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Laboratory Measurement of Ice Sheet Creep and Recovery Under Varying Loads

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ABSTRACT

Experiments were conducted in a laboratory cold room to investigate the effects of varying loads on ice sheet creep and recovery. These types of varying loads occur when ice sheets are used as construction platforms or for geotechnical investigations. When a load is placed on an ice sheet, the ice defects elastically; but, if the load remains on the ice for any length of time, additional plastic deformation or creep also occurs. The objective of the experiments was to gain an understanding of the creep recovery process after a load is removed from the ice and the effect of this recovery on the ultimate load capacity of the ice sheet under creep conditions.

In the experiments, a load was first left on an ice sheet until failure occurred and after a new ice sheet of the same thickness was formed, the same load was applied and removed repeatedly over time until the ice sheet failed. The differences in load duration between the tests were then evaluated to determine the amount of additional time the loads occupied the ice sheet under cyclical loading relative to constant loads.

These experimental results will be used to reduce the level of conservatism applied in determining acceptable load duration limits for construction platforms, which may increase the allowable working time on an ice cover.

1. Introduction

Ice covers are used as platforms for geotechnical investigations and construction activities in cold regions because they can be more cost effective and convenient than using barges in open water. These activities often require that large loads be placed on the ice for significant lengths of time. When loads are placed on the ice, the ice deflects, producing a deflection bowl around the load. The ice deflects elastically under short duration loads, but behaves inelastically when loads are left in place for longer durations. Over time, the ice continues to deflect, or creep, even though the load remains constant. The design of these ice platforms requires the specification of both a maximum load and a maximum duration that the load can remain in place.

Maximum allowable loads for creep conditions can be determined from the strain energy criterion developed by Beltaos (1978) which states that the work required to fail the ice sheet is a function of the ice thickness. The work is defined as the load multiplied by the deflection at the onset of failure. For short duration loads, the deflection can be determined from the analysis of an infinite sheet on an elastic foundation. However, as the load remains in place the deflection increases due to creep and the allowable load must be reduced to keep the total work less than the work required to fail the ice sheet.

In many cases, ice platforms are exposed to a variety of complex loading conditions which may vary over time. For example, during the construction of a bridge, cranes may be placed on the ice to lift a heavy girder from a tractor-trailer onto the piers. The cranes must then remain in place supporting the girder while it is bolted in place. This process is then repeated for the next girder with the cranes only a few meters from their previous location. Another example of loads varying over time comes from the demolition of a bridge. In this case, first the bridge deck was broken up and the pieces dropped on the ice for removal by loader and truck. Next, the bridge structure was lowered to the ice where it was cut up and removed by truck. Finally, the bridge piers were broken up and the concrete rubble was allowed to fall onto the ice where it was again removed by loader and truck.

The rate of creep must be known to predict the creep deflection for a given load duration. This may be calculated by a numerical method developed by Van Steenis, et al. (2003) or a simpler empirical method developed by Beltaos and Lipsett (1979). These methods are able to simulate reasonably well the single load event data published in the literature. These data were collected from field experiments carried out with single constant loads, increasing loads, and stepped loads. The empirical method was also able to simulate the measured deflections collected by Erye and Hesterman (1976) during an unloading period. This experiment is the only source of data for a loading and unloading cycle that was found in the literature. No data was found for more complex varying loading conditions where an ice platform was reloaded after being unloaded. Therefore, the suitability of these methods to predict the deflections resulting from these types of loading conditions is not known.

The objective of this study was to determine if the work done to the ice platform is cumulative or if the ice platform recovers during the unloading cycle. If the ice is found to recover, then the ice platform can safely be designed with a smaller thickness and both time and money can be saved.

The results of the study may also be used to validate or improve creep prediction methods for complex loading sequences.

To assess creep behaviour under varying loading conditions, a series of experiments were carried out in a cold room facility located in Northwest Hydraulic Consultants' (NHC) Edmonton laboratory. These experiments were limited in ice thickness due to the size of the facility, but were designed to provide an indication of complex creep behaviour under controlled conditions. The initial experiments were carried out to determine the air temperature and loading conditions necessary to produce creep failures. After a set of experimental conditions were found which could produce a repeatable creep failure under a constant load, similar experimental conditions were utilized with the only change being that the load was removed for a period of time in the middle of the experiment. The results of these experiments were then compared with those from the previous constant load experiments to determine if the total loading time was extended by removing the load for a period of time.

2. Experimental Setup

Ice creep experiments were conducted in a water tank built inside NHC's cold room facility. The cold room is approximately 6.9 m long by 5.7 m wide, and 2.4 m high, with two entrance doors on opposite corners to facilitate access. Cold air from the freeze unit is blown from two sets of fans installed along the top of the long sides of the room. Air temperature in the cold room can be varied between -25 and +20°C with ±1°C fluctuations due to the cycling of the freezer unit.

