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Numerical analysis of ice loads on Taraldsvikfossen dam

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Static ice loads (ice actions) are a key design parameter for dams in cold climates. Since 2012, ice stresses have been measured at Taraldsvikfossen reservoir located in Narvik, Norway. Similar to earlier observations in Canada, it became evident from the first three years of data that various effects resulted in stresses, including thermal expansion and water level fluctuations, and that the relative dominance of the processes varied between seasons. A numerical model, using the commercially available finite element software LS-DYNA, is presented for the prediction of the stress field in an ice sheet due to temperature changes and water fluctuations as a function of time, under a variety of conditions. The finite element model accounts for variable temperature and properties through the thickness, an elastic foundation representation of the underlying water, nonlinear constitutive behavior of the ice, temperature dependent mechanical properties, flexibility of resisting structures. For verification of the numerical model, results from simulation are compared with measured temperatures and stresses at Taraldsvikfossen reservoir.

1. Introduction

The age of the dams in Norway is increasing. The dams are a considerable value in terms of fixed capital assets and future profits. The consequences of a dam failure can often be very significant, causing both environmental and economic damage and loss of life. The safety of dams in Norway are regulated trough national regulations (Damsikkerhetsforskriften (2010)), in addition to this NVE has guidelines detailing how the stability calculation of dams should be done (e.g. NVE (2003) and NVE (2005)). One of the main changes that was introduced in 2010 was that ice load should be included in the stability calculation. It should be noted that the dams are reassessed every 10 – 20 years depending on the consequence a failure will have. The dam is reassessed according to the current regulations/guidelines. Ice loads where not considered as a load case, when many of the older dams were designed. Therefore, these dams do not fulfill the required theoretical safety factor with respect to stability as specified in the current guidelines. Approximately 90 % of the dams in Norway is what considered small dams, i.e. the maximum height is less than 15 meters. The ice load for these small dams is often the main issue when reassessing the stability of the dam according to the guidelines from 2003 by NVE (2003), this is due to the fact that the ice load in the guidelines (100 - 150 kN/m) is high in comparison with the self-weight of the dam body. This motivated a field measurement program that was implemented to measure the ice stresses at the Taraldsvikfossen reservoir, Narvik, Norway in 2012 and is still running. Some of these results can be found in Petrich et al., (2014), O'Sadnick et al. (2016). Thermal stresses in ice have been discussed in the context of elastic behavior over short periods of time, only (e.g. Comfort et al., (2003); Morse et al., (2011)). However, ice is clearly not an elastic material and alternative formulations of ice rheology have been proposed, e.g., Bergdahl (1978); Drouin and Michel (1974), Royen (1922). The model of Bergdahl (1978) enjoyed considerable success when compared with field measurements when the originally proposed coefficients were adjusted, Cox (1984); Fransson (1988), Petrich et al. (2015). Former work found encouraging agreement between numerical models and field and laboratory measurements Azarnejad and Hrudey (1998).

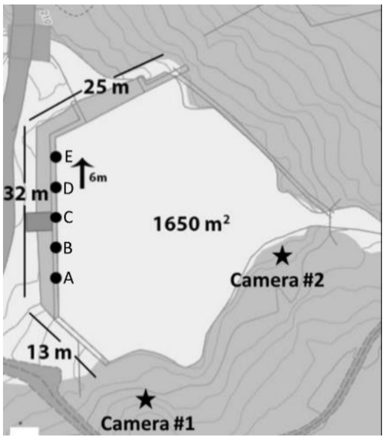
The overall problem of ice forces on dams is very complex. For instance, it will be important to study how the effects of rapid temperature change and the topology of the reservoir and infrastructure affects ice forces on dams. Initially, the problem is going to be simplified, and first look at how a temperature variations of the ice cover affects a dam, i.e. how the ice forces built up in the dam. Furthermore, take into account the stiffness and strength of the dam. Or if creep buckling occurs in the ice cover. These effects may reduce the estimated ice pressure acting on the dam face. The following knowledge gaps has been identified:

- The need for a physically meaningful constitutive model for freshwater ice. The model should include anisotropic behavior, and different compressive- and tensile strengths, (which are dependent on strain rate). The model should account creep and strain softening due to damage, and cracking caused by thermal contraction or mechanical loading.
- It is important to include the entire structural stiffness using the real shape and material properties of the structural components of the dam in the numerical model for ice-structure interaction process.
- Hydrodynamic forces acting on the floating ice sheet, as well as the dynamic coupling between ice and structure by means of contact and frictional forces at the ice-structure interface.

