in Figure 4). Modeled ice stresses are consistent with measurements except between 1 and 4 Feb when the model failed to reproduce the observed compressive stress. While we cannot explain this failure conclusively we hypothesize that ice stresses during this time were at least partially due to mechanical forces other than thermal expansion. For example, water level changes can lead to ice stresses through various mechanisms (cf., Comfort et al., 2003; Stander, 2006; Petrich et al., 2014; O'Sadnick et al., 2016). The modeled stresses trace the measured stresses nicely during Phase II. In Phase III the thermal model did not deal correctly with phase transition due to temperatures above freezing, which lead to a modeled peak stress that has not been observed. This issue needs further investigation and may be related to the coarse mesh of 0.1 m vertical resolution. The modeled stresses trace the measured stresses nicely during Phases IV and V. However, measured stresses dropped suddenly during a period of cooling at the beginning of Phase V. This sudden drop was most likely due to ice fracturing, a process that the current model does not capture. Simulations in Phase VI are again affected by issues related to the phase transition, a situation the model seems to recover from in Phase VII.

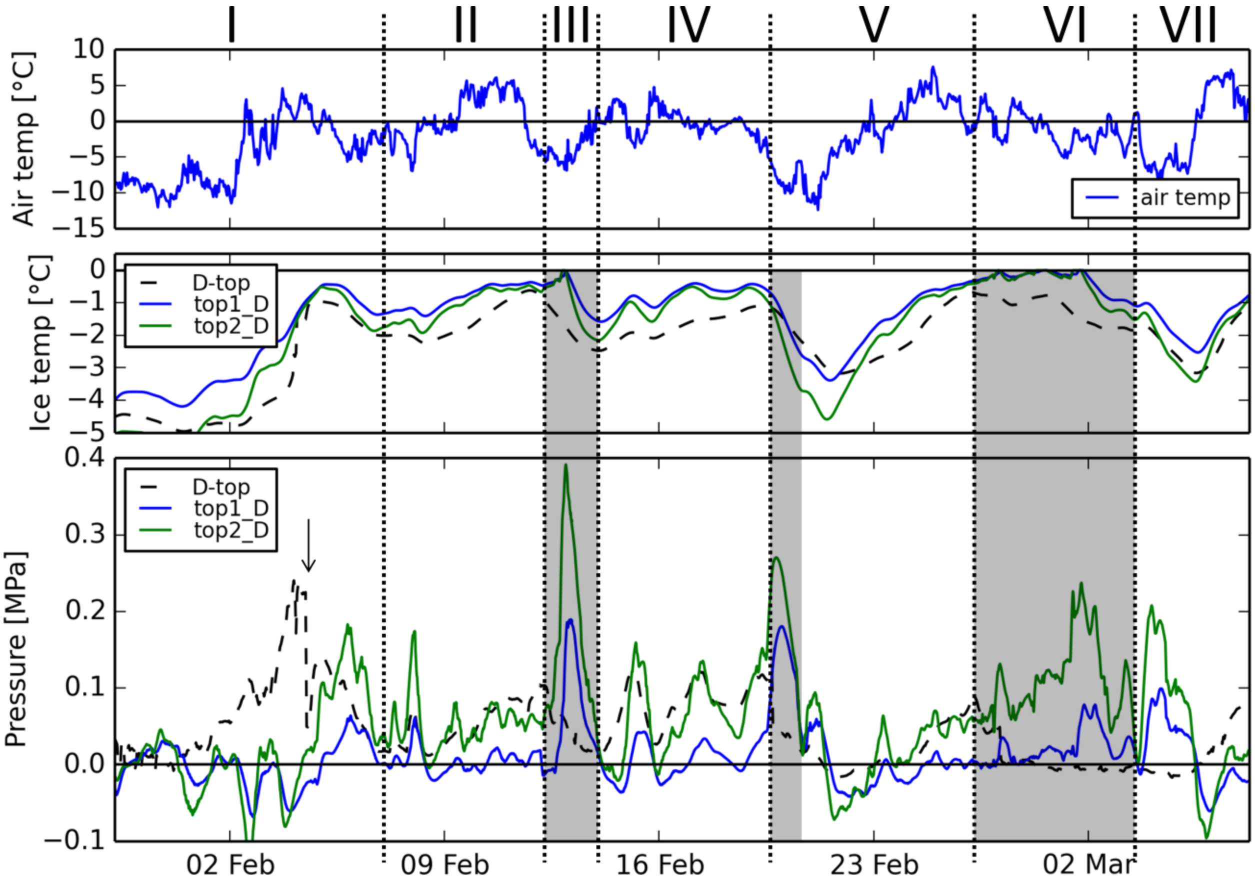

Figure 4. Measured 2 m air temperature (top), measured and modeled ice temperature (middle), and measured and modeled ice stress (bottom). Model scenario MAIN. Data of sensor "D-top" located 0.55 m below the ice surface at the center of the dam. The small arrow marks a sudden drecease in stress on 4 Feb. Modeled peaks in shaded areas are explained in the text.

