Behaviour of an Ice Sheet under Heavy Loading

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ABSTRACT

Floating ice covers have been used successfully as a temporary working platform in the past. Ice bridges, ice roads and ice runways are generally subjected to short term loads. Long term loads can be found on ice platforms, which have to support drill rigs for days or weeks. Regardless of the loading scenario, under "normal" operating conditions, a designer has to consider two basic criteria when determining the bearing capacity of an ice cover: a) maximum flexural stresses are not allowed to exceed a predetermined strength level; and b) the maximum ice sheet deflection has to remain below the available freeboard.

This paper presents cases of "abnormal" conditions or heavily loaded ice covers where at least one of the two criteria – exceeding the available freeboard – had been violated.

Floating lake ice had been loaded at 14 places with up to 2,000 t of Run of Mine (ROM) rock material at each shoal location at the two mine sites in the Canadian Territory of Nunavut. The material was dumped on the ice using 60 tonne trucks. The purpose of this project was to construct fish rock shoals. With spring approaching, the rock piles fell to the bottom of the lake creating fish habitats.

Despite extensive crack formations and "abnormal" large deflections, failure of the ice cover did not take place until later in spring due to flooding.

The objective of this paper is to present a challenging project, safely been executed through high level monitoring.

BACKGROUND

The operation of mines in the Canadian North could sometimes result in the harmful alteration or disruption, or the destruction of fish habit. If this is likely to occur, an Authorization pursuant to the *Fisheries Act* must be issued by the Department of Fisheries and Oceans Canada (DFO), which generally includes the requirement for appropriate mitigation and compensation measures to achieve no net loss of productive capacity of habitat. The shoals were placed typically near the lake shore in water depths of about 3 to 8 m. The DFO left the method of construction to the mine operator. The placement of rock material at the bottom of the lake during the open water season was not considered an option.

With no information available to guide winter construction of rockfill shoals, two construction methods were considered: a) placing the rockfill material either through openings in the ice or b) storing the rockfill on the ice and expecting it to drop to the lakebed where the ice melts during spring to form the shoals. For safety reasons, the latter method had been selected.

In 2007 and 2011, at total of 14 rockfill shoals were constructed on floating ice at two mines in the Nunavut Territories. Eight shoals were built on floating lake ice near the Jericho diamond mine in March/April 2007. In April 2011, another six shoals were built on Windy Lake at the Hope Bay gold mine. The two mine locations are shown in Figure 1.

Each shoal consisted of sorted Run of Mine (ROM) rock material, ranging from 0.1 m to 1.0 m with occasional oversized rock of up to 2.0 m diameter size. A typical shoal covered an area of about 1,000 m^2 with a height of 1.2-1.3 m and a total rock weight of approximately 2,000 t. The material was dumped on the ice using 60 tonnes trucks.

Loading a floating ice cover with 2,000 t of rock material and experiencing deflection in excess of 3 x the available freeboard (FB) is from an operational perspective unacceptable and it raised concerns about the safety of the on-ice operators. This paper describes that the risk of a breakthrough can be mitigated through proper monitoring procedures. All 14 rockfill shoals were successfully completed without an on-ice incident!

