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MEASUREMENT OF LOADS EXERTED BY SEA ICE ON THE QUAY AT KAPP AMSTERDAM ON SVALBARD

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ABSTRACT
Visual observations show significant deformations of construction elements in the cofferdams supporting the coal quay Kapp Amsterdam in Van Mijenfjorden on Svalbard. Ice pressure measurements were performed at the quay at during the winter season 2013 and 2014 using Geokon Earth Pressure cells. The pressure cells were mounted at two different depths on both the inside and outside of one of the open cofferdams supporting the quay. The temperature of the ice and water column was monitored using a thermistor string from Geoprecision. A tidal effect of when an increase in pressure in the water underneath the enclosed ice, inside the cofferdam, causes water to migrate through the ice is observed. In combination with the water freezing effect it produces ice loads up to 0.5 MPa at the walls of the cofferdam at specific phases of semidiurnal tide. Highest loads were observed in April and May, when the air temperature was higher than -10ºC. A small scale ice tank experiments where the water pressure is artificially raised underneath an ice sheet is presented to demonstrate this effect. In the ice tank experiment ice temperature and strains were registered with fiber optics sensors, and the water pressure was registered with a Seabird SBE-39 recorder.

INTRODUCTION
Kapp Amsterdam is the quay used for coal shipping from Svea mine located in Sveabukta in inner part of the Van Mijen fjord on Svalbard. The quay is owned and operated by Store Norske Spitsbergen Kullkompani. It was designed and reconstructed in 2000 by AF Anlegg Harbour for the loading operation on vessels with dead weights up to 70 000 t. The total length of the quay is 195m. It is keyed to the seabed with vertical piles of 80 cm diameter and steel joggle skirts (cofferdams) connects some of the piles (Fig. 1). Each cofferdam has two lateral walls perpendicular to the shore and one frontal wall from the sea side of the quay. The lateral walls extend further and are fixed on the shore outside the quay. Soil was added at the bottom inside the cofferdam. The difference between sea bottom and the soil inside the cofferdam is about 10 m. Sea water penetrates through the skirt and in the ice free season the water level inside and outside the skirts is the same. Since the quay is located in Van Mijen fjord which is closed at its entrance with the island of Akseløya the quay is naturally protected from the actions of ocean waves and drifting sea ice. Main physical environmental actions on the quays are related to the creeping of weak soils, thermal expansion of ice, coastal erosion and sediment transport.

During winter time ice is formed on the sea surface inside and outside the quay. The ice inside the quay is confined by the vertical piles supporting the quay and the joggle skirt. Ice bustles regularly form on the piles outside the sheet piling (Løset and Marchenko, 2009). Previous studies on the quay include Marchenko, A. et al. (2011) and Sinitsyn, A. et al. (2012).