By implementing these effects, advanced numerical FE models can be developed to simulate ice loads on dams. The different mechanisms such as of thermal expansion and contraction, out of plane bending and buckling and ice jacking mechanisms on the ice action can then be differentiated in a realistic manner. It is necessary to carry out a stepwise development, and the complexity of the numerical models is extended during the project. The first step in the development of a numerical model will be in a simplified approach where the geometry, thickness of ice floes and boundary conditions are simplified, idealized and parameterized. To establish the temperature load in the ice cover, transient thermal analysis will also be simplified and idealized. The hypothesis that forms the basis for model development is based on the following: The temperature of the ice bottom is approximately equal to $0^{o}C$ and constant, while the temperature on the top surface of the ice cover fluctuates with air temperature. The aim of this paper is to get a better understanding of how the measured ice load is influenced by environmental variables as temperature, water level fluctuations and interaction with dams and its structural stiffness. A numerical model, using the commercially available finite element software LS-DYNA, utilized for the prediction of the stress field in an ice sheet due to temperature changes and water fluctuations as a function of time, under a variety of conditions. The finite element model accounts for variable temperature and properties through the thickness. The most sophisticated method to account for hydrodynamic effects is by explicitly simulating the water medium by a coupled Arbitrary Lagrangian Eulerian (ALE) method. This approach is accurate, but not computationally efficient. Therefore, a mass-spring-dashpot model to account for hydrodynamic effects has been developed at SINTEF Narvik and implemented into the commercial FE code LS-DYNA and this approach will be employed in this project. In this manner, water level fluctuations, flooding, out of plane bending, buckling and ice jacking mechanisms of the ice sheet are accounted for. For verification of the numerical model, results from simulations are compared with measured temperatures, stresses and global load at Taraldsvikfossen reservoir. Better understanding of thermal and mechanical ice-structure interaction forces will contribute to reducing the rehabilitation costs of the existing Norwegian dams.

2. Field measurements

Taraldsviksfossen reservoir is a small reservoir of approximately 1650 m^2 located 212 m.a.s.l in the town of Narvik, Norway. Confined by a straight sided concrete dam 6 m in height, it is maintained to provide a backup water supply and not regulated (Fig. 1a). The reservoir is fed by a creek, called Taraldsvikelva. In winter, the creek freezes limiting the flow into the reservoir significantly. Given its relatively stable water level and accessibility, ice stress measurements were performed at Taraldsviksfossen reservoir. Five frames with stress sensors (A - E) was installed 6 m apart on 3 October 2014 as shown in Fig. 1. Stress was recorded using custom modified GeoKon 4850 pressure cells consisting of two rectangular steel plates (100 mm x 200 mm) separated by de-aired oil. In addition to stress, each cell measured temperature. Three frames (B, C, D) held five cells placed 0.15 m vertically apart (center-to-center) with the center of the uppermost cell placed 0.075 m above the nominal water line. Nominal waterline is 0.5 m below the top of the dam. The other two frames (A, E) held one cell each with the center placed 0.075 m below the surface. Cells are designed to measure normal compressive stresses up to 1 MPa. A detailed description of the setup is given by Petrich et al. (2015) and preliminary analysis of the ice stresses at Taraldsvikfossen for the season 2014-2015 is described by O'Sadnick et al. (2016).



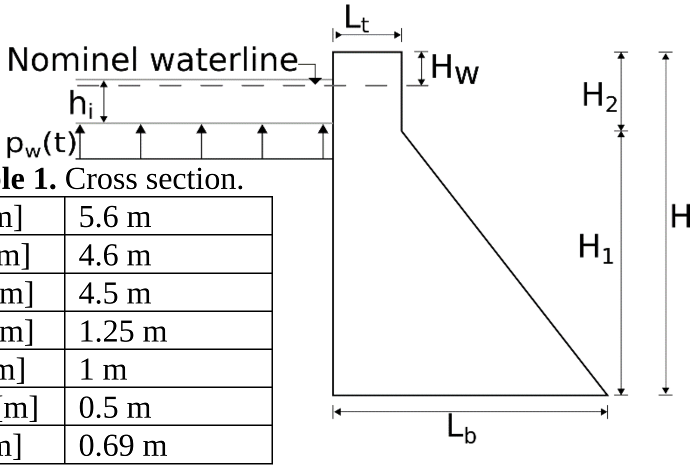


Table 1. Cross section.