A 4.7 m square tank 0.6 m deep was built inside the cold room for the ice creep experiments. The floor and sides of the tank were insulated, with two heat tracers installed along the tank sides at depths of 0.37 m and 0.40 m, respectively. These heat tracers were used to melt the ice sheet from the sides of the tank before loads were placed on the ice. Figure 1 shows a picture of the experimental setup used for the creep experiments.

The load was applied to the ice using a load carriage with a vertical cylinder of 16.8 cm diameter, and 24.0 cm in height at its base. A vertical rod was mounted atop the cylinder to secure individual weights added to the loading cylinder. The carriage was connected to a system of pulleys to control raising and lowering of the load. A wooden pathway was constructed above the tank (passing by its centre) to facilitate ice thickness measurements and access to the load carriage.

Measured ice thicknesses were found to vary significantly (±5 mm) across the tank during the initial experiments. Ice was thicker at the centre of the tank, and thinner under the pathway and along the sides. This was because the water surface exposed to cold air blowing from the fans was growing ice faster than the water surface in the rest of the tank. A tarp tent was installed above the tank to deflect the cold air and prevent it from directly hitting the water surface. This resulted in a reasonably uniform ice sheet with thicknesses that varied by only five percent.

Air and water temperatures inside the cold room were recorded every 5 minutes during each experiment using a platinum resistance temperature sensor of ±0.05°C accuracy and 0.003°C resolution [Solinst Levelogger, Model 3001, Canada].

A pressure sensor (accuracy ±0.05 kPa, and 0.0024 kPa resolution) was mounted on the tank bottom, just underneath the loading carriage to measure the pressure changes caused by the deflection of ice sheet. The pressure sensor was sampling at a frequency of 2 Hz.

Ice thickness was measured using an ultrasonic thickness gauge [model QTG-I, Qualitest, USA] that had a resolution of 0.01 mm, and a measuring range between 1 and 400 mm. The instrument was calibrated to ice thickness measured using a digital caliper. It was found that a sound speed of 3600 m/s provided ice thicknesses within ±1 mm of the caliper values. This non-destructive technique allowed ice thickness to be measured at the load location without allowing water to pool in the deflection bowl.

Ice sheet deflection during loading was measured using a draw-wire sensor of 0.1 mm resolution and a measuring range of 1000 mm [WDS-1000-P60-SR-I, Micro-Epsilon, Germany]. The draw-wire was mounted on the ceiling just above the load carriage, and its cable end was attached vertically to the load carriage to record the deflection. Draw-wire readings were sampled at 2 Hz frequency. In order to visually monitor ice creep and failure, a digital webcam (mounted on the wall and pointing downward towards the ice sheet) and an underwater camera (pointing upward at an angle towards the loading cylinder) were used during each experiment and time-lapse images were recorded every 1 minute.

All of the instrumentation was connected to a computer located outside of the cold room and equipped with data-logger software to control and record the data for each creep experiment.

3. Experimental Procedures

The test procedure outlined herein was repeated during each experiment. The ice tank was filled with tap water to a depth of 0.38 m. The freezer was first set to 0°C until the water temperature decreased initially to approximately 1.5°C. The air temperature was then set to -20°C and the ice sheet started to form at an average rate of 1.2 mm/hr. Ice thicknesses were measured periodically (during ice formation) at eight locations: one on each corner, and four at the centre around the loading area. Once the average measured ice thickness was between 17 and 20 mm, the air temperature was set to -1°C to stop ice growth, but also to prevent the ice sheet from melting. The heat tracers were turned on to melt the ice from the tank sides. Typically, this process took about 2 hours for the air temperature to warm to -1°C and the ice sheet to be floating freely. The load carriage was then lowered slowly until it touched the ice sheet without exerting any load on it. The initial draw-wire reading was recorded and then the load was lowered to rest freely on the ice sheet. Deflections were measured until breakthrough failure occurred. Failure typically progressed over time from an initial crack to multiple cracks before breakthrough occurred (Figure 2).

For loading/unloading experiments, the load was lifted off the ice after approximately 3 hours from the start of loading then the load was applied again after a similar time period and left in place until failure occurred.

4. Results and Discussions

A total of 25 creep experiments were conducted. The results of these experiments are summarized in Table 1. Reported ice deflections are the sum of the draw-wire measurements and the water pressure changes: the water level in the tank increased due to the finite volume of the tank as the ice deflected downward, thereby reducing the deflection measured by the draw-wire.