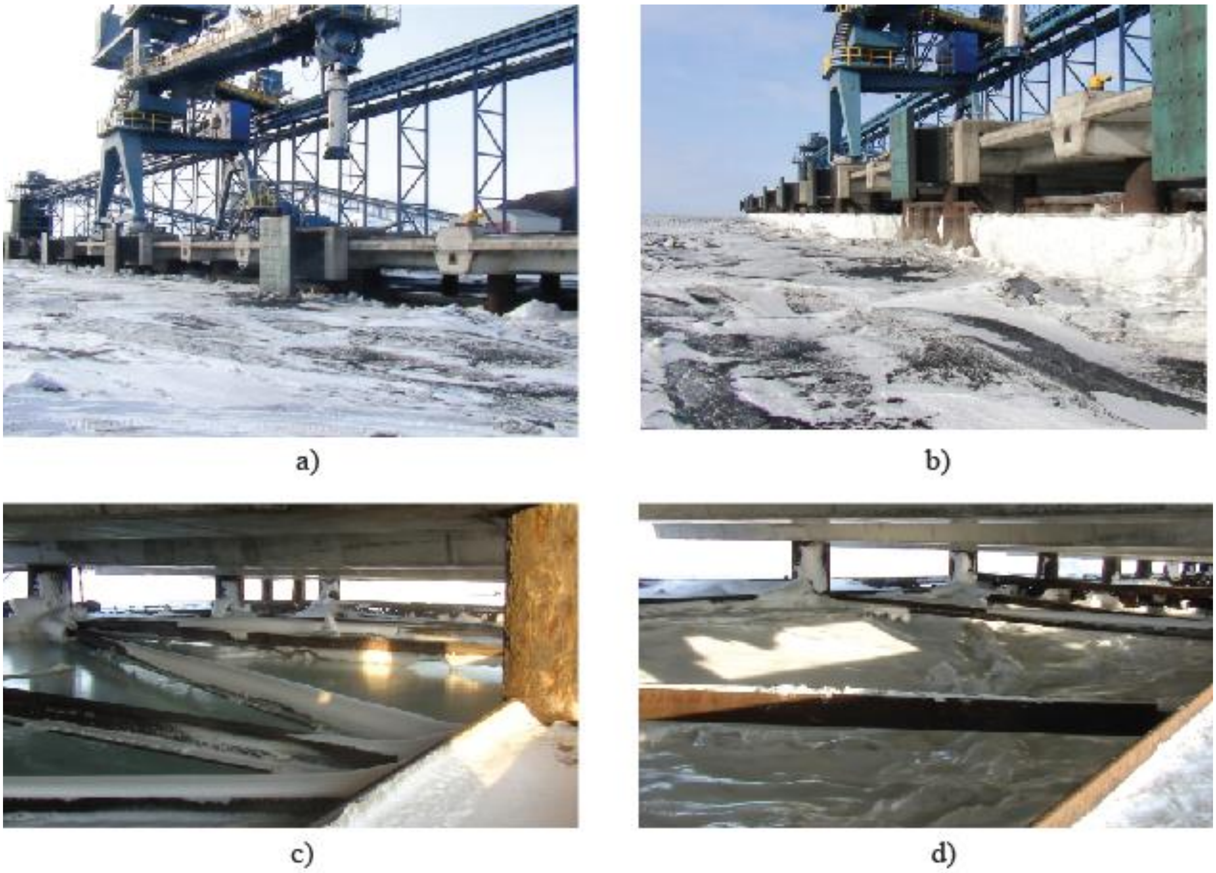

Figure 1. Photos of Kapp Amsterdam. a) Front of quay at high tide. b) Front of quay at low tide. c) Inside cofferdam at high tide (notice the water on top of ice) d) Inside cofferdam at low tide.

ICE PROCESSES BELOW KAPP AMSTERDAM

The ice below the quay is frozen to the cofferdam and hangs on the walls in winter time. The ice between the quay and the shore is grounded. The hanging ice is extending approximately 25 m alongshore and on 10 m in the perpendicular direction to the shoreline. At low tide the ice inside hangs along the skirt with the lowest point of the ice in the middle. At high tide the increasing water pressure below the ice causes water to penetrate through the ice onto its surface (Fig. 1c and Fig 2). The water drains through the ice downward when the water level decreases again. This process was registered by the measurements of the salinity of ice cores taken from the ice inside the cofferdam (Marchenko et al, 2011). The ice salinity during flood phase was higher by several ppt compared to salinity during ebb phase of the tide. The water pressure at the bottom inside the cofferdam was changing synchronously with water level in the sea near the quay without phase shift.

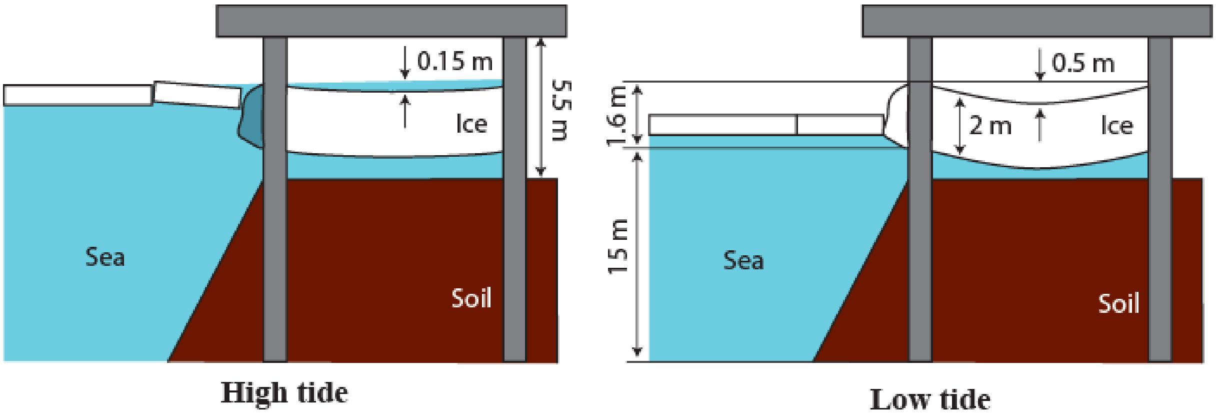

Figure 2. Scheme of quay and the ice formed around it.