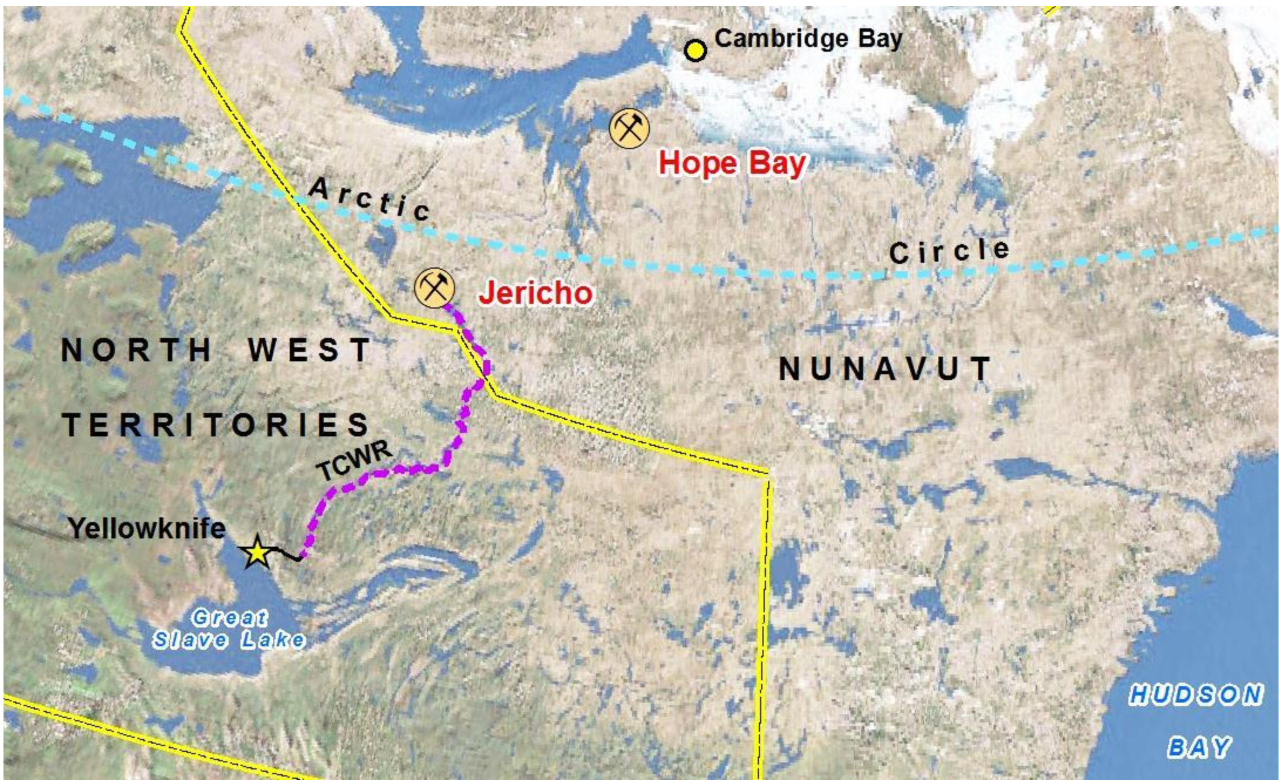

Figure 1. Locations of Rock Fish Shoal mine sites

PLANNING, CONSTRUCTION AND MONITORING

Planning

When planning a floating ice structure subjected to vertical loads, it is considered to be safe if it is allowed to deflect only within the allowable freeboard, and the maximum calculated flexural stresses are less than a predetermined allowable ice stress. Applying these two criteria, would have been prohibitively conservative and would have precluded shoal construction in the time frame required by DFO.

In early April, 2007 shoal construction started at one lake at the Jericho mine. The mine owner left the method of construction up to the contractor. The contractor cleared the ice from snow and placed several loads of ROM material onto the ice. The ice cover cracked and deflected extensively and went into negative freeboard. The area around the dumped rock material flooded. For safety reasons, the mine owner stopped the shoal construction work and insisted on the involvement of an on-site professional ice engineer.

Due to the absence of similar project experience, a safety and monitoring plan was developed involving the design engineer, mine management, safety officers and equipment operators. The plan included effective use of available equipment, rock placement methods, ice cover design, safety and emergency response considerations and monitoring efforts. Safety training sessions were conducted to continuously monitor the behaviour of the ice cover in the shoal vicinity, during rock placement.

30 t CAT 730 articulated trucks with a payload of 30t were used to dump the ROM onto the designated shoal areas. About 60 truckloads were needed to construct one shoal. Ice roads leading to the shoals were designed to carry a fully loaded truck and an empty truck passing by. Conservatively, and for safety reasons only one truck was allowed on the ice at a time.

All shoals were located close to the lake shore in water depths of at least 3 m. The reason for this was that moving ice with an assumed maximum thickness of up to 2 m would not damage the fish habitat in the spring during break-up. The average thickness of the ice cover supporting the shoal material was 1.75 m at all shoal locations. Therefore, all rock piles were placed on floating ice.

Construction

As a first step, snow was removed at the shoal locations. Shoal boundaries were surveyed and ice thickness, freeboard and water depth measurements were taken at the four shoal corners. Next, a 30 cm thick layer of 150 mm maximum size crush material was within the shoal area. The purpose of this protective layer was to minimize damage to the ice during placement of the ROM material.

