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Measurements of Deformations and Displacements of Stationary Quays in Svalbard with 3D Laser Scanner Riegl VZ-1000

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Deformations and displacements of structural elements of two quays in Spitsbergen were investigated in details using the 3D Terrestrial Laser Scanner Riegl VZ-1000. Modeling of ice action on the quays was performed with Comsol Multiphysics. It is shown that observed deformations of the coal quay in Longyearbyen are caused by wind loads and wind induced ice loads. The deformations observed in the coal quay in Kapp Amsterdam are probably caused by thermal expansion of the ice hanging on the joggle skirt of the quay.

1. Introduction

In decades to come, the Arctic believed to play increasingly prominent role in human life. Robust technology solutions are needed to develop industrial in particular and society as whole related projects. One component of such technology solutions is development of life-cycle management systems for engineering structures. Engineering survey is important part of such systems.

The assessment of spatial position of structure elements is among the parameters included in an engineering survey. That assessment can be implemented by geodetic and special measurements. Geodetic measurements, photo and video fixation provide reliable data. But these methods can collect limited amount of information, surveying process and data processing are rather time-consuming (Pennington et al., 2008). Requirement for operator of being close to observable object is one of limitations of geodetic methods.

The use of laser scanning systems enables to provide possibilities which were not accessible earlier by traditional techniques: measurements of difficult to access objects with high accuracy on a tight timetable. This technic has found application in wide range of geology and engineering surveys for coastal erosion (Pennington et al., 2008), for deformation measurements of bridges (Berényi et al., 2009), for surveying of electrical power infrastructure (Gorbunov, 2008), for monitoring of road bed (France et al., 2011), for mining operations (RIEGL, 2011), surveys on water ways (Studnicka et al., 2011).

In the present study we aim to describe deformations and displacements of two stationary quays in Svalbard and to specify physical environmental processes causing the observed deformations. In the first section the location and structural characteristics of the quays are described. The second section performs the survey implementation with 3D Long-range Terrestrial Laser Scanner Riegl VZ-1000. The displacement and deformation analysis is performed in the third section. The results of mathematical modeling of ice loads on the quays are formulated in the forth section.

2. Description of Investigated Quays

We studied displacements and deformations of two coal quays owned by Store Norske Spitsbergen Kullkompani in Svalbard. Their locations are shown by black dotted squares in Svalbard map (Fig. 1a). The Longyearbyen coal quay is located in the Advent fjord in inner part of the Ice fjord (Fig. 1b), and the Kapp Amsterdam coal quay is located in Sveabukta in inner part of the Van Mijen fjord (Fig. 1c). Thus both of the quays are 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.

The coal quay in Longyearbyen is supported by wooden piles of 25 cm diameter connected with each other by wooden beams. The quay consists of two piers with sizes 30x15 m and 10x15 m. The distance between the piers is 18 m. The plane view of the quay constructed with the laser scanning is shown in Fig. 2a. The top side structure of the Longyearbyen quay was destroyed in the winter 2011 and now the construction of new quay is planned in this place. Damage of the quay is performed by the soil collapses along the contact line between the quay and the land (Fig.

2b) and by inclined wooden piles (Fig. 3). Photographs of inclined wooden piles supporting the quay are performed for the View 1 (Fig. 3a), View 2 (Fig. 3b), View 3 (Fig. 3c) and View 4 (Fig. 3d). Locations of View 1-4 are shown in Fig. 2a. It is possible to conclude that the wooden piles inclined to the shore side. Measurements of inclination angles were performed with the laser scanning integrated sensors.