Significant deformations of the sheet piling are observed in alongshore direction. The sheet piling has been deformed outwards from the filled part of the foundation with displacements up to 1 m from the line connecting the vertical piles supporting the quay (Fig 3). This has been described and analyzed by Sinitsyn et al (2012). The origin for the deformation can be related to either soil, ice actions or both. It was registered that along shore displacements of the sheet piling increase gradually from year to year. SNSK used regular welding of steel roads and plates between horizontal beams connecting the vertical pipes and the sheet piling to prevent the creeping of the sheet piling from the original position, but the forces applied to the sheet piling are so high that the weld connection are broken in a few seasons.

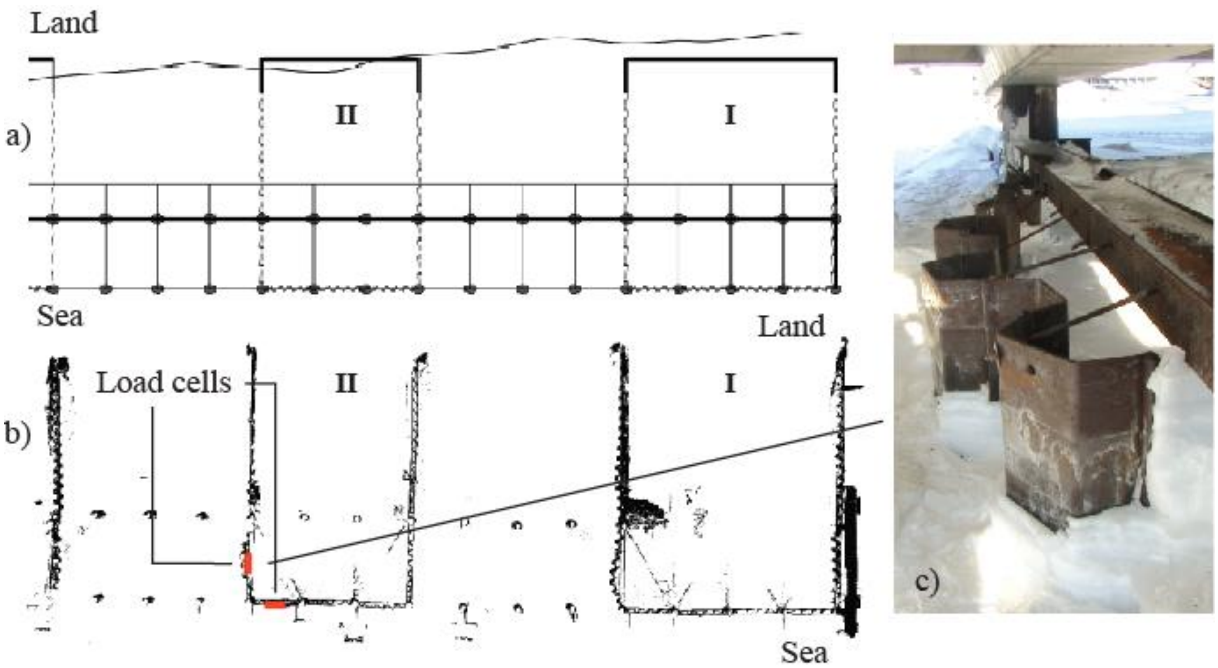

Figure 3. a) Drawing of the sheet piling supporting Kapp Amsterdam. b) Laser scan from 2012 of the sheet piling were deformation can be seen. c) Photo of the deformed sheet piling.