The initial experiments were conducted to optimize the loading conditions that would result in creep failure at a reasonable time frame. Creep failures between 4 to 6 hours after loading were considered optimal. This prevented significant variation in the ice sheet properties and allowed the individual experiments to be completed in a reasonable time period. Ice thicknesses between 14 and 30 mm and loads between 16 and 73 kg were tested.

Figure 3 shows the work done at failure versus ice thickness for all the tests. Initially, the loads were selected on the basis of the relationship between work done at failure and ice thickness developed by Beltaos (1978), but the work done at failure for these thin ice sheets was found to be lower than predicted by this relationship. The trend shown in Figure 3 indicates that failure occur on average when the work done was about one-third of the value predicted by Beltaos' relationship. Test loads were reduced so that the failure would not occur immediately due the elastic deformation of the ice.

The initial ice stress, defined as the load divided by the square of the ice thickness, provides an indication of the relative magnitude of the initial work done to the work required for failure. Figure 4 presents the experimental results for initial ice stress versus time to failure. As expected, the data show a trend of decreasing time to failure with increasing initial stress, but there is considerable scatter.

Some of the scatter in time to failure was found to be a function of the timing of the experiments. Figure 5 shows the change in creep rate with the delay between the time of setting the thermostat to -1°C and the time of loading. There was a considerable change in creep behaviour between a delay of 30 minutes (ID-13) and a delay of 150 minutes (ID-15) and further change when the delay was increased to 720 minutes (ID-17). Most of the effect occurs in the first 150 minutes, but there is still a significant effect after this time. This change in behaviour may be due to the time required to equalize the ice surface temperature with the thermostat setting after the ice growth period is completed.

Two further experiments, ID-21 and ID-24, with initial ice stresses of 543 and 497 kN/m^2 produced failure at 300 and 500 minutes respectively. These loading conditions were then repeated in two further experiments, ID-30 and ID-31, but with the load removed for a period of time. In ID-30, the stress of 701 kN/m^2 was removed after 151 minutes and then reapplied after a further 151 minutes where it remained until failure occurred. In ID-31, the stress of 743 kN/m^2 was removed after 175 minutes and reapplied after a further 215 minutes where it remained until failure occurred. The same load was used for all four of these experiments, but the ice thickness varied slightly. The results of the four experiments are shown in Figure 6. These experiments were carried out with delays in loading of about 120 minutes, so there may be some effect of ice temperature adjustment in the results.

The net time to failure for experiments ID-30 and ID-31 was calculated by subtracting the period for which the load was removed from the total time to failure. As shown in Figure 4, these values are higher relative to the initial ice stress than the two similar experiments with constant loading; they are also higher than the other previous experiments with constant loading. This indicates that the net time to failure increases when the load is removed for a period of time.

The two experiments with varying loads were simulated using the empirical procedure developed by Beltaos and Lipsett (1979) for a variable load scenario. The results of these simulations are shown in Figure 7. Both simulations were carried out with a creep constant of 1100 minutes, which was found to fit the data very well for the initial period before unloading occurred. Unfortunately, no deflection data were collected during the unloaded period, because the draw-wire was attached to the load carriage. After the loading was replaced, the simulations under-predicted the initial deflection and over-predicted the rate of creep. The measurements indicate that the deflections return to the same values when the ice is reloaded, which occurred just before the load was removed and are not lower as suggested by the simulations. The reduced deflection rate also indicates that the ice does not recover from the previous load event. In ID-30, the creep behaved as if the unloading period did not occur, while in ID-31, after a short adjustment period, the creep continued as if the load were applied over the entire time, including the unloading period.

The results of these experiments may not be directly applicable to field-scale load scenarios. Zufelt and Ettema (1996) suggest that thin ice sheets do not deform in the same manner as thick ice sheets and deformation processes may progress at different time scales. The experiments were carried out with natural ice, so there would be no scale effects due to ice strength or modulus of elasticity. However, the grain size of the ice in the experiments was much larger relative to the ice thickness, which might have some effect on creep rates and failure loads.

The ice thickness in most of the experiments was limited to about 20 mm so that the deflection bowl would not be significantly affected by the size of the tank. At this thickness and a typical modulus of elasticity of 2 GPa, the characteristic length of the ice sheet is about 0.6 m. The deflection bowl in an infinite ice sheet has a diameter of about six times the characteristic length, which results in a deflection bowl of about 3.6 m for 20 mm thick ice (i.e., less than the 4.7 m width of the tank). Most of the experiments had characteristic lengths between 0.45 and 0.65 m, thus edge effects are expected to be small. However, some of the experiments carried out with thicker ice would have some edge effects since the characteristic length of these experiments was as great as 1.0 m (Table 1).