The placement of the ROM material followed a predetermined sequence developed by the on-site ice engineer. The moment the loaded truck entered the shoal area, the ice engineer walked closely with the truck and was in continuous contact with the truck operator via a two-way radio to alert the driver in case of an unusual behaviour of the ice cover. The most critical moment occurred during unloading of the material when the two rear axles carried most of the load.

Different loading scenarios were applied depending on the shape of the shoal. In case of a near square shape, the first load was dumped in the middle of the shoal on top of the crushed rock as shown in Photo 1. A scaled wooden stick was planted among the rock for monitoring the shoal deflection. Deflection readings were taken and recorded following the placement of 2 to 3 truckloads. After the first load placement, loading of the shoal area was accomplished by placing material at both shoal ends and advancing towards the shoal centre as shown in Photo 1.

In case of a rectangular shaped shoal, placement of the ROM material started at one shoal end and continued towards the other end as shown in the background of Photo 2. In the foreground, a completed rock pile can be seen along with colored ice crack markings. Of interest is a large crack between the lake shore and the rock pile, which marks the boundary between ground fast and floating ice.

Monitoring

The monitoring routine consisted of:

- Taking deflection readings;
- Monitoring number and location of truck loads being dumped;
- Observing and marking crack development on ice and snow; and
- Continuously plotting load versus deflection.

Ice sheet deflections were observed at the shoal centre and at the end of the shoal with the aid of a survey level, which was positioned on the shore. Each truck load was recorded by assigning a number and location on a sketch depicting the shoal layout.

Cracks were monitored by marking the ice with a spray can and indicating the end of a crack with a date and time. Width, depth and location of a crack were recorded. Large cracks with up to 25 cm width were observed at the interface between ground-fast ice and floating ice. No wet cracks were encountered during the shoal construction period. The presence of wet cracks would have ended shoal construction activities. The operation of equipment on water covered ice is unacceptable for safety reasons.

Establishing the real-time relationship between shoal deflection and shoal load, during loading was another important monitoring tool. The start of a non-linear load/deflection relationship would have been an indicator of an eminent failure. To capture long term deformations, deflection measurements were recorded at a few shoals for several days following the completion of the rock placement.

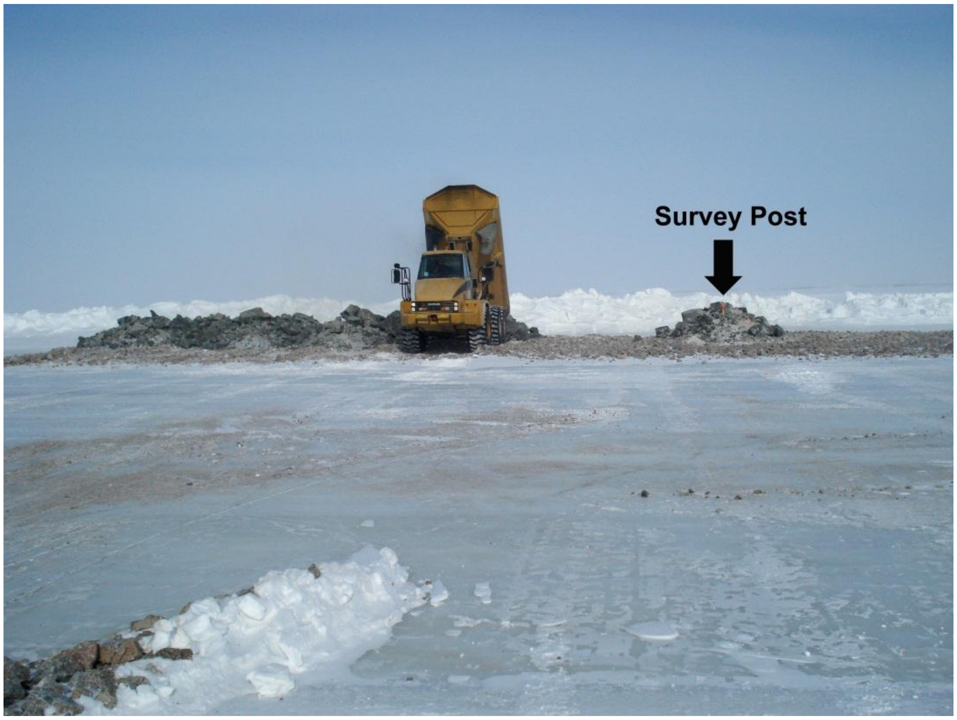

Photo 1. Rock shoal construction with survey post in shoal centre

Photo 2. Completed rock pile with crack markings in foreground; rock pile construction in background

DATA AND OBSERVATIONS

Ice data was collected prior to, during and following the rock placement at all rock shoal locations.