INSTRUMENTATION AT KAPP AMSTERDAM

To better understand the ice processes around cofferdams supporting the quay four Geokon earth pressure cells model 4800 and a Geoprecision thermistor string were installed. Two pressure cells of rectangular shape (10x20cm) were screwed to one steel beam. Two other pressure cells were screwed to two separate steel beams. The beams were bolted to the sheet piling. One on the outside and one on the inside of the front pile sheet wall parallel to the shoreline, and the beam with two pressure cells was bolted on the inside of the lateral pile sheet wall perpendicular to the shoreline (Fig. 4a). The beams were bolted to the sheet piling in the phase of lowest tide in November 2012. The work for the mounting of the beam was performed from plastic oared boat placed inside the cofferdam below the quay. Locations of the pressure cells relatively water level in low and high tide are shown in Fig. 4b. The cells mounted on the lateral inner side of the sheet piling are designated as UC (upper cell) and BC (bottom cell). The cells mounted on the sea side on the cofferdam are designated as SC (sea cell) and IC (inner cell). A thermistor string with 20 thermistors was installed on the outward pile supporting the quay. The top sensor was placed approximately 1.5m above the high tide water mark. The distance between the top sensor and the next sensor is 1m and then there is a sensor every 20cm until the second last sensor. The distance between the two last sensors is 50cm.

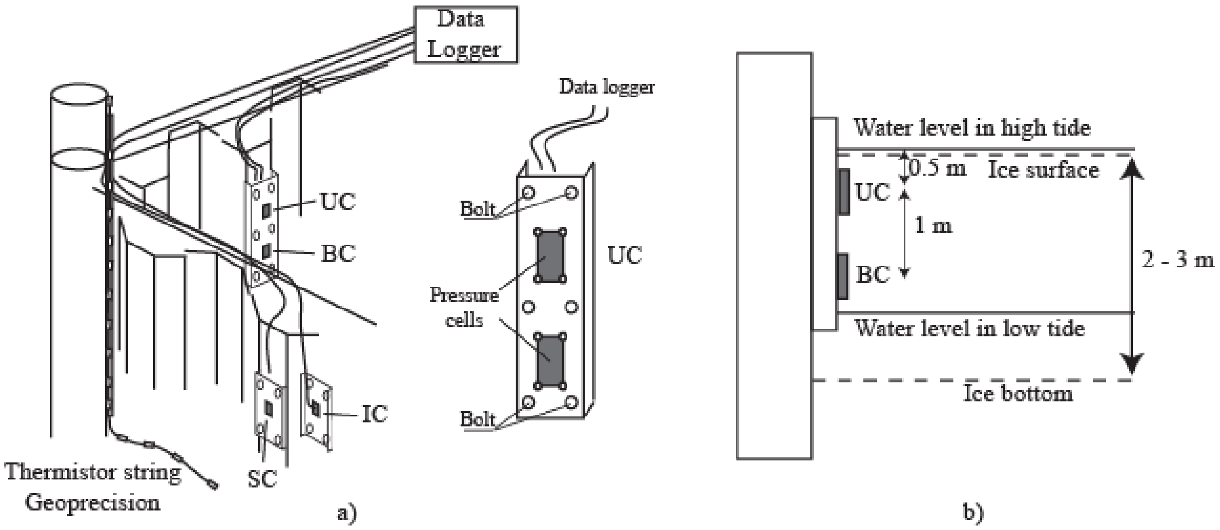

Figure 4. Scheme showing the position of the sensors.

MEASUREMENTS RESULTS

Figure 5a shows typical temperature profile through the ice inside the cofferdam. The ice thickness below the quay reached 1.5 m in March 2013. Records of thermistor 1 show the air temperature below the quay at the distance 1.5 m from the ice. It is very close to the air temperature recorded by the weather station in Svea. Records of thermistors 2-4 are affected by the ice and water at the ice surface inside the cofferdam. Therefore these sensors show higher temperatures. Thermistors 5-9 show almost linear temperature profile within the top layer of the ice of 0.8 m thickness. Thermistors 10-20 show almost constant temperature similar to the freezing point of the sea water. Figure 5b shows thermistor records versus the time over 3 months from March to May in 2013. Oscillations with amplitudes up to 2-3^{o}C in records of thermistors 1-4 are related to daily variations of the air temperature. It is colder in night time and warmer in day time due to the sun radiation. Records of the other thermistors are more stable.