5. Summary and Conclusions

The results of these experiments provide an indication of the behaviour of ice creep under varying loads. In the experiments, the time to failure appears to be increased somewhat due to the removal of the load for a period of time; however, the ice did not appear to recover from creep during the unloading sequence. These results are not consistent with each other so it is recommended that the results of these experiments not be used for design until they are confirm with further experimental results.

Further experiments are required to quantify the effects of varying loads more precisely. Additional experiments with the current geometry should be carried out to confirm the results presented herein and also explore a wider range of load sequences. Additional experiments with ice covers with modified strength and elasticity would also allow experiments to be carried out with thicker ice covers. As well, field-scale experiments should be carried out to confirm the creep behaviour for natural ice conditions.

References

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Table 1. Summary of experimental data.

Test	Ice Thickness (mm)	Load (kg)	Instantaneous Deflection (mm)	Net time to Creep Failure (min)	Deflection at Failure (mm)	Characteristic length (m)
ID-1	14.1	50.5	15.2	0	15.2	0.65
ID-4	28.9	50.5	7.0	1500	18.6	0.95
ID-5	30.2	73.2	30.0	3	30.0	0.55
ID-6	32.0	50.5	25.5	7.35	25.5	0.50
ID-7	25.0	16.5	4.5	N/A[1]	N/A[1]	0.68
ID-8	18.1	39.2	20.0	5.1	42.1	0.49
ID-9	25.0	39.2	5.0	NA[1]	NA[1]	0.99
ID-10	14.0	16.5	2.5	0.6	3.5	0.91
ID-11	20.0	18.8	3.5	N/A[1]	N/A[1]	0.82
ID-13	21.0	27.9	15.0	300	23.8	0.48
ID-14	18.0	27.9	15.0	6	20.0	0.48
ID-15	21.0	27.9	15.0	40	20.0	0.48
ID-17	21.0	27.9	15.0	15	20.0	0.48
ID-18	24.0	34.7	20.0	1	20.0	0.47
ID-19	18.0	25.7	10.0	35	20.0	0.57
ID-20	19.0	23.4	10.0	35	20.0	0.54
ID-21	20.1	22.4	10.0	300	20.0	0.53
ID-22	21.0	22.4	4.2	N/A[1]	N/A[1]	0.82
ID-23	18.0	22.4	11.6	60	17.6	0.49
ID-24	21.0	22.4	6.5	500	12.0	0.66
ID-25	18.0	22.4	11.3	450	18.0	0.50
ID-27	21.0	22.4	3.9	N/A[1]	N/A[1]	0.85
ID-29	17.0	22.4	10.0	30	16.5	0.53
ID-30[2]	17.7	22.4	10.0	400	15.2	0.53
ID-31[3]	17.2	22.4	8.0	480	17.0	0.59

Notes:

1. Ice sheet continued to creep for a duration over 1500 minutes with no sign of failure, and accordingly the experiment was terminated before failure occurred.
2. The ice sheet was unloaded for 151 minutes during the experiment.
3. The ice sheet was unloaded for 215 minutes during the experiment.