H [m]	5.6 m
L_b [m]	4.6 m
H_1 [m]	4.5 m
H_2 [m]	1.25 m
L_t [m]	1 m
H_W [m]	0.5 m
h_i [m]	0.69 m

a) b)

Figure 1. a) Diagram of reservoir including position of frames (black dots) and cameras. From O'Sadnick et al. (2016). b) Dimension of the modelled cross-section.

The ice thickness, h_i, produced by static ice formation is most commonly predicted based on the accumulated Freezing Degree Days (FDDs), as given below:

$$h_i = \alpha_{ig}\sqrt{|FDD|}\ \text{[m] with } \alpha_{ig} = 0.033\ \text{m/(day}^{o}\text{C)} \quad \textbf{[1]}$$

α_{ig} is an empirical coefficient that varies from site to site depending on local conditions such as the snow cover, winds, and solar radiation. The predicted ice thickness is compared with the average measured ice thickness in Fig. 2.

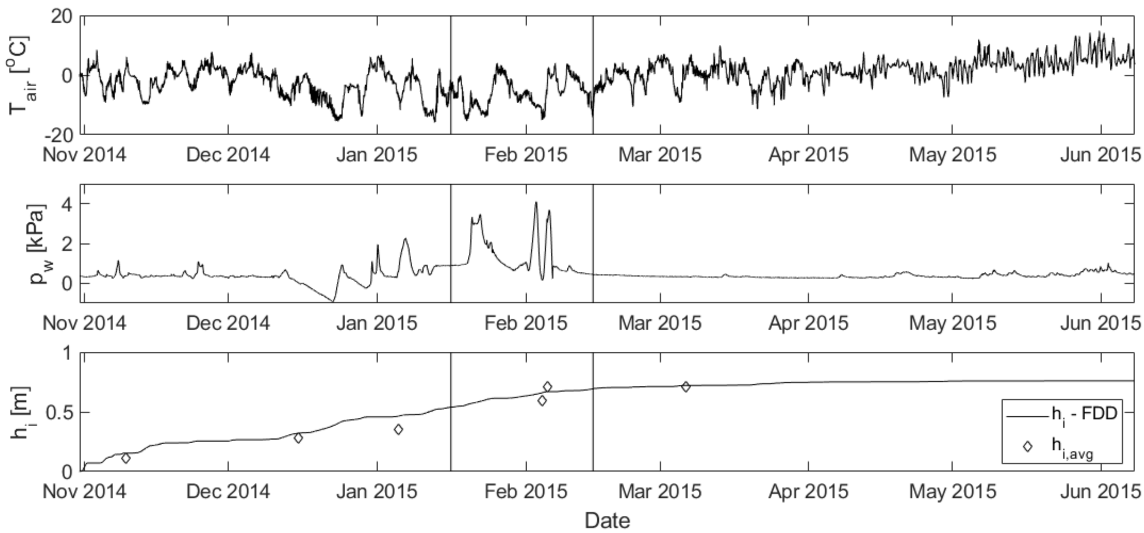


Figure 2. Measured air temperature, water pressure and ice thickness, Taraldsvikfossen dam for season 2014-2015. Vertical lines indicate the time span for numerical simulations, which starts at :16-Jan-2015 09:15:00 and ends at 15-Feb-2015 00:45:00.

Ice crack patterns are important as they are an indication of the motion of the ice cover near the wall of the dam as illustrated in Fig. 3. Similar crack patterns in the ice were observed for the ice at Taraldsvikfossen dam for season 2014-2015. The formation of ice cracks may be induced by either thermal contraction or mechanical loading most often associated with changes in water level. Crack formation due to thermal contraction is described by Ashton, 1986 and Bažant, 1992. Water level variations create hinge effects near the wall characterized by cracks in the ice. Two important cracks were found within meters from the wall, as shown on Fig. 3. They determine a segment of ice from the wall called the "crutch". As the water level changes, the ice cover moves up or down forcing the "crutch" to pivot about the "Ballycatter", a piece of ice that always stays frozen to the wall of the dam. This effect can contribute to generate an increase in load against the dam. As water level variations pivot the "crutch" up or down, it can snag at the hinges and develop a horizontal thrust against the dam, term called "ice jacking". Conditions that favor this effect are: (a) the presence of thermal ice expansion; and (b) the profile of the ice crack, for example: a jagged crack profile as opposed to a worn and rounded one. Another effect is when water rises and seeps through the cracks and refreezes, thereby increasing the aerial extent of the ice cover. Cracking and refreezing of water between cracks are described in detail by Ashton (1986). As water floods over the cold ice cover, it forces the surface temperature of the ice to increase, producing an expansion of the ice surface. A subsequent rise in water level then places the ice cover in compression as it is forced to fit into a now undersized basin. This phenomenon is called ice jacking. This repetitive cycle and a drop of the water level will produce tension in the upper part of the ice cover, and compression below, while a rise in water level will produce the inverse stress profile.