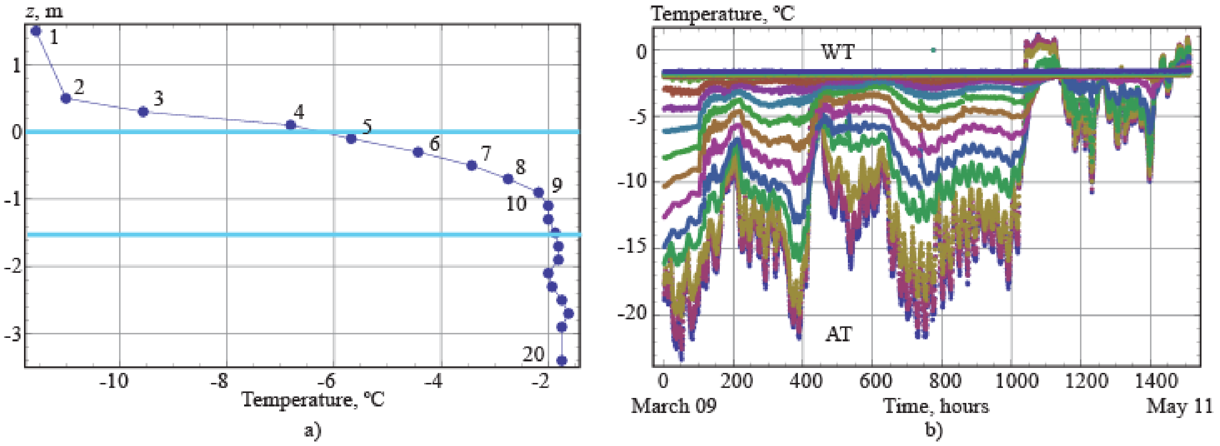

Figure 5. Typical temperature profile through the ice and locations of the thermistors (a).
Temperatures registered by the thermistors versus the time in 2013 (b).

Figure 6 show records of thermistors 1-4 and thermistors 5-8 over 200 hours. Semidiurnal oscillations of the temperature with amplitude up to 0.5^{o}C are very visible in Fig. 6b. These oscillations are related to the brine migration through the ice under the influence of the water pressure increase below the ice induced by semidiurnal tide. The temperature oscillations are most visible in the records of thermistor 5 located on the top of the ice where the amount of water (brine) is much higher than inside the ice.

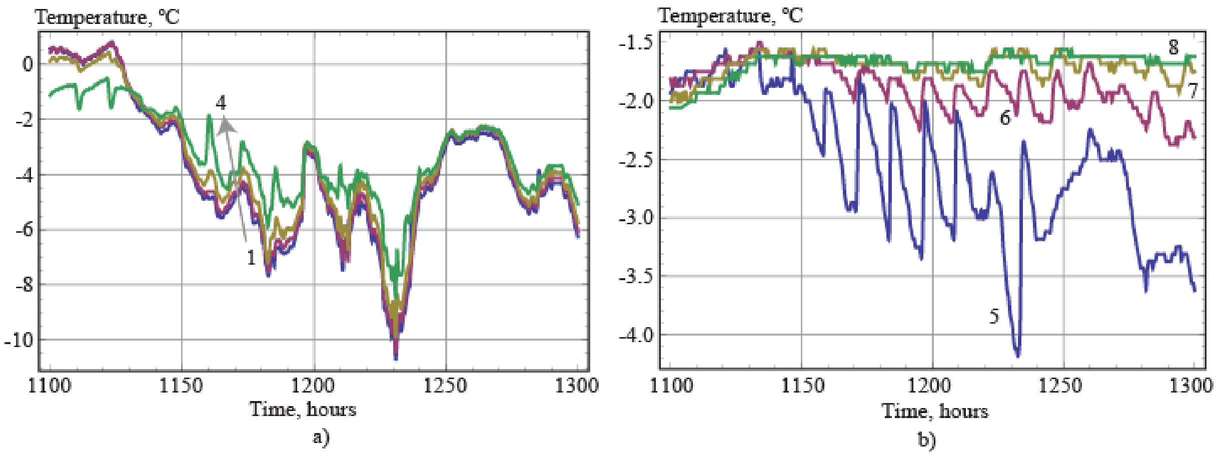

Figure 6. Records of thermistors located above the ice (a).
Records of thermistors located inside the ice (b).

Records of the pressure cells are shown in Fig. 7. One can see that pressures recorded on the frontal side of the cofferdam (Fig. 7a) are much lower the pressures recorded on the lateral side of the cofferdam (Fig. 7b) except of very high pressures registered during very short time by the pressure cell SC mounted on sea side of the frontal cofferdam. Semidiurnal oscillations of the pressure are well visible on all graphs. Highest pressures up to 0.5 MPa measured by pressure cell UC on the lateral side of the cofferdam were registered in the end of the April and in the beginning of the May when the air temperature was negative but above -10^{o} C. Pressures measured in coldest time were below 0.2 MPa.