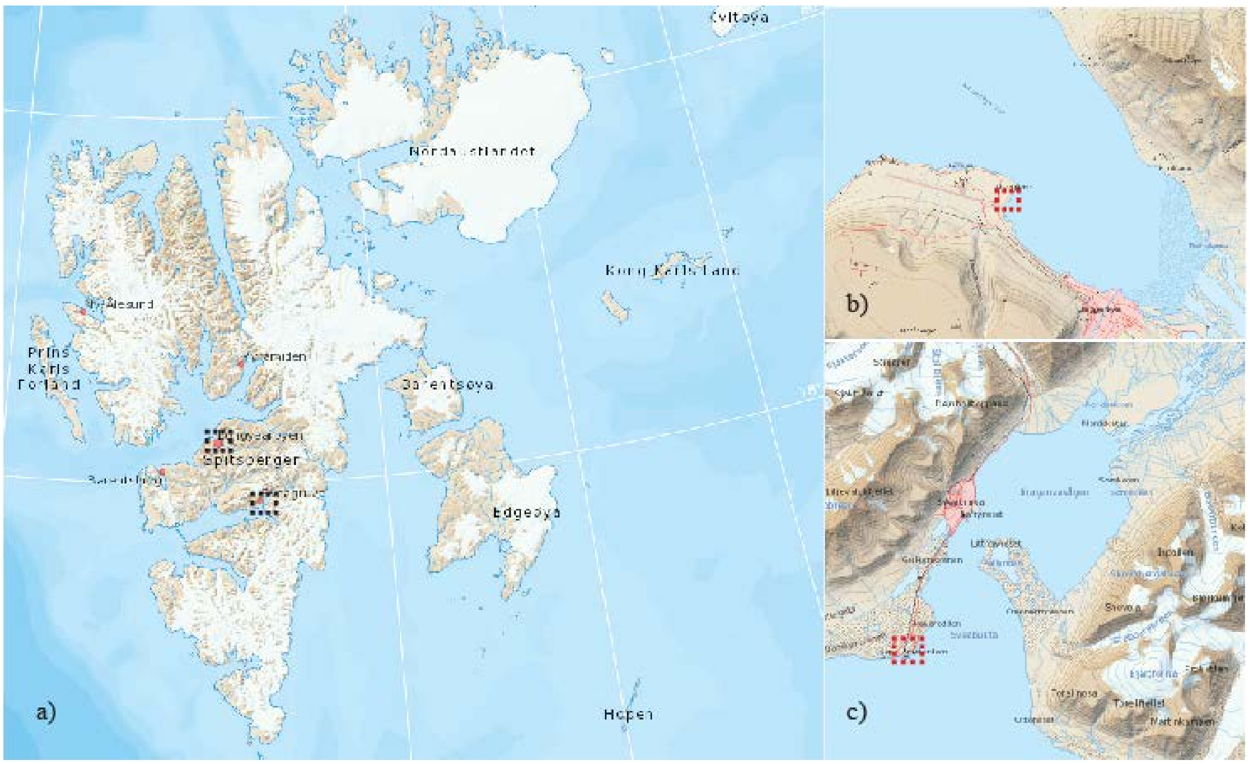


Figure 1. Locations of the quays in Svalbard map are shown by black dotted squares (a). Location of the old coal quay in Advent fjord (b), and coal quay in Kapp Amsterdam in Sveabukta (b).

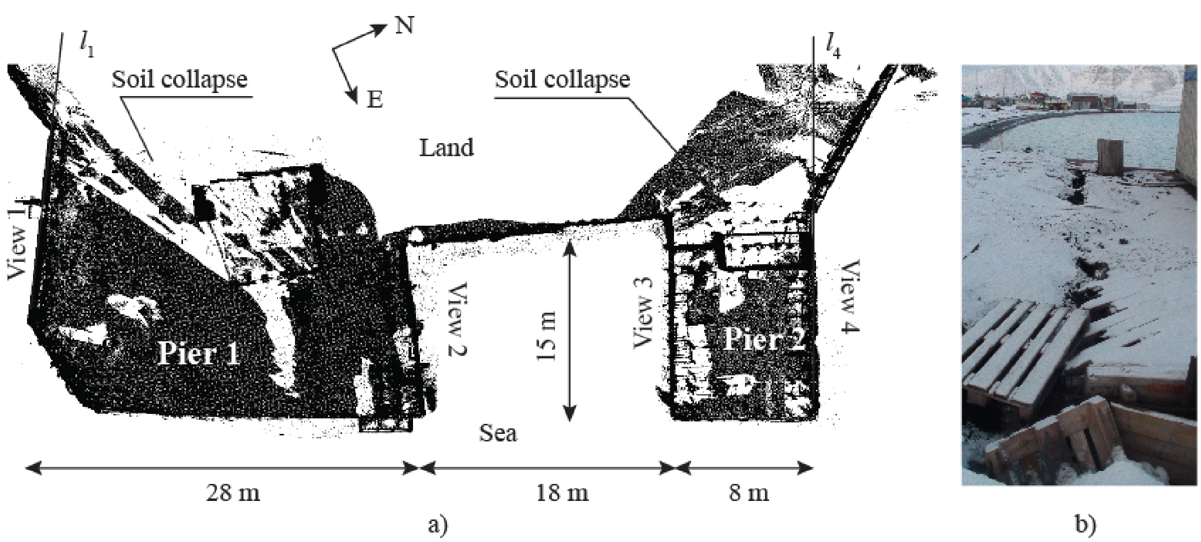


Figure 2. Plane view of the coal quay in Longyearbyen (laser scanning) (a). Soil collapse between the quay and the land (b).