The good agreement between measured and modeled stresses was somewhat unexpected, in particular with respect to the timing of peaks. Comfort et al. (2003) attempted to model ice stresses in a reservoir with a 0-dimensional elastic box model and found that a separate set of parameters had to be used for each short stress event. Petrich et al. (2015) were able to extend the

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time horizon to reproduce stress development over a period of weeks. For this they had to consider the creep of ice based on the work of Bergdahl (1978). However, the present study seems to suggest that stresses can be predicted over an extended period of weeks even with an elastic model if that model is a 3-dimensional finite element model rather than a 0-dimensional box model. This very interesting hypothesis calls for further investigation.

Having established that model results are reasonable representations of measurements, the following results are from an inter-comparison of model runs with different boundary conditions.

The influence of an inhomogeneous snow cover on stress along the dam is illustrated in Figure 5. Ice stress is simulated for two locations near the respective ends of the dam (A and G, cf. Figure 1). As shown in Figure 2, reduced ice–air heat transfer has been applied in a region around measurement station A. In scenario MAIN, stresses are nearly indistinguishable (“num_top1_A” and “num_top1_G” in Figure 5). The small difference in simulated stresses is due to slightly different ice thicknesses near the dam. However, in the partially snow-covered scenario CONV we found a notable reduction of the stresses at both locations during periods of local peaks (“num_top1_conv_A” and “num_top1_conv_G”). In particular, simulated maximum peak stresses in the snow-covered area (A) were only half of those in the exposed area (G). However, the difference between those two sites decreased with decreasing stress magnitude. Such an observation could be explained by the fact that material properties are temperature dependent and that warm ice (i.e., snow-covered ice) would be more prone to creep and produce less stress (cf. Petrich et al., 2015). However, neither is creep part of the numerical model, nor are material properties temperature dependent in the model. Instead, the significant difference between A and G can only have been brought about by different rates of change of ice temperature in the two regions.

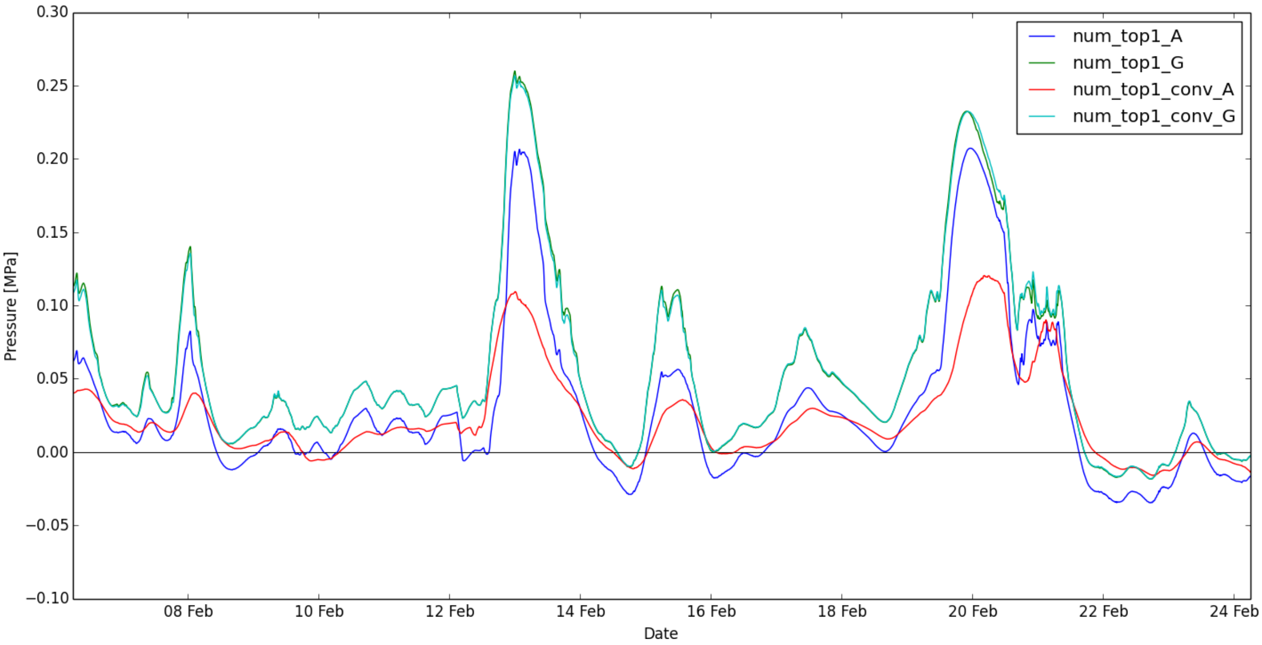

Figure 5. Comparison of modeled stresses at two locations along the dam in scenarios MAIN and CONV.