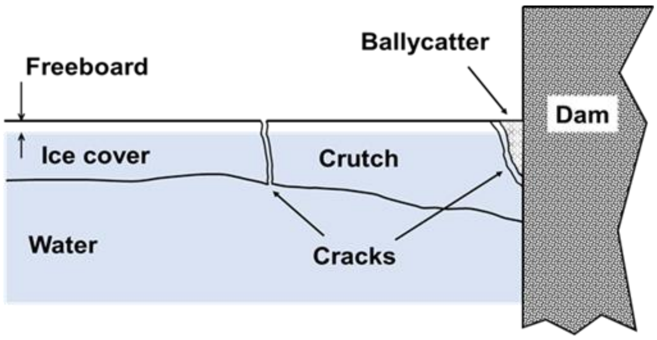


Figure 3. Observed cracks during field measurements.

2. Numerical model

Numerical analysis of ice loads on Taraldsvikfossen dam were with the LS-DYNA general purpose finite element code (Hallquist, 2006) as coupled thermal stress analysis using an implicit code. Simulations are driven by measured air temperature data.

The finite element model for simulation of ice forces acting on the dam is illustrated in Fig. 4 where both the concrete dam and the ice sheet are modeled with hexahedral elements. The ice thickness h_i and the total length of the ice sheet, L_i, is 36 m. As a first approach, only a unit width of 1 m is modeled. The cross-section dimensions of the dam are given in Fig. 2b). The concrete dam is modeled as a linear elastic material with elastic modulus E_c. The mechanical boundary conditions of the dam and ice sheet is modeled in such a way that plane strain is simulated. All the nodes at bottom of dam structure is fixed and all the nodes at the end of the ice furthest from the dam are also fixed. It is also assumed that the ice sheet is frozen to the face of the dam. This is achieved by specifying tied contact between the nodes on the ice and the surface of the structure at the ice-structure interface. The ice sheet is modelled with six hexahedral elements trough the thickness and two elements along the width as shown in Fig. 4. Buoyancy and gravity of the ice sheet is modeled with a nonlinear spring attached to all the nodes defining the bottom surface of the ice. In this manner, the effects of the elements on the ice sheet being lifted out of the water or being submerged is taken account for. Water level fluctuations is modelled by applying the water pressure p_w as a uniform surface pressure at the bottom of the ice sheet as function of time as shown in Fig. 2b).

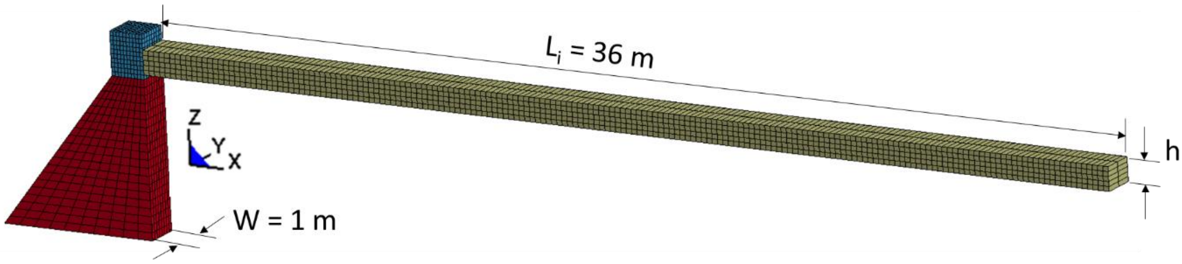


Figure 4. Finite element model for simulation of ice forces on Taraldsvikfossen dam with H = 5.6 m, h_i = 0.69 m and L_i = 36 m. Cross section dimensions are given in Fig. 1b).