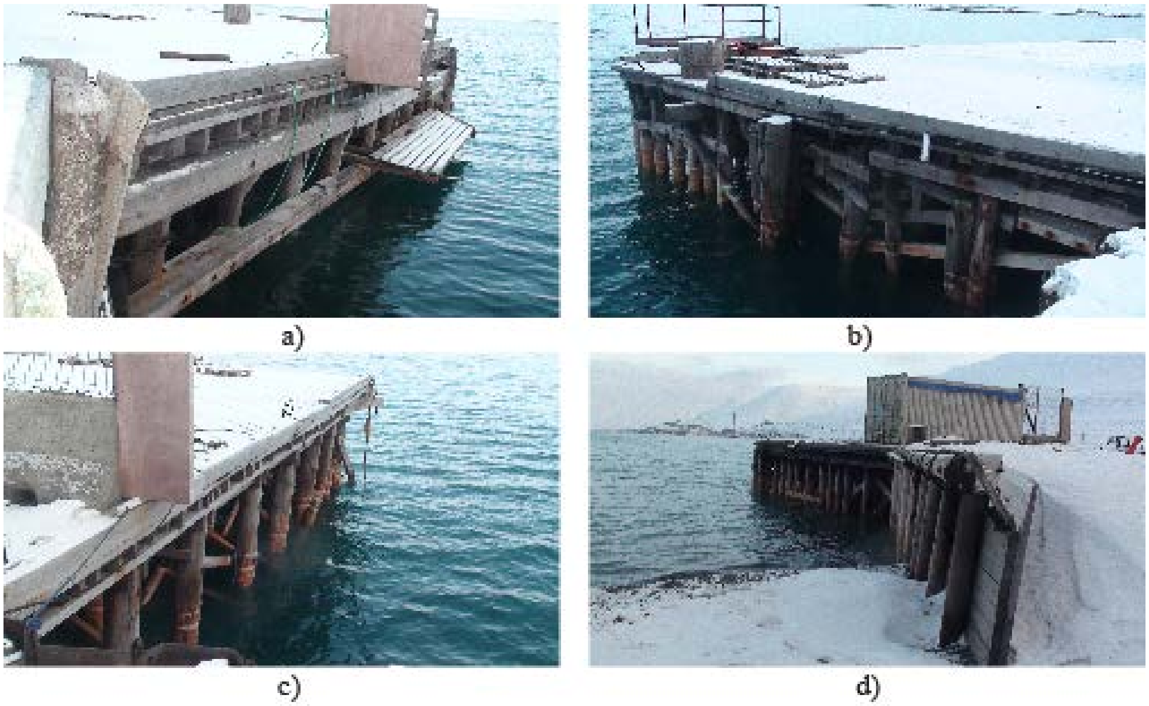


Figure 3. Character of damage of the coal quay in Longyearbyen.

The coal quay in Kapp Amsterdam was designed and reconstructed in 2000 by AF Anlegg Harbour for the loading operations on vessels with dead weights up to 70 000 t. The total length of the quay is 195 m, it is keyed in the seabed with vertical piles of 80 cm diameter and steel joggle skirts connecting some of the piles (Fig. 4 and Fig. 5a). The soil is added at the bottom inside the skirts. The water depth inside the skirts is smaller than the water depth outside them on 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. Damage of the quay is performed by the deformations of the joggle skirts (Fig. 5b-5c). The deformation analysis was performed with the laser scanning.