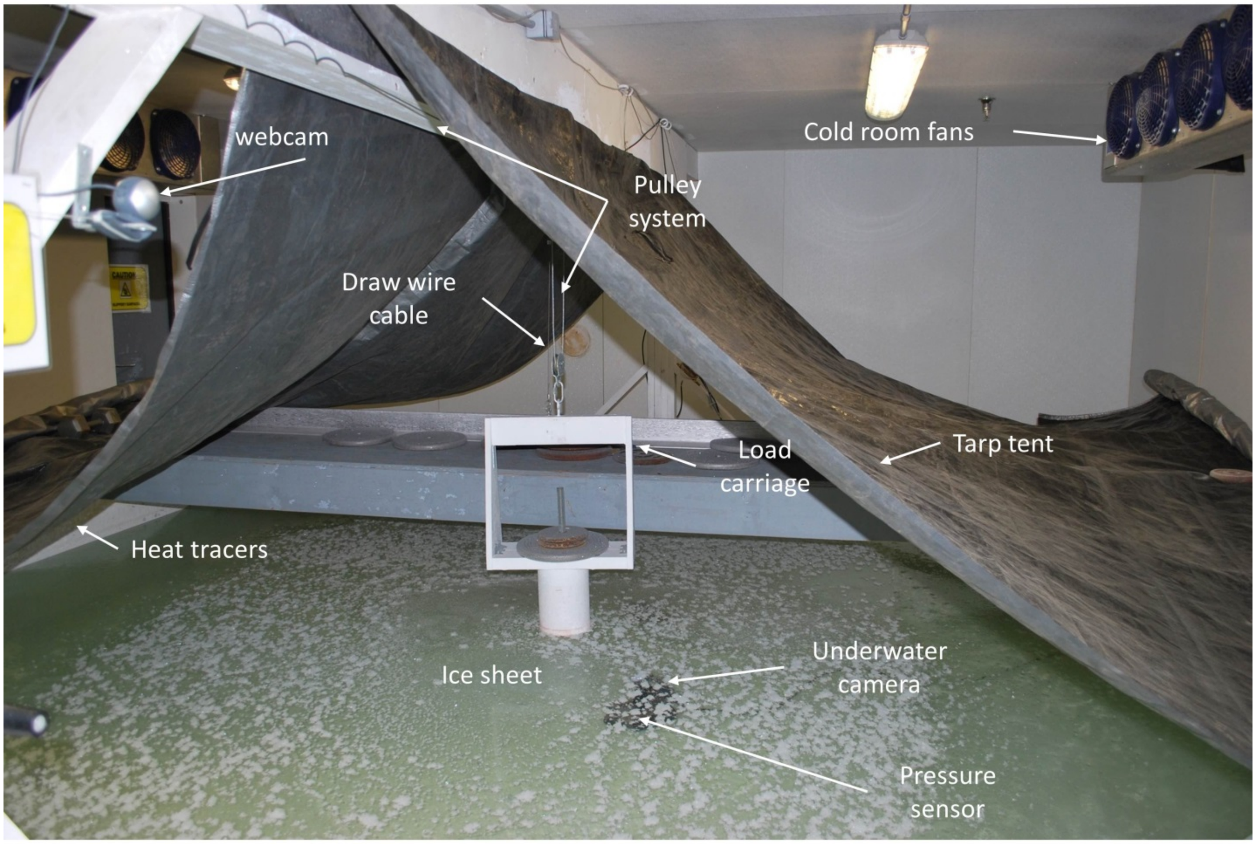

Figure 1. Photograph showing the setup and the location of the instrumentation used for the ice creep experiments.

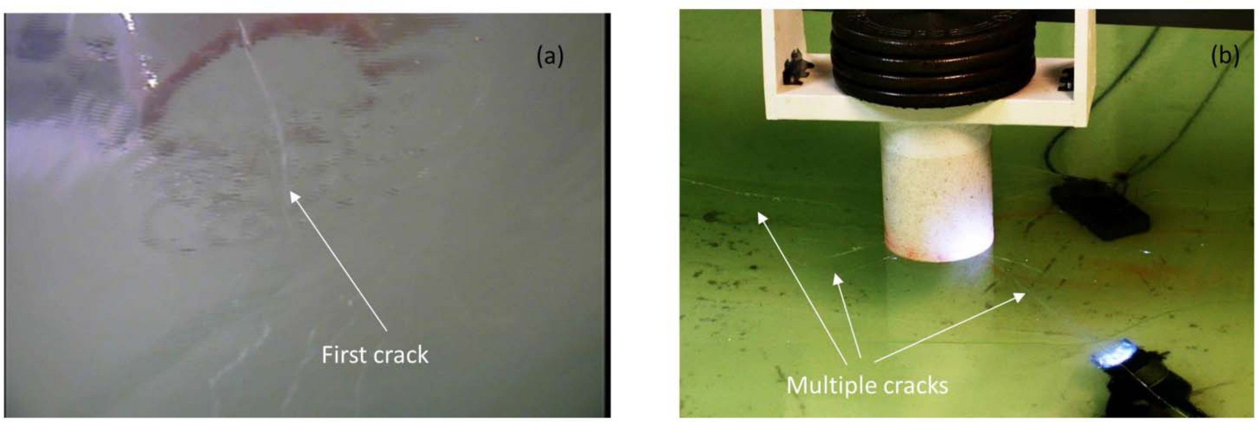

Figure 2. Images of the evolution of ice sheet failure showing (a) the formation of first crack from an underwater camera, and (b) the formation of multiple radial cracks on the ice sheet.