For simplicity, the boundary condition at the top surface of the ice the surface is equal to the air temperature, which is function of time, i.e. $T_{air}(t)$ as shown in Fig. 2. It is assumed a linear distribution of temperature through the ice sheet with $T_{air}(t = 0)$ equal to -3 ^{o}C. as initial condition and the ice–water interface, the temperature is assumed to remain at the freezing point. One of the most difficult aspects of any stress analysis involving ice is the selection of values for the mechanical properties. Values adopted in this study are based on published data presented by others. However, finding appropriate data in the literature is complicated by the fact that the strain rates encountered in the thermal stress problem are of the order of 10^{-8} s^{-1} to 10^{-7} s^{-1}, whereas most published test results are for strain rates above 10^{-7} s^{-1}. Data from other studies concerned with thermal ice loads were also considered (Bergdahl 1978 and Cox 1984). In the uniaxial form, the total strain under both mechanical and thermal loading consists of three parts: an elastic strain, ε_e; a viscous strain, ε_v; and a thermal strain ε_T, eq.

$$\varepsilon = \varepsilon_e + \varepsilon_T + \varepsilon_v \quad \textbf{[2]}$$

The elastic strain is related to the stress σ through the elastic constitutive relation:

$$\varepsilon_e = \frac{\sigma}{E_i} \quad \textbf{[3]}$$

E_i is the elastic modulus of ice. Thermal strain due to a temperature change ΔT are given by

$$\varepsilon_T = \alpha_i \Delta T \quad \textbf{[4]}$$

The viscous strain is provided by the Bailey-Norton law, sometimes called power law. This is given by Murat et al. (1989) as:

$$\varepsilon_v = A\sigma_e^n t^{m+1} \quad \textbf{[5]}$$

Where *A*, *m*, n are temperature dependent material parameters and σ_e is the equivalent von Mises stress in multiaxial stress states and *t* is the time. Eq. 5 is often expressed in rate form as

$$\dot{\varepsilon}_v = K\sigma_e^n t^m \quad \textbf{[6]}$$

where $K = A(m+1)$. In this study a material model already implemented in LS-DYNA (MAT_188) is employed. By neglecting effects of plasticity, i.e., viscous effects of plastic strain rate, isotropic and kinematic hardening in MAT_188 model, the thermo-elastic creep model, as outlined above is obtained. The thermal and mechanical properties are summarized in Tab. 2. In this approach, elastic modulus E_i and creep parameter *A* are assumed to be temperature dependent. Cracking of the ice, which is important for thermal and mechanical loads on structures is neglected.

Table 2. Thermal and mechanical properties

Latent heat, ice L_i	Jkg^{-1}	$3.34\cdot10^5$
Density ice ρ_i	kgm^{-3}	910
Density water ρ_w	kgm^{-3}	1000
Heat capacity, ice C_{pi}	$Jkg^{-1}K^{-1}$	2100
Thermal conductivity, ice k_i	$Wm^{-1}K^{-1}$	2.1
Coefficient thermal expansion, ice α_i	K^{-1}	$5.5\cdot10^{-5}$
Elastic modulus, ice E_i	MPa	$6.1(1-0.012T)$
Poisson's ratio, ice ν_i	-	0.3
Elastic modulus, concrete E_c	MPa	$2.8\cdot10^4$
Poisson's ratio, concrete ν_c	-	0.3
Creep parameter K	$MPas^{-1}$	$4.3\cdot10^{-6}$
Creep parameter A	$MPas^{-1}$	$K(1+m)\vert T\vert^{1.97}$
Creep parameter n	[-]	2.2
Creep parameter m	[-]	-0.22

3. Results

The ice load, P_{LL}, acting on the dam, calculated from the measured stresses at stations (St.) B, C, and D, is shown in Fig. 5, together with the line load obtained from the finite element analysis with ice thicknesses h_i = 0.54 m and h_i = 0.69 m. The maximum P_{LL} and time of occurrences are given in Tab. 3. Positive values of P_{LL} is defined as compressive line load. Fig. 5 shows that the ice load obtained with finite element analysis, is correlating with the one obtained from the measured data. It should be noted that the numerical results give higher negative values, this is most likely due to the material model used in these analyses. Furthermore, the variation of ice thickness during the period of measurements considered in these analyses here is not considered. The results for h_i = 0.54 m and h_i = 0.69 m show that the ice thickness will affect the magnitude of the ice load.