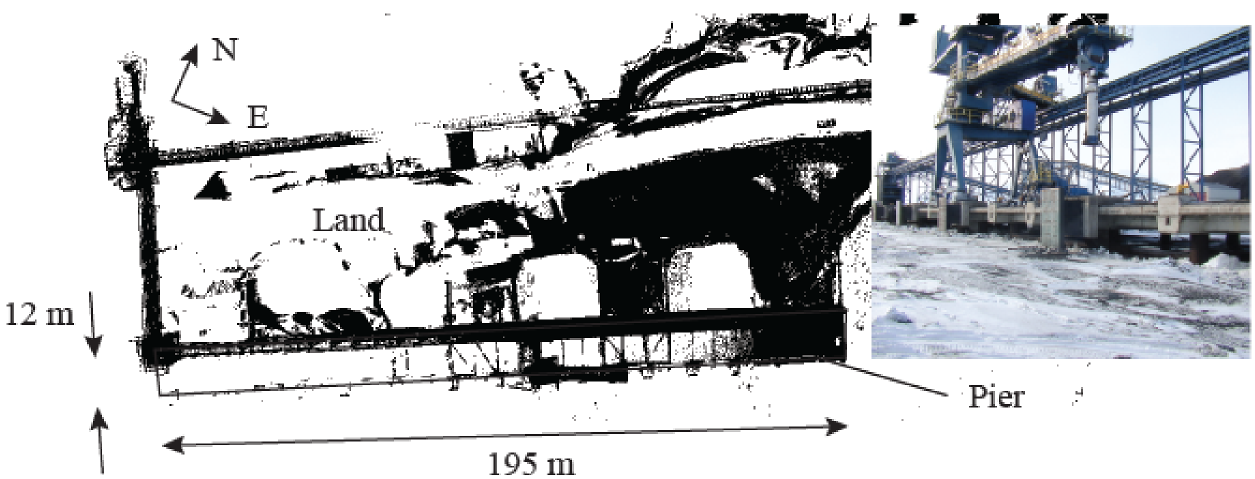


Figure 4. Coal quay in Kapp Amsterdam: laser scan image and photograph.

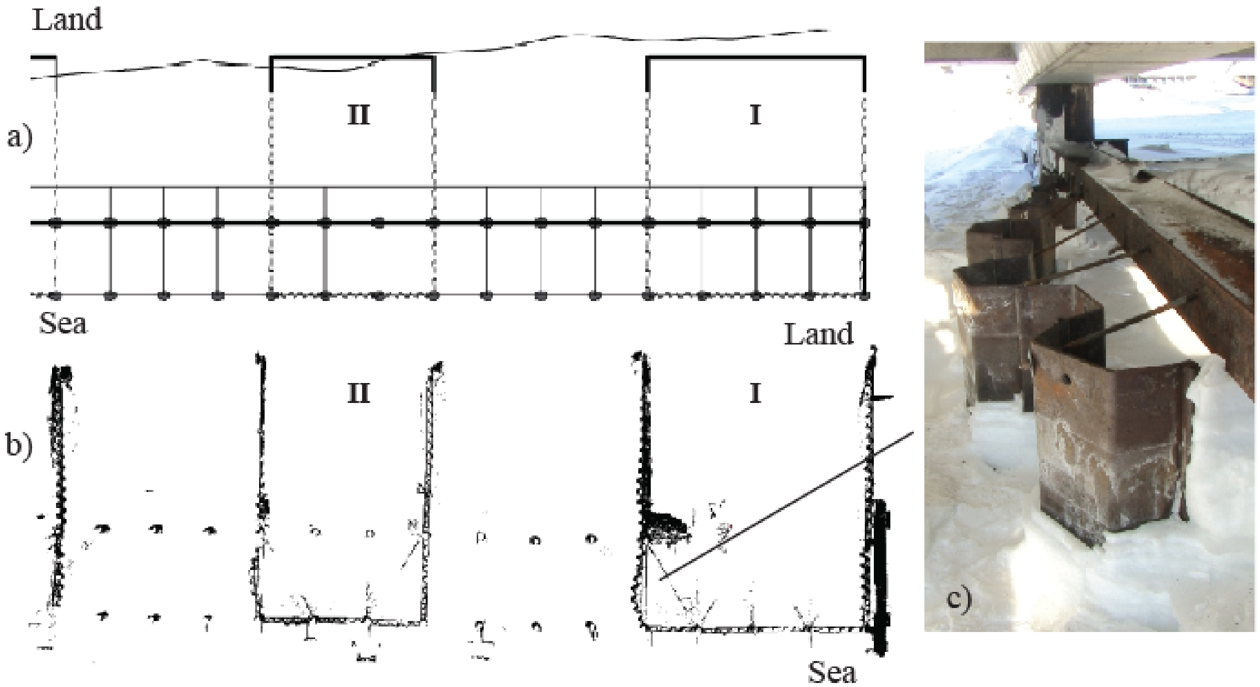


Figure 5. Scheme of the joggle skirts in the East part of the quay (a), laser scan image of the joggle skirt (b), photo of the deformed joggle skirt (c).