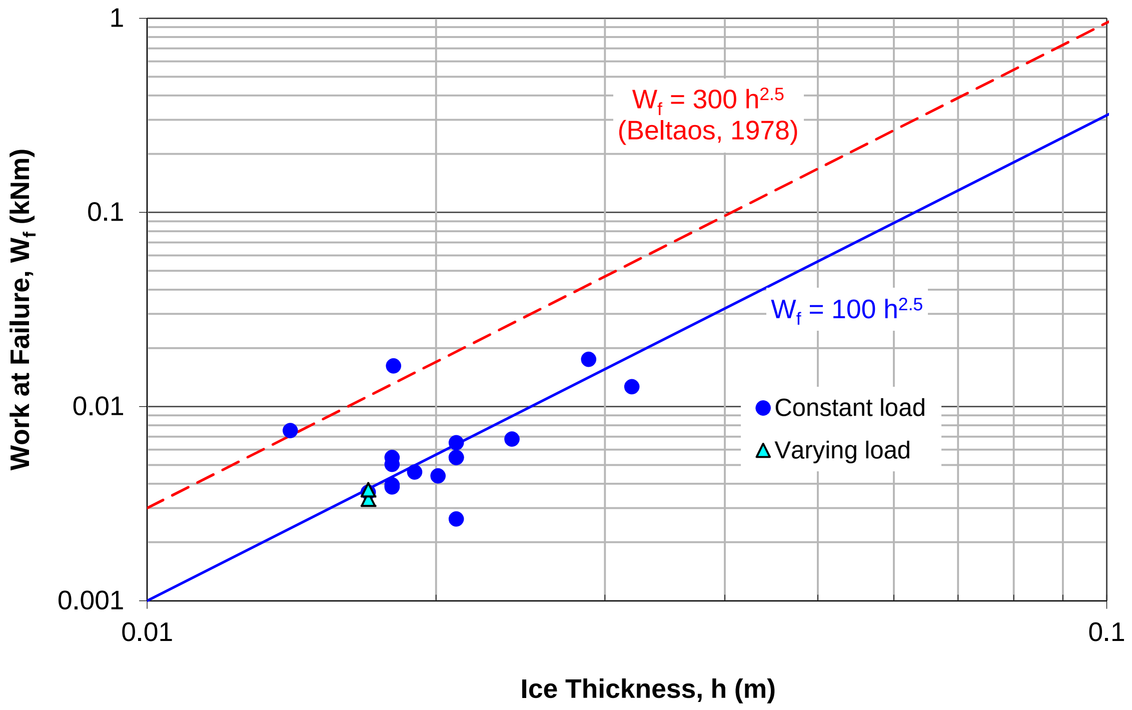

Figure 3. Variation of work done at failure with ice thickness.

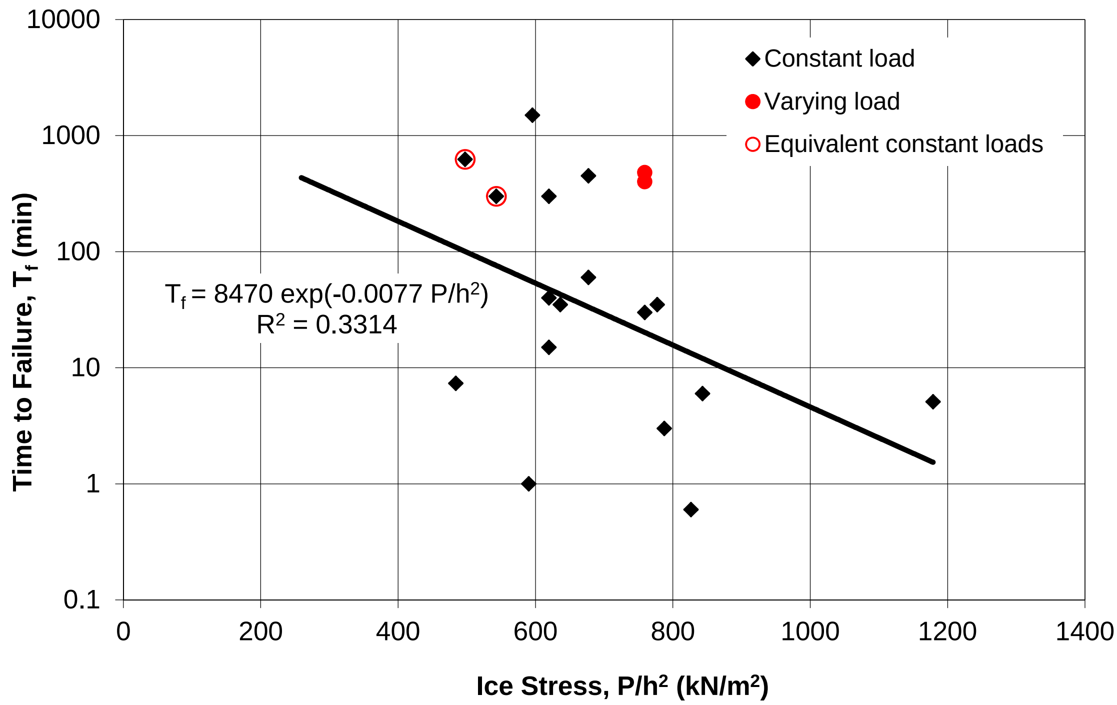

Figure 4. Variation of time to failure with ice stress for different loading scenarios.