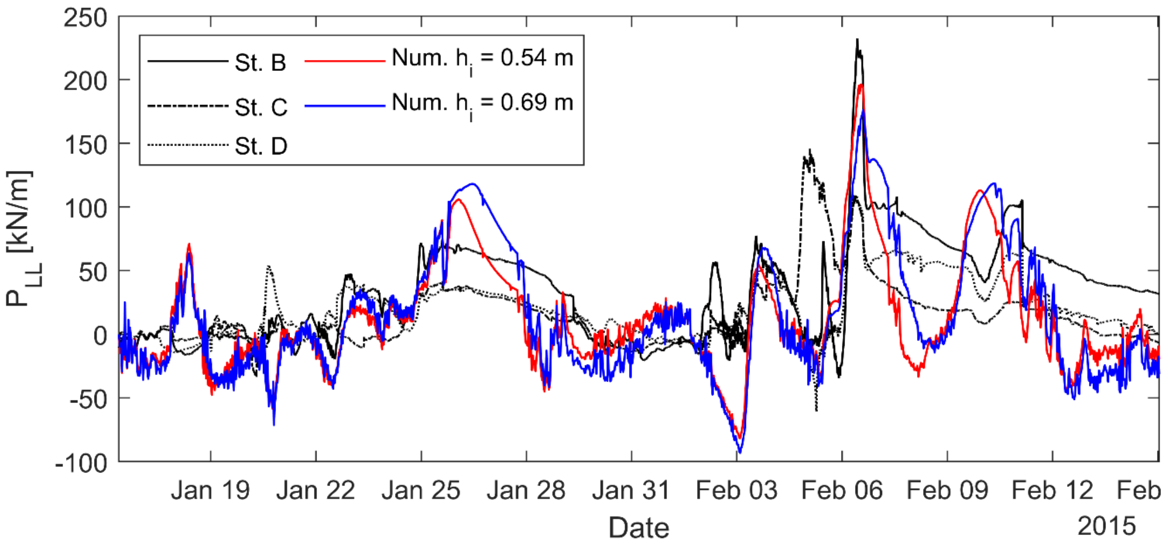


Figure 5. The line load acting on the dam obtained from the finite element analysis compared to the measured data.

The temperature profile obtained from the finite element analysis with h_i = 0.54 m at maximum ice load is shown in Fig 6a, and for h_i = 0.69 m is shown in Fig. 6b. For both analyses the temperatures are retrieved from the nodes in the intersection between the dam and ice sheet.

The measured temperature profile at maximum ice load at St. B, C and D is shown in Fig. 6c. In Fig. 6a and 6b the temperature profiles are plotted at the time of maximum ice load at the different stations (see Tab. 3). The z-coordinate of the temperatures measured was not recorded during the measurement and has here been estimated. This fact is likely to explain some of the differences in the profiles obtained from the finite element analysis and the measured data.

Table 3. The maximum ice load acting on the dam from the measured data and finite element analysis.

	Time [Date time]	*Maximum P_{LL} [kN/m]*
St. B	2015-02-06 10.25	230
St. C	2015-02-05 01.55	150
St. D	2015-02-06 07.05	110
h_i = 0.54 m	2015-02-06 13.18	200
h_i = 0.69 m	2015-02-06 14.25	180