3. Survey Implementation

The laser scanner used for the measurements was a Riegl VZ-1000 which is part of Riegls V-line 3D Terrestrial Laser Scanners. It uses a narrow infrared pulsed laser beam in conjunction with fast rotating multi-facet polygonal mirror to acquire fast and precise laser ranging. It uses frequencies in the range from 70 to 300 kHz and achieves its maximum range of 1400m at 70 kHz. The Riegl VZ-1000 incorporates On-line Waveform Processing, capable of detecting and processing multiple echo from the same direction, which means complex structures, fences, wires and vegetation can be handles. The minimum measurement distance is 1.5m. Accuracy (conformity with actual value) is reported to be 8mm and precision (degree to which further measurements show same results) 5mm (RIEGL VZ-1000 datasheet, 2011). A high-resolution, full-frame, calibrated Nikon D700 was used to automatically acquire RGB images for making textures during post-processing.

When the scanning is performed from different positions the different scans are fit to each other by first manually doing a course registration in Riegl RiSCAN PRO software, which supports pointcloud and image data acquisition, processing and visualization. This was done either by selecting 4 mutual points in the corresponding scans or by manually translating and rotating the scans into a fit depending on which was easiest in the particular case. VZ-1000 has integrated GPS, inclination sensor and compass to aid registration of scan positions.Then the point clouds were reduced to polydata objects by using Surface Plane Filter. The resulting polydata objects are used by the Riegl Multi Station Adjustment Tool for automatic fine adjustment using a best-fit iterative least-squares iterative method (RiSCAN PRO Software Description & User's Instructions, 2011).

Measurements of the inclinations of piles on the old cold quay in Longyearbyen were performed by fitting a plane to the surface of the quay and touching surfaces of the Pier 1 and Pier 2 (Fig. 6a), and using points on the surface of the piles to create vectors representing the direction of the piles (lines A_1C_1 and A_2C_2 in Fig. 6a). Lines representing the direction of the quay were created on two sides of the quay (lines l_1 and l_4 in Fig. 6a). The direction of each wooden pile marked in Fig. 6 b-6c by numbers 1, 2,… was characterized by two angles α_1 , β_1 (View 1 side) and α_4 , β_4 (View 4 side) (Fig. 6a). The angle α_1 is equal to the angle between lines A_1C_1 and A_1B_1, and the angle α_4 is equal to the angle between lines A_4C_4 and A_4B_4. The points B_1 and B_4 are the projections of the point A_1 and A_4 on the horizontal plane of the piers. The angle β_1 is equal to the angle between lines B_1C_1 and C_1D_1, and the angle β_4 is equal to the angle between lines B_4C_4 and C_4D_4. Lines B_1C_1, C_1D_1, B_4C_4 and C_4D_4 lie in the horizontal plane. Lines C_1D_1 and C_4D_4 are parallel to the lines l_1 and l_2 shown in Fig. 2 and Fig. 6. Positive direction of the angles β_1 and β_4 is accounted in clockwise direction from the lines C_1D_1 and C_4D_4, so that the angle β_1 is negative and the angle β_4 is positive in Fig. 6a. Lines C_1D_1 and C_4D_4 are parallel to the lines l_1 and l_2 shown in Fig. 2a and Fig. 6a.
The results of the measurements are presented in the Tables 1 and Table 2. Mean values of the angles are as follows

$$\langle\alpha_1\rangle = 9.14^\circ,\ \langle\beta_1\rangle = -12.34^\circ,\ \langle\alpha_4\rangle = 4.52^\circ,\ \langle\beta_4\rangle = 151.79^\circ. \quad \textbf{[1]}$$

The mean values of the angles β_1 and β_4 demonstrate the existence of onshore and along shore components of the quay displacement. The along shore displacement is directed from Pier 2 to Pier 1 in Fig. 6a).