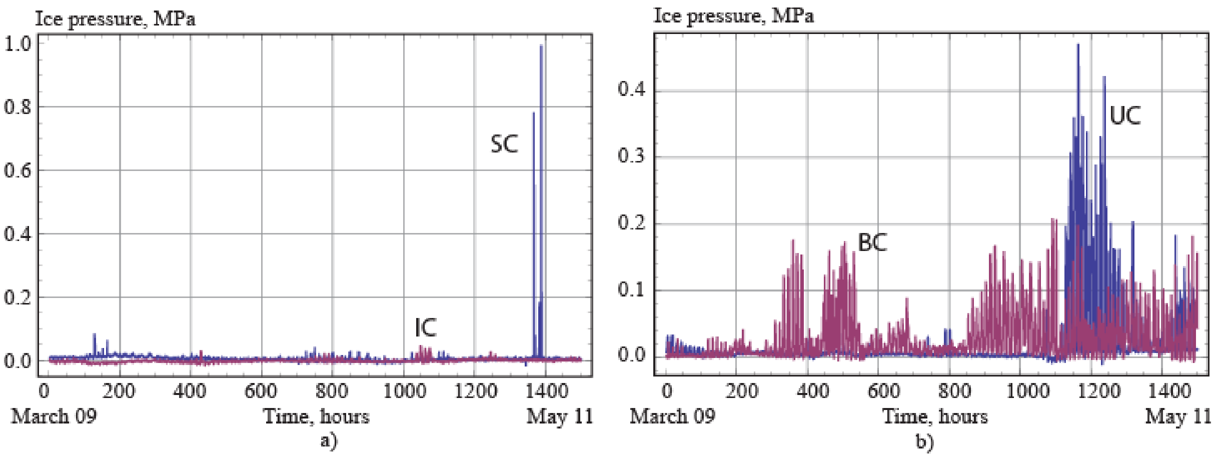

Figure 7. Records of pressure cells mounted on the sea side (a) and lateral side (b) of the cofferdam.

Figure 8 shows pressure and temperature records on the same graph. One can see that pressure and temperature variations have the same period similar to the period of semidiurnal tide 12.42 h. Local maxima of the temperature are associated with local minima of the pressure and vice versa. It can be explained by the expansion caused by the freezing of the water expulsed on the ice surface through the ice and the water trapped between the cofferdam walls and ice.

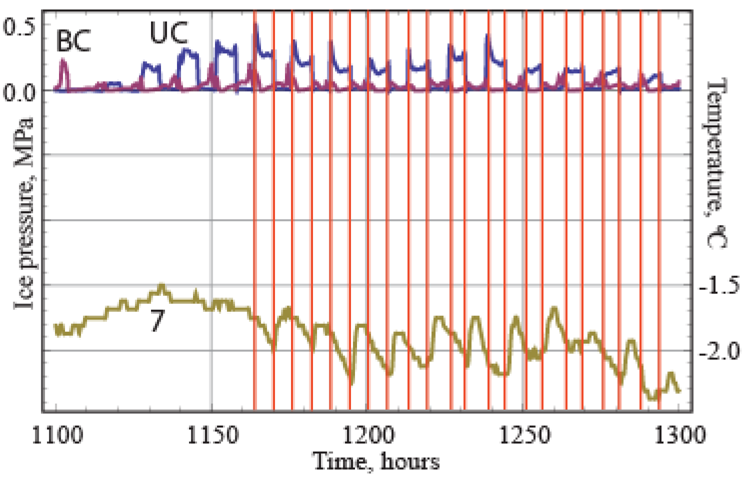

Figure 8. Ice pressure on the lateral wall of the cofferdam and temperature recorded by thermistor 7 versus the time.