The primary purpose for monitoring the rock shoal construction was to ensure the safety of the equipment operators at all times. Continued deflection measurements were taken following the completion of the rock shoal construction to better understand long term ice sheet deformations under constant loading.

Following the removal of the snow and prior to placing any load onto the ice, ice thickness, freeboard and water depth were measured and recorded at the four shoal corners. The average ice thickness and freeboard measurements at the two mine sites, amounted to 175 cm and 17 cm respectively.

a) During Construction (7-10 hrs.)

It was assumed that with each truck load 30 t of ROM material were added to the rock shoal pile. The construction time of one shoal varied between 7 and 10 hrs. depending on equipment availability. During loading, the truck number and the time at which the truck dumped its load were recorded along with the deflection reading. This enabled the observer to monitoring the behaviour of the ice sheet in real time by plotting the number of truck loads vs. deflection. This was done for three shoals at Jericho and one at Hope Bay (HB6) as shown in Figure 2. Of interest is that the four shoals follow initially the same trend. At about 30 loads, the HB6 deflections increase non-linearly due to delays in loading. Loading of shoal J2 was discontinued for about two weeks. As shown in Figure 2, ice deflections exceeded the available freeboard following the placement of about 50% of the ROM material.

The same deflection data is shown in Figure 3 as a function of construction time. As mentioned above, it should be kept in mind that the ice sheet was loaded gradually. At Hope Bay, deflection measurements were taken at the end of the shoal (E) in addition to the centre location (C). It should be noted that at all time deflection curves (except HB6(C)) pass through the available FB level between two and four hours.

Following the placement of the initial few rock loads, the first dominant crack developed at the ground-fast ice/floating, ice interface due to the difference in support conditions. This initial crack opened up to 25 cm at some shoals with increased loading as shown at the centre of the shoal in Photo 2. This crack continued around the shoal ends away from the shoal. Smaller, circumferential cracks developed at higher loads parallel to the initial crack 8-10 m away on the other side of the shoal. These cracks did not connect forming on continuous circumferential crack. No radial cracks were found at any loading stage at any of the shoals.

The same rock shoal is shown in Photo 3 at the end of May, before it went through the ice. Note the water accumulation around the shoal within a depressed ice cover.

Photo 3. Rock fish shoals, May 28

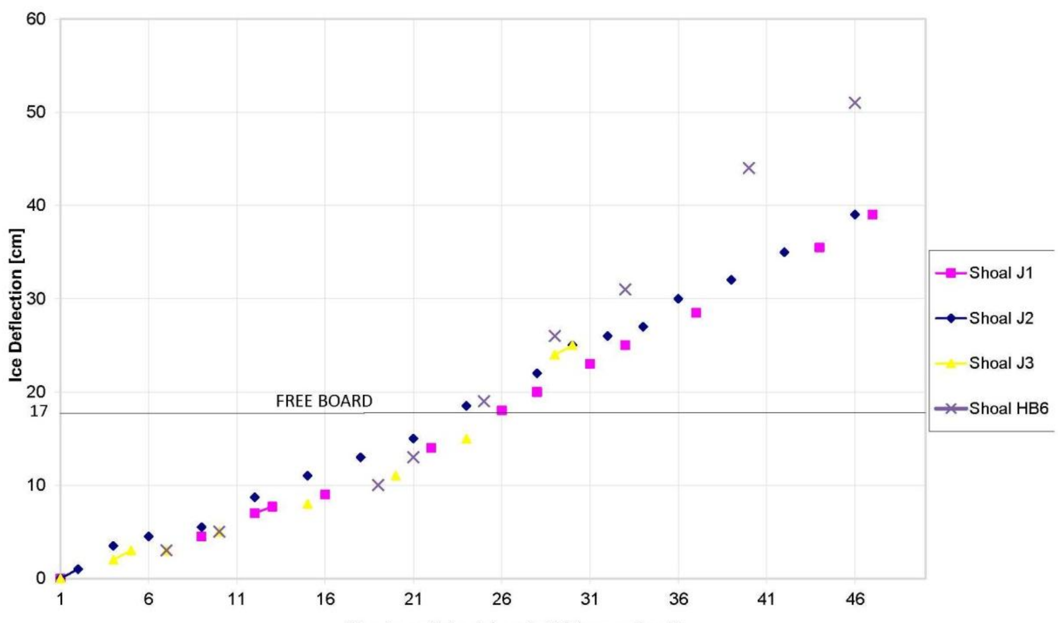

Figure 2. Load-ice deflections during rock shoal construction

b) Post Construction (>10hrs<17 days)