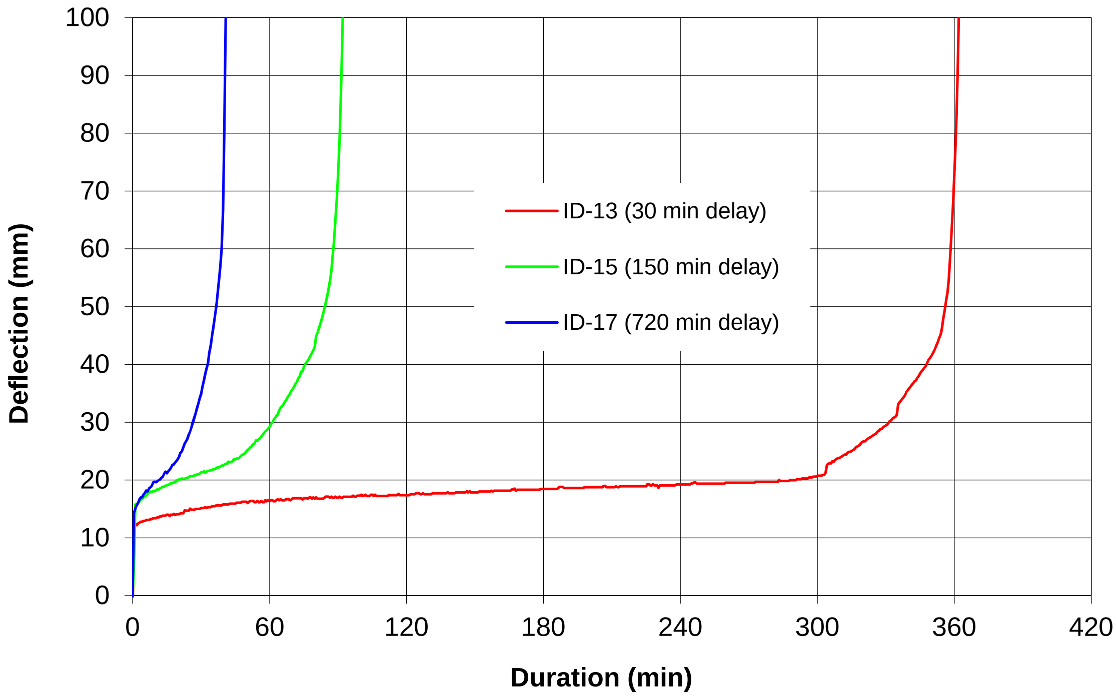

Figure 5. Variation of deflection with duration for various delays in loading.

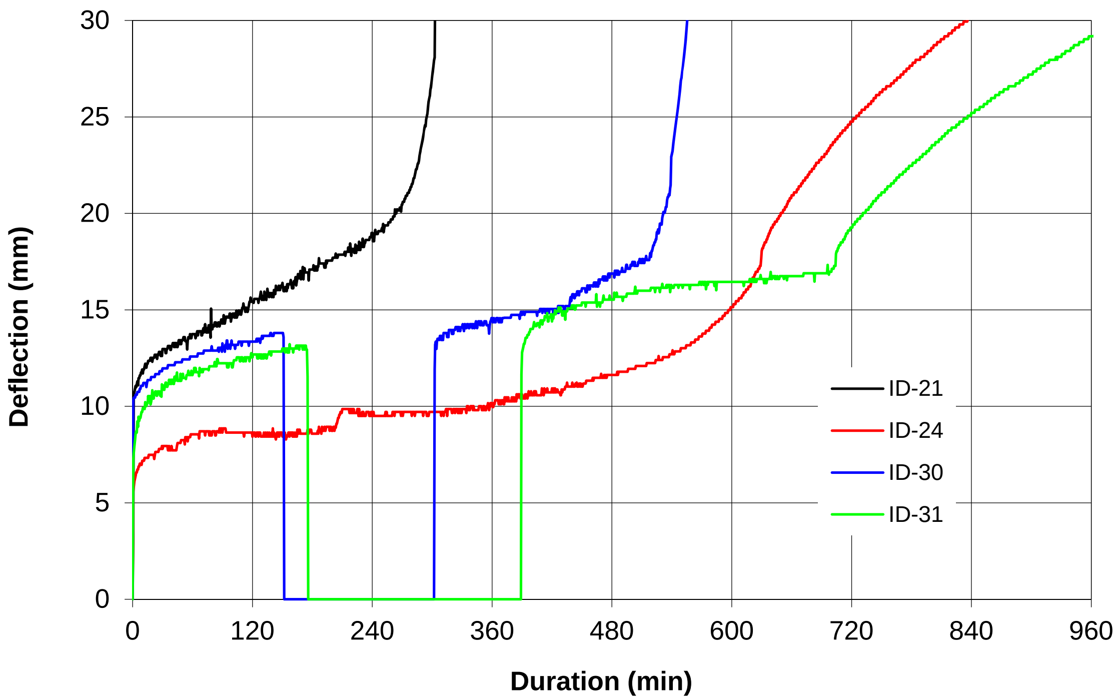

Figure 6. Variation of deflection with duration for two constant load experiments (ID-21 and ID-24) and two varying load experiments (ID-30 and ID-31).