LABORATORY EXPERIMENT

A laboratory experiment was performed in the ice tank in the cold laboratory at UNIS to confirm possibility of ice expansion under the influence of under ice water pressure. Saline ice of 8 cm thickness was frozen on the surface of sea water of 1 m depth with initial salinity 12 ppt. The ice salinity was about 6 ppt. An over pressure in the tank was created by gradually pumping air into a submerged car wheel tube using an electrical pump. The pump was powered by a laboratory power supply with variable voltage so that the pumping speed could be regulated (Fig. 9). Extension or compression of the ice in the horizontal plane was measured with FBG fiber optic strain sensor AOS GmbH mounted on steel angle brackets frozen into the ice (Fig. 9b and 10a). Earlier the FBG strain sensors were used to measure thermal expansion of ice samples (Marchenko et al., 2012). The resolution of strain measurements is 1 μstrain. The other FBG strain sensor was mounted on the tank wall on similar brackets fixed on the wall (Fig. 9b and 10a). This sensor recorded compression or extension induced by bending deformation of the wall under the ice action. The FBG thermistor string with 12 thermistors distant from each other by 1 cm was used to measure air temperature and temperature profile through the ice (Marchenko et al, 2013). The resolution of the temperature measurement is 0.08°C. A temperature and pressure sensor SBE-39 was used to record water pressure below the ice during the experiment. The resolution of pressure measurements was $4{\cdot}10^{-4}$ dbar. All sensors were synchronized and provided measurements with sampling interval 1 s.

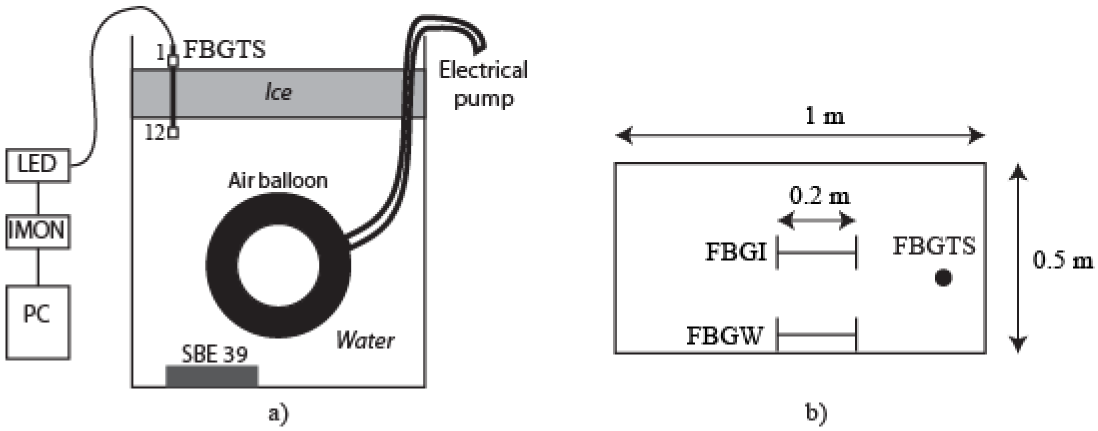

Figure 9. Scheme of the experiment on ice extension due to the water pressure increase in the ice tank (a). Locations of FBG strain sensors on the ice surface (FBGI) and on the tank wall (FBGW) (b).

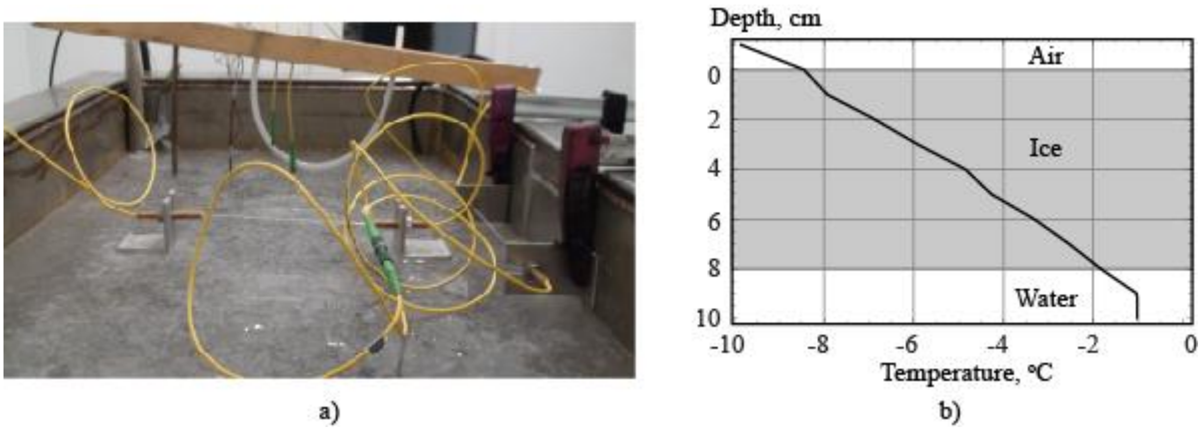

Figure 10. a) Photo of laboratory experiment in the ice tank.
b) Temperature profile in model ice measured with FBG thermistor string.