Following the completion of the shoal construction, daily readings were taken over a period of up to 17 days with the survey level remaining at the site. Occasional back site readings were taken to ensure the accuracy of the deflection measurements. Time/deflection data are plotted in Figure 4.

As expected and typical for all shoals is the change of slope deflection after the ice sheet was fully loaded. Long term deflections amounted to 25% and 100% of the initial deflection for shoals HB1 and HB6, respectively. Deflections at the Jericho site were measured at the shoal centre only. At Hope Bay, shoal deflections were monitored at one shoal end and the shoal centre. Centre deflections exceeded deflections at the shoal end. Only during initial loading, higher end deflections were recorded at some shoals as the result of the loading sequence. In these cases, loading commenced at the shoal ends and was completed at the shoal centre.

RESULTS AND DISCUSSION

For safety reasons, deflection measurements, load recordings and crack observations were used to monitor the behaviour of ice covers during rock shoal construction. During construction, deflection measurements were made up of flexural ice sheet deformations, formation and opening up of cracks and time dependent ice deformations (creep). All shoals experienced deflection far in excess of the available freeboard during rock placement.

Continued ice sheet deflections were recorded some time following the completion of rock placement to capture long term (creep) displacements. With the completion of the rock placement, it was assumed that only creep contributed to the continuously increasing deflection of the ice sheet. Creep is defined as the increase in deformation under sustained loading. Creep manifests itself as a progressive decrease in stress with time, also termed as relaxation.

Probably, the most critical moment during construction occurred when the truck unloaded the rock material over the two rear axles amongst previously placed material. Attempts were made to determine the minimum required ice thickness by applying Westergaard's model (1947). Calculations showed that superimposing stresses from adjacent loads, with those from the truck load, would have exceeded allowable stresses.

During the placement of the first few loads, attempts were made to detect a "first crack" which could possibly have initiated a failure mechanism or yield line failure. In this failure mechanism radial cracks or "first cracks" propagate some distance away from the loaded area towards a circumferential crack. A completed circumferential crack most likely initiates an immediate breakthrough. The transition from the "first crack" to a breakthrough occurs normally faster in thinner ice. Peters et al. (1982) stated that thicker ice breakthrough may only be achieved, after additional load increments have been applied, following the development of the circumferential crack pattern. It should be noted and as shown in Photo 2, only "circumferential cracks" but no radial cracks were observed during construction. The “circumferential cracks” did not connect into one complete crack around the shoal.

Within two to four hours following the start of rock placement, measurements indicated that deflections exceed the available freeboard as shown in Figure 3. The data confirms recommendations made in the Government of Alberta Ice Safety Guide (2009), which defines short term loading as a load which remains at one location on the ice for up to two hours.

Following the completion of rock placement, the ice sheet continued to deflect through creep. With no water seeping through cracks onto the ice surface, more water was being displaced with increasing deflection. As shown in Figure 4, some shoal ice depicted little or no deflection increase indicating a steady state. In other instances, creep deflections were as large as deflections obtained during construction.

CONCLUSIONS

1. This paper demonstrates that challenging ice projects can be undertaken, provided all parties involved in the project understand the relationship between monitoring and safety. The risk of a breakthrough of a heavily loaded truck on an already overloaded ice sheet must be managed through proper safety training and high level monitoring. The safety of the equipment operator is the highest priority at all times.
2. Design criteria normally used in the design of ice structures under operating conditions, cannot be applied to the type of heavily loaded ice covers described in this paper. For instance, offshore drilling ice platforms in the high Arctic were thickened to 6 m to support similar loads. Maximum deflections amounted to about 50% of the available freeboard in those cases. Deflections of ice covers supporting rock material exceeded the available freeboard at less than 50% of the fully loaded shoal structure.