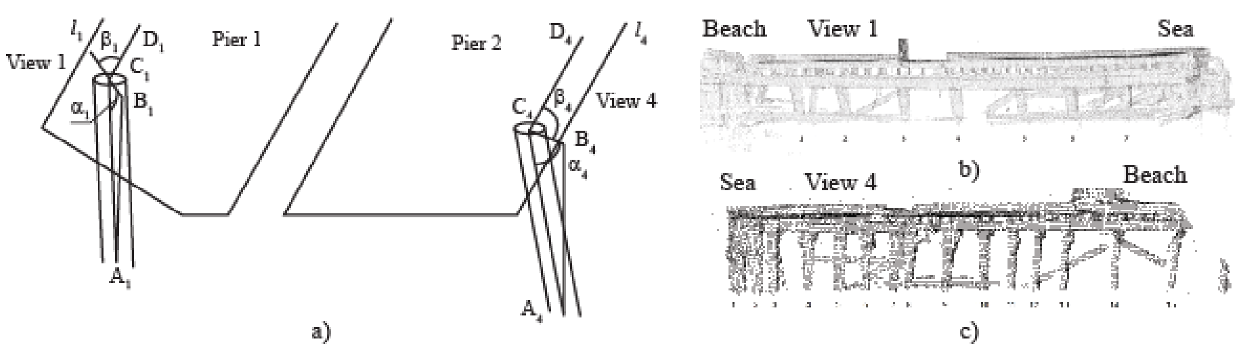


Figure 6. Schematic for the explanation of the inclination angles of the supporting piles of the coal quay (a), images of laser scanner from sides View 1 (b) and View 4 (4) of the quay.

Table 1. Inclination angles of supporting piles on the side View 1 of the quay.

Angles\Piles	1	2	3	4	5	6	7
α_1, degrees	10.69	11.67	9.96	9.33	6.80	7.93	7.65
β_1, degrees	-1.7	-14.69	-11.9	-10.24	0.06	-17.89	-30.07

Table 2. Inclination angles of supporting piles on the side View 4 of the quay.

Angles\Piles	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
α_4, degrees	5.39	0.61	2.61	4.02	5.61	5.05	6.35	6.64
β_4, degrees	89.84	159.37	120.35	135.45	128.3	129.06	166.43	-172.77
Angles\Piles	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
α_4, degrees	8.11	2.79	5.64	3.51	3.41	2.39	5.73	
β_4, degrees	-177.95	127.66	162.34	154.82	165.71	170.01	-162.04	

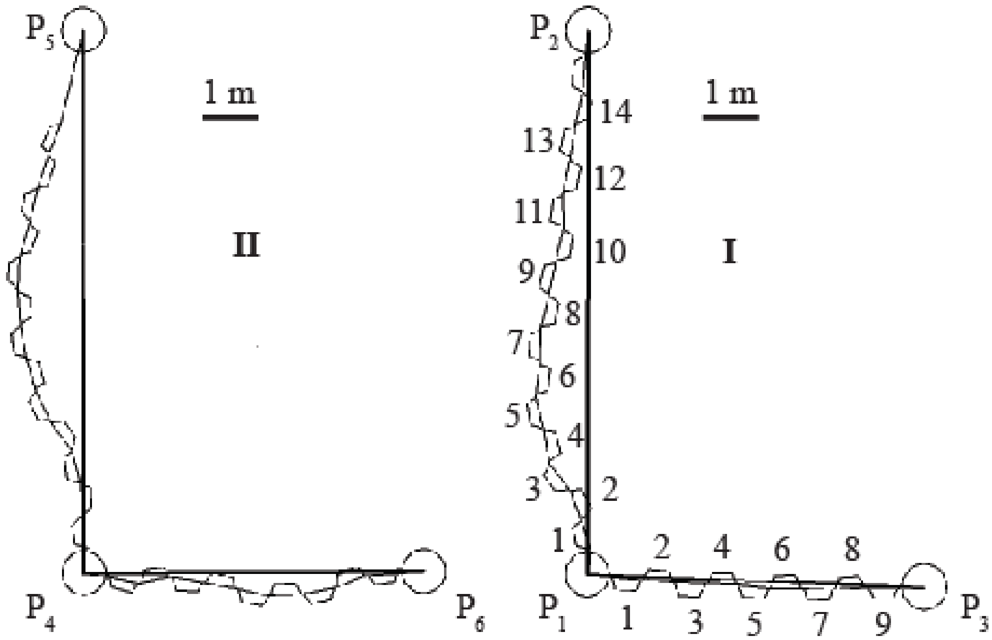


Figure 7. Laser scanner images showing the deformation of the joggle skirts I and II.