Temperature profile through the ice was practically linear during the experiment. Temperature deviations from the initial profile (values before starting the experiment by raising the water pressure) are analyzed. As the pressure was gradually increased in the water the strain measured in the ice also increased (Fig. 11a). At the same time the strain sensor on the wall of the ice tank gradually decreased indicating that the wall bent a bit outward from the increased water pressure and/or ice pressure. The temperature at 1 cm depth and deeper increased as an effect of water migrating through the ice sheet (Fig. 11b). This water could also be visually observed on top of the ice. Temperature on the upper surface of the ice decreased but this is believed to be caused by an overall temperature decrease in the cold lab where the experiment was conducted. This temperature decrease was also registered by the thermistor located at 1 cm distance above the ice surface.

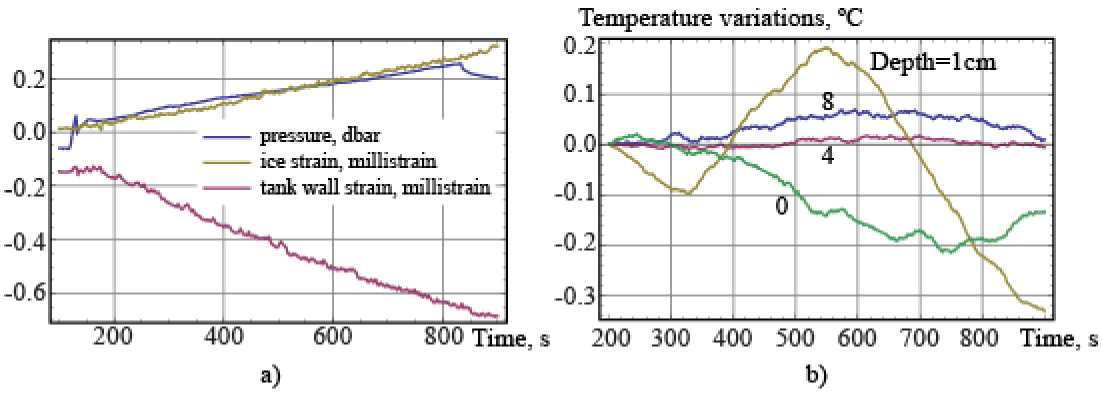

Figure 11. a) Strains in ice and tank walls induced by the increase of the water pressure below the ice. b) Temporal variations of the ice temperature induced by brine migration through the ice.

CONCLUSIONS

Systematic investigations of ice actions on the cofferdam below the coal quay in Kapp Amsterdam, Svalbard, have been conducted since 2012. In 2012 laser scanning showed significant deformations of the lateral walls of the cofferdam. Pressure cells and a thermistor string were installed on the cofferdam walls in November 2012 and data from them were collected in winter 2013 and 2014. It is discovered that ice pressure on the cofferdam walls and ice temperature varies synchronously with semidiurnal tide. Ice pressure reached maximal values on the lateral wall of the cofferdam where maximal deformations of the sheet piling are observed. In 2013 maximal pressure was about 0.5 MPa. Maximal ice pressures were registered in the end of April and beginning of May 2013 when the air temperature was above -10^{o}C. In March and April 2013 maximal ice pressures didn't exceed 0.2 MPa. Winter 2014 was much warmer, the ice was not frozen to the cofferdam, and ice loads on the cofferdam walls were insignificant.

Laboratory experiment has confirmed that extension of saline ice in horizontal plane can be caused by the increase of water pressure under the ice. This process is accompanied by the increase of the ice temperature.

We support the following physical mechanism of ice load formation on the cofferdam walls. The increase of water pressure below the ice influence upward migration of brine through the ice. On the way through the ice the brine fills all cracks inside the ice and gaps between the ice and the cofferdam walls. Atmosphere cooling influence the freezing of this brine. It influences the increase of the pressure inside the ice and ice loads on the cofferdam walls. Maximal deformations and loads occur in alongshore direction because the cofferdam has a longer extension along the shore. Maximal ice pressure is formed in conditions of relatively warm weather (the air temperature is above -10^{o}C) because of higher permeability of the ice and specific property of the coefficient of thermal expansion of saline ice discovered by Malmgen (1927).

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