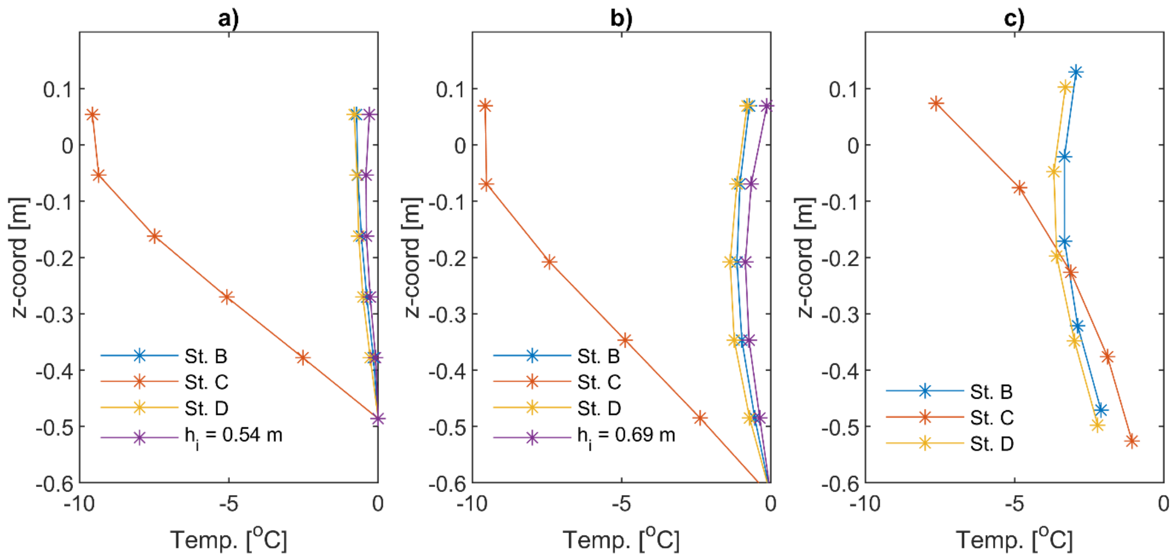


Figure 6. The temperature profiles at maximum ice load (P_{LL}) from the finite element analysis is shown with different ice thickness, h_i in a) h_i = 0.54 m and b) h_i = 0.69 m. c) The measured data.

The profile of the stress in x-direction (longitudinal direction of the ice sheet) in the ice are shown in Fig 7, with compressive stresses as negative. For the finite element analysis with h_i = 0.54 m and 0.69 m are shown in Fig 7a and Fig 7b, respectively, at the time of maximum ice load at the different stations (see Tab. 3). For both analyses the stresses are retrieved from the elements in the intersection between the dam and ice sheet. For h_i = 0.54 m the maximum compressive stress is -1.6 MPa and the minimum tensile stress is 1.12 MPa. For h_i = 0.69 m the minimum compressive stress is -1.4 MPa and the maximum tensile stress is 0.97 MPa. The measured stress is shown in Fig 7c, where the minimum compressive stress -0.56 MPa and the maximum tensile stress 0.02 MPa occurs at St. B. Fig. 7 shows that the numerical analysis highly overpredicts the tensile stresses in the ice, this is caused by the high tensile strength assumed in the material model used in the analyses. Furthermore, the numerical analysis overpredicts the compressive stresses. These differences is likely to errors in the water pressure ($p_w(t)$) applied to the ice and how the temperature loading was implemented (heat convection between the air temperature and ice was neglected).

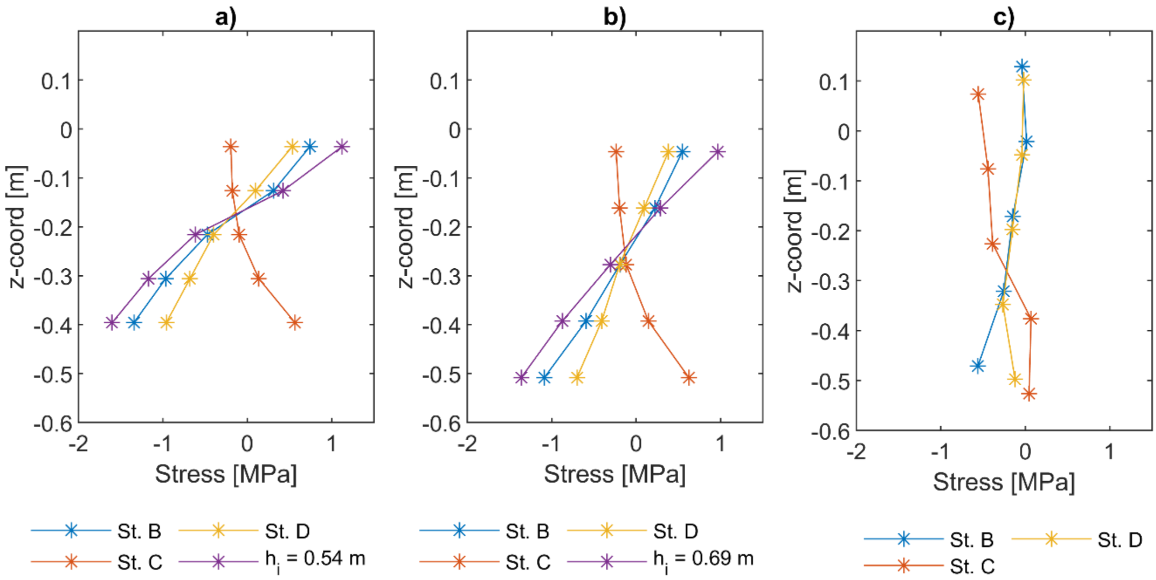


Figure 7. The stress profiles at maximum ice load (PLL) from the finite element analysis is shown for different ice thickness. a) h_i = 0.54 m and b) h_i = 0.69 m. c) Measured stress at stations B, C and D.

4. Conclusion

This paper presents a simplified numerical model for simulating ice-structure interactions forces on hydropower dam structures.