Table 3. Inclination angles of the joggle skirts elements.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0.6	2.13	3.07	3.49	2.4	3.54	-0.26	0.16	-1.07	0.42	-2.03	-4.1
13	**14**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
-2.56	1.44	2.13	-1.09	-1.23	1.29	-2.54	1.44	-1.23	-0.22	-1.05	

Deformations of the joggle skirts I and II (Fig. 5a-5b) in the coal quay in Kapp Amsterdam are shown in Fig. 7. Maximal values of the lateral displacements of the joggle skirts from the beam connecting pipes P_1P_2 and P_4P_5 exceeds 1 m. The inclination angles showing the deviation of the joggle skirt elements marked in Fig. 7 from the vertical direction are shown in Table 3. Positive and negative angles show the inclination in out and inward directions with respect to the joggle skirt.

4. Estimates of Physical Environmental Loads

For the interpretation of physical environmental loads causing observed deformations we analyzed the action on of thermal expansion of sea ice and wind forces on the Longyearbyen coal quay, and thermal expansion of the ice hanging on the walls of joggle skirt in the coal quay in Kapp Amsterdam. The modeling was performed with Comsol Multiphysics 4.2a using 2D

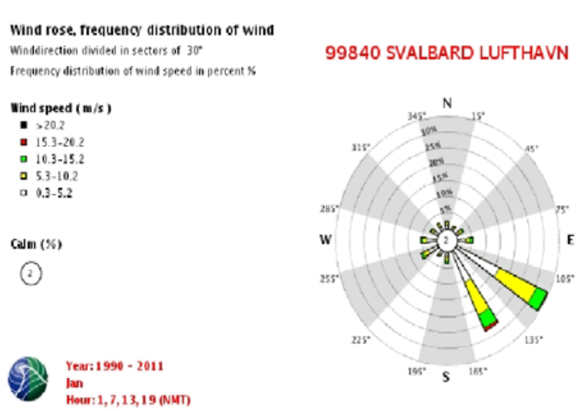
Thermal Linear Elastic Material Model and 2D Linear Elastic Material Model. In the simulations we use the following characteristics of the ice: Young's modulus - 3 GPa, Poisson ratio - 0.33, density – 920 kg/m^3, coefficient of linear thermal expansion $5 \cdot 10^{-5}$ C^{-1}.

Computational domain for the simulations of ice loads in the Advent Fjord is shown in Fig. 8b by solid line A, B, C, O, D,.., J. The location of the coal quay is marked by the black square on the interval OC in Fig. 8b). Wind stresses on the unit area of the ice are determined according to the formula

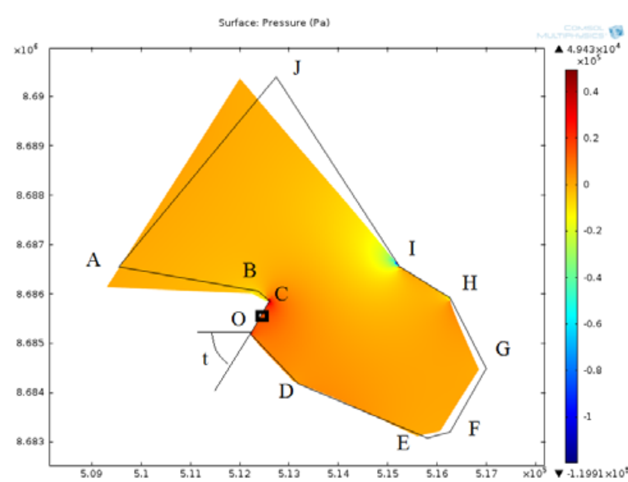
$$F_{wi} = \rho_a C_a |V_a| \mathbf{V}_a, \qquad \textbf{[2]}$$

where $\rho_a = 1.27\,\mathrm{kg/m^3}$ is the air density, $C_a = 0.002$ is the wind drag coefficient, and $\mathbf{V}_a = (V_{a,x}, V_{a,y})$ is the wind velocity. The wind rose performed in Fig. 8a shows that the direction of dominant winds is within 105^o-135^o SE. In numerical simulations we used the absolute wind velocity 30 m/s, wind direction 115^o SE and ice thickness 1 m. The boundaries OC and HI were assumed fixed, and all other boundaries were assumed free in order to exclude their influence on the ice loads over the interval OC. Maximal pressure on this interval was calculated below 50 kPa. This load is very small, but very recurring because of the dominant wind direction.