The influence of changing boundary configuration around the edges of the reservoir was small with the exception of scenario RAND2, i.e. limited confinement parallel to the dam (Figure 6).

The most-confined ice cover of scenario, MAIN, resulted in the highest stresses. However, in the case of RAND2, stresses were typically 50 kPa lower than in other scenarios. More surprising than the ordering of the scenarios is maybe the relatively small difference between these extreme scenarios even at times of peak stresses. This significant yet limited sensitivity could be taken as an indication that ice stress assessments considering reservoir boundary conditions could be reasonably feasible without too much error.

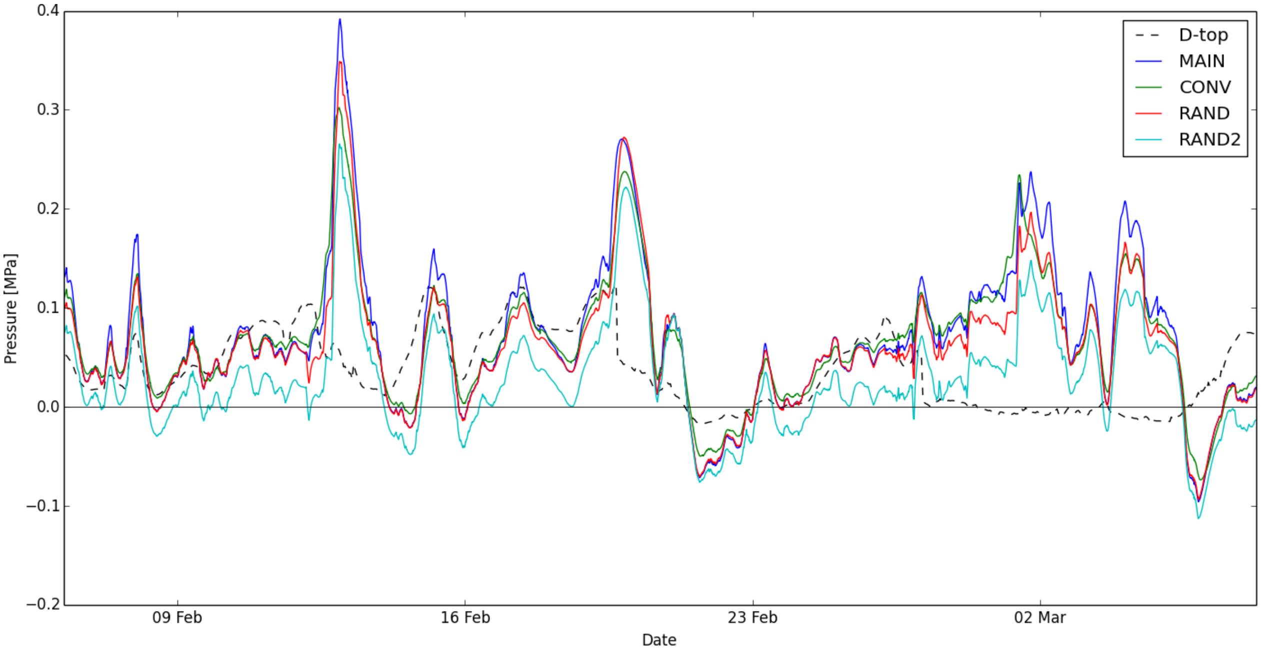

Figure 6. Comparison of model results for different domain configurations shown in Figure 2 at the center of the dam (Station D). Model results for scenario MAIN are shown in more detail in Figure 4. Dashed line are measurements.

4 Conclusion

We simulated thermal stress development in an ice-covered reservoir over an extended period of 5 weeks. It became clear that measured stress data were not just due to thermal loads but also included melt and mechanical events. Excluding those periods from the discussion, stresses were modeled successfully using standard material properties. It is very encouraging for future work to see that modeling extended periods seems to be possible with an elastic model. Sensitivity tests showed that boundary conditions affect stresses in a systematic manner. In particular, systematic snow thickness variations and wide unconstrained boundaries can affect stresses significantly. The magnitudes of stress variation appear to be suitable for the development of practical approaches in dam engineering. We are uncertain at this point why we were able to reproduce quantitatively both magnitude and the timing of peaks in ice stresses with a 3-dimensional thermoelastic model, i.e. a model that does not include the effects of creep. Exactly why this model was able to reproduce measurements in a creeping material has to be investigated further. Successful numerical modeling of stresses in the ice will help guide the design of ice load reducing measured.

Acknowledgments

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