In these simulations the measured air temperature was used as the "driving" force for the thermal expansion of the ice sheet, and the heat convention at the air-ice, ice-water and ice-concrete interfaces was neglected. This is a likely source for the discrepancy between the measured temperature distribution and the resulting temperature distribution obtained by numerical simulations as shown in Fig. 6. Furthermore, the discrepancy in the temperature distribution also affects the predicted stress distribution within the ice cover and can be the source of the overprediction of the compressive stresses by the numerical model as shown in Fig. 7.

The numerical model for the mechanical properties of ice behavior presented herein does not take account for cracking of the ice cover. Therefore, this model overpredicts the tensile strength of the ice, as shown in Fig. 7, and thus gives to high tensile ice loads acting on the ice-structure interface as shown in Fig. 5. The simplified numerical model presented herein shows promising results in estimated ice pressure when compared to measured data. Further work will be to take account for tensile cracking which may lead to redistribution of stresses within the ice sheet and more realistic behavior of the ice cover.

Acknowledgments

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References

Ashton G.D. (editor) 1986. River and Lake Ice Engineering, Water Resources Publications, Michigan.

Azarnejad, A., Hrudey, T.M., 1998. A numerical study of thermal ice loads on structures. Can. J. Civ. Eng. 25 (3), 557–568.

Bažant, Z. P. (1992), Large-scale thermal bending fracture of sea ice plates, J. Geophys. Res., 97(C11), 17739–17751.

Bergdahl, L., 1978. Thermal ice pressure in lake ice covers. Report Series A:2. Department of Hydraulics, Chalmers University of Technology, Göteborg, Sweden (164 pp.).

Comfort, G., Gong, Y., Singh, S., Abdelnour, R., 2003. Static ice loads on dams. Can. J. Civ. Eng. 30, 42–68.

Cox GFN. 1984. A preliminary investigation of thermal ice pressure. Cold Reg. Sci. Technol. 9, 221–229.

Damsikkerhetsforskriften, 2010. Forskrift om sikkerhet ved vassdragsanlegg (FOR-2009-12-18-1600). Retrieved from https://lovdata.no/dokument/SF/forskrift/2009-12-18-1600

Drouin, M., Michel, B., 1974. Pressures of Thermal Origin Exerted by Ice Sheets upon Hydraulic Structures. Draft Translation 427. Cold Regions Research and Engineering Lab, Hanover, NH, USA (429 pp.).

Fransson, L., 1988. Thermal Ice Pressure on Structures in Ice Covers (Ph.D. Thesis), Luleå University of Technology, Luleå, Sweden (161 pp.).

Hallquist, J.O., 2006. LS-DYNA Theory Manual. Livermore Software Technology Corporation, 680 pp.

Morse, B., Stander, E., Côté,A., Richard,M., Desmet, V., 2011. Stress and Strain dynamics in a hydro-electric reservoir ice sheet. Proc. of the 16th Workshop on the Hydraulics of Ice Covered Rivers,Winnipeg, MB, Canada, 18–22 September 2011, pp. 303–316.

Murat, J.R., Ladanyi, B., Huneault, P. 1989. In situ determination of creep properties of sea ice with the pressuremeter. Canadian Geotechnical Journal, 26: 575-594.

NVE, 2003. Retningslinje for laster og dimensjonering. Norges Vassdrags- og Energidirektorat, Retrieved from http://publikasjoner.nve.no/retningslinjer/2003/retningslinjer2003_01.pdf

NVE, 2005. Retningslinjer for betongdammer. Norges Vassdrags- og Energidirektorat, Retrieved from http://publikasjoner.nve.no/retningslinjer/2005/retningslinjer2005_01.pdf

O'Sadnick, M., Petrich, C., Arntsen B.,Sand, B., 2016, Observations of Ice Stress at Taraldsvikfossen Reservoir, Narvik, Norway, 2014/15, 23rd IAHR International Symposium on Ice, Ann Arbor, Michigan, USA, May 31 to June 3.

Petrich, C., Sæther I., Fransson L., Sand B., Arntsen B., 2014. Preliminary results from two years of ice stress measurements in a small reservoir, In Proceedings of the 22nd IAHR International Symposium on Ice, Singapore, 11–15 August 2014,

Petrich, C., Sæther I., Fransson L., Sand, B., Arntsen B., 2015. Time-dependent spatial distribution of thermal stresses in the ice cover of a small reservoir. Cold Regions Science and Technology, 120, 35-44.

Pounder, E. R. 1965. The physics of ice. Oxford, UK: Pergamon Press.