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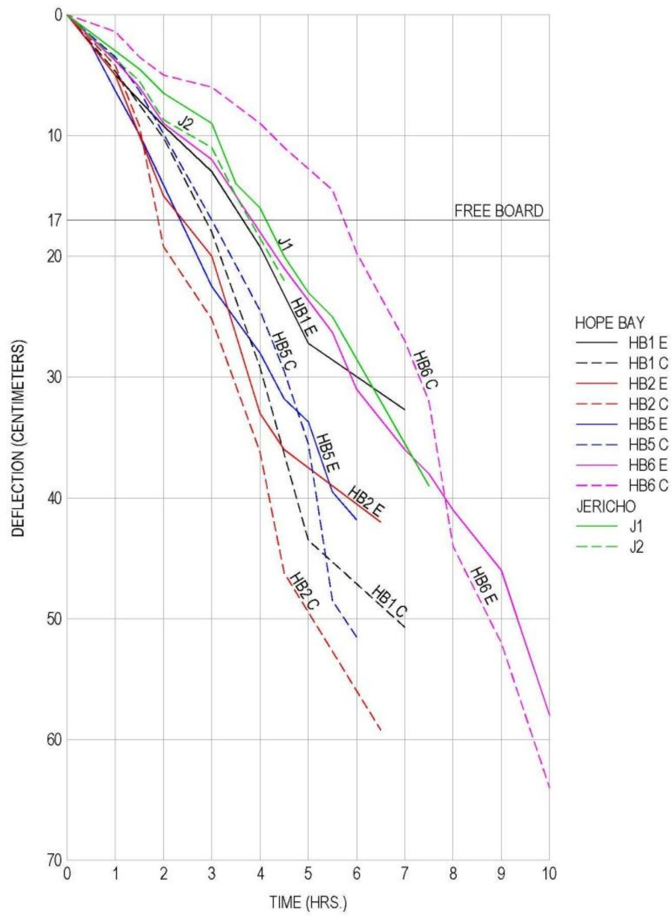

Figure 3. Ice deflections vs. time during shoal construction

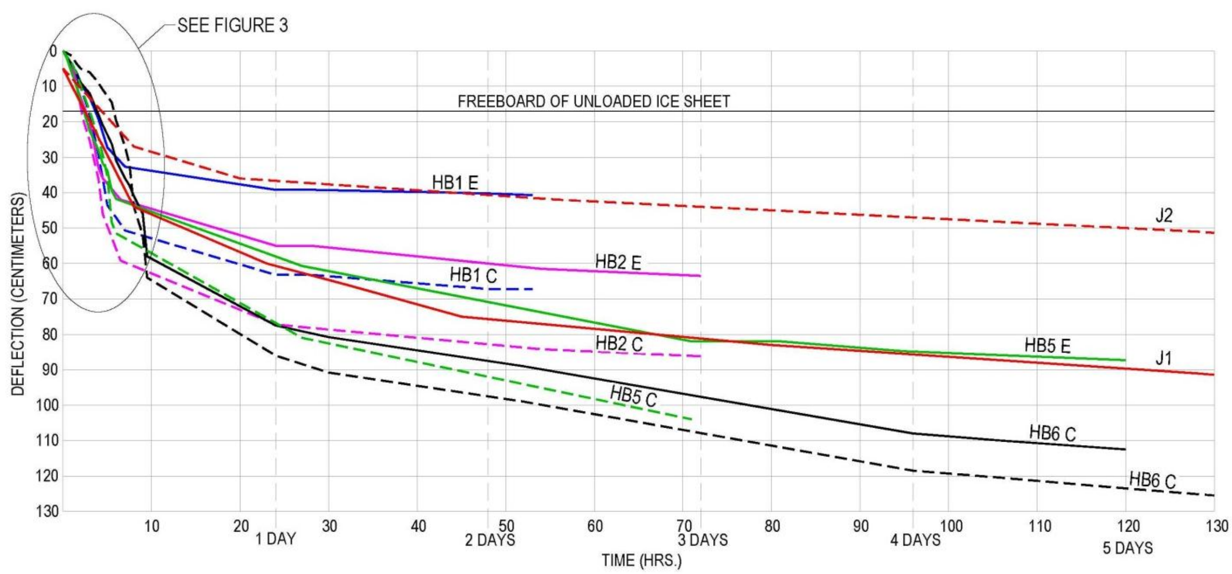

Figure 4. Rock shoal ice deflections vs. time