In simulations of thermal ice loads on the beach of the Advent fjord it is assumed that the boundaries CO, OD, DE, EF, FG, GH, and HI are fixed, and the other boundaries are free. The simulations ice loads were caused by the change of the ice temperature averaged over the ice thickness 0.8 m on 2 C. The displacement fields along the x- and y-directions are performed in Fig. 9. Simulations demonstrated that the ice pressure along the segment OC is varied from 0.8 MPa in the point O to 2.7 MPa in the point C. This load is much higher than the ice load induced by the wind drag, but its repeatability is much lower, because the ice in the Advent fjord is typically destroyed. The angles t (Fig. 8b) of wind and thermal ice loads on the boundary OC are shown in Fig. 9a. One can see that wind induced load could cause the observed deformation of the Longyearbyen coal quay.

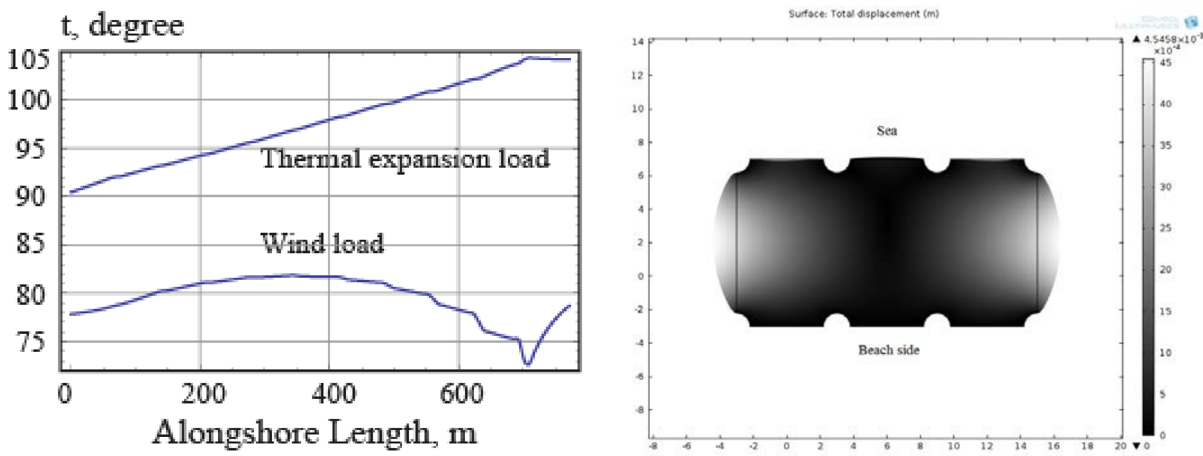


a)



b)

Figure 8. Wind rose for Svalbard Lufthavn (1990-2011) (a), and ice pressure field induced by the wind drag force (b).



a) b)

Figure 9. Angles of ice action on the beach around the Longyearbyen coal quay (a). Deformation of ice confined by joggle skirt in the coal quay Kapp Amsterdam (b).

The results of simulations of ice thermal loads on the coal quay in Kapp Amsterdam are performed in Fig. 9b. It is assumed that the ice thickness is 2 m and the loads are caused by the change of the ice temperature on 2 C. The fixed boundary conditions are used at the boundaries of the supporting pipes, and on beach boundary at the bottom of the computational domain in Fig. 9b. The lateral and sea boundaries of the computational domain bounded by the joggle skirt satisfy the spring condition with the spring constant $10\,\mathrm{T/(m\cdot cm)}$ showing that the load 10 T is necessary for the lateral displacement of the joggle skirt with 1 m length on 1 cm. Fig. 9b demonstrates that the lateral deformations of the joggle skirt are much higher than deformations of the joggle skirt on the sea side. Absolute values of lateral displacements are about few millimeters. Physical processes responsible for the build up of big deformations of the joggle skirt of the quay are related to the brine migration through the ice under the influence of tide induced under ice water pressure and consequent refreezing of the brine (Marchenko et al., 2011).

5. Conclusions

The survey of two quays in Spitsbergen was performed with 3D Terrestrial Laser Scanner Riegl VZ-1000 to clarify natural physical loads caused observed deformations. The use of the laser scanner gave possibility to collect all necessary information in two days. The processing of collected data was performed with RiSCAN PRO and AutoCAD with Kubit PointCloud. From the collected data we extracted the inclination angles of supporting piles in the coal quay in Longyearbyen and distinguished the direction of total displacement of the quay relatively the shoreline. The analysis of dominant winds and ice load shows that they could influence the observed displacement of the quay. From the data collected during the survey of the Kapp Amsterdam quay we extracted the deformation of the joggle skirt. Numerical simulations have shown that this deformation could be caused by thermal expansion of the ice hanging on the walls of the joggle skirt.

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