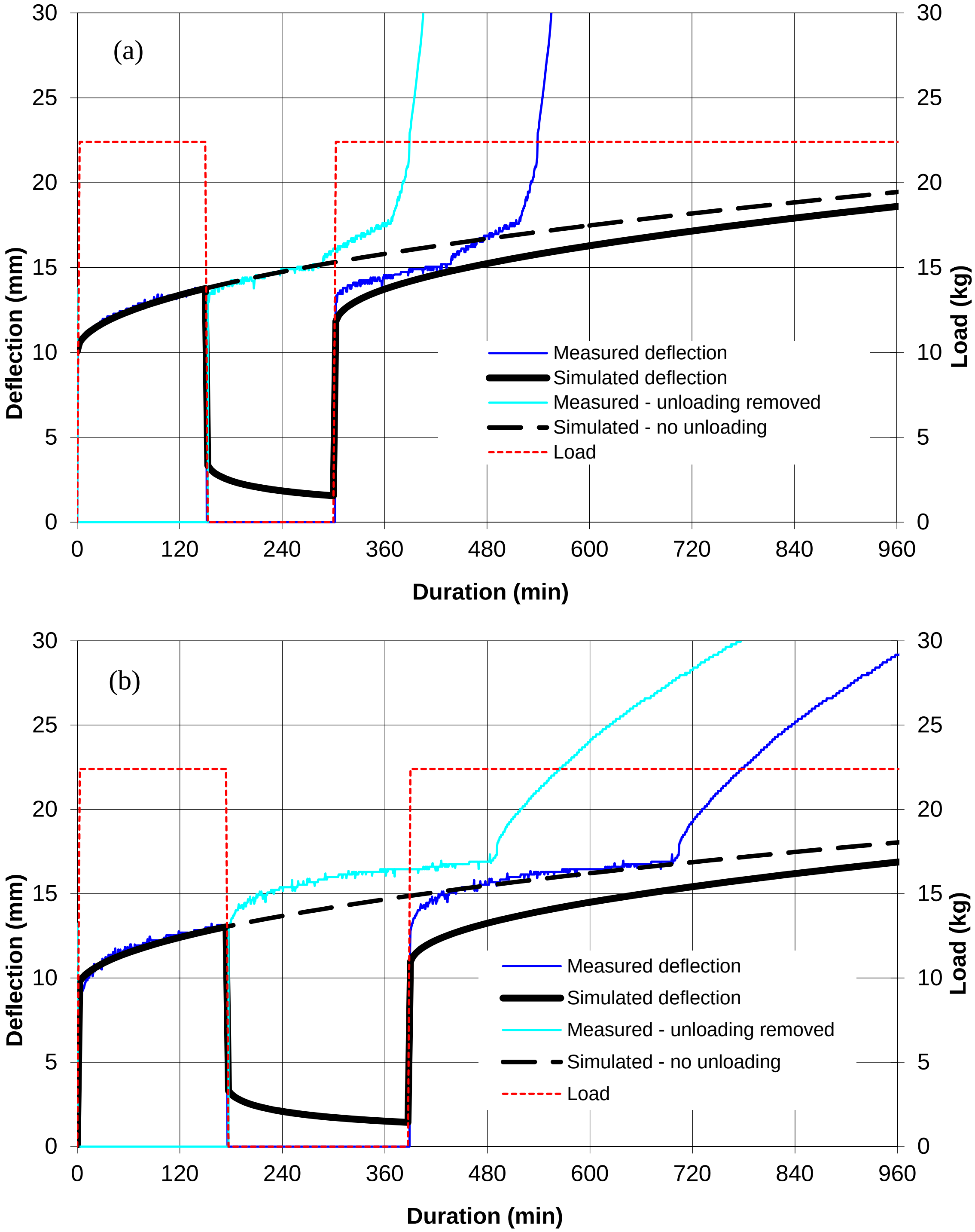

Figure 7. Variation of measured and simulated deflection with duration for (a) ID-30 and (b) ID-31.