File Number:
60240644

Date:
November 2012

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Behavior of Ice Covers under Moving Loads

The Driving Mechanism

Le Gouvernement du Québec, Ministère des Transports

Behavior of Ice Covers under Moving Loads – the Driving Mechanism

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Le 30 novembre 2012

Christian Therrien
Direction de l'environnement et de la recherche
Le gouvernement du Québec, Ministère des Transports
930, chemin Sainte-Foy, 6e étage
Québec (Québec) G1S 4X9

Objet : Comportement d'un couvert de glace soumis à une charge mobile
N/Réf. 60240644

Monsieur,

AECOM Canada Ltd. (AECOM) est heureuse de soumettre au Ministère des Transports le rapport pour le projet cité en rubrique. Vous trouverez en pièce jointe le rapport complet dans les deux langues, français et anglais, comprenant une version électronique et cinq copies papier pour chacune des versions.

Ce rapport présente 1) les résultats des épreuves en chantier réalisées sur la route d'hiver de Tibbitt - Contwoyto aux Territoires du Nord-Ouest durant l'hiver 2012; 2) notre interprétation des processus physiques qui contrôle le comportement d'un couvert de glace sujet à une charge mobile, et; 3) les recommandations pour des études supplémentaires.

Nous espérons que ce rapport soit à la hauteur de vos attentes et vous remercions pour votre collaboration et contribution dans ce dossier.

Nous resterons disponibles à votre convenance pour répondre à vos questions ou pour discuter de l'information présentée. Vous pourrez me rejoindre au (867) 873-6316, poste 22.

Veuillez agréer, Monsieur, l'expression de nos sentiments les meilleurs.

AECOM Canada Ltd.

Michel Lanteigne, M. Ing., P. Ing.,
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ML/jr
p.j. Rapport « Comportement d'un couvert de glace soumis à une charge mobile »

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5	yes	Gouvernement du Quebec, Ministere des Transports
3	yes	Tibbitt to Contwoyto Winter Road Joint Venture
3	yes	Nuna Logistics Ltd.
3	yes	RTL Robinson Enterprises Ltd

Revision Log

Revision #	Revised By	Date	Issue / Revision Description

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Executive Summary

The prevailing theory describing the behaviour of ice covers under moving loads is based on the "hydrodynamic wave concept" developed by L.W. Gold (1971), which states:

"When a vehicle travels on ice covers, a hydrodynamic wave is set up in the underlying water. This wave travels with a speed that depends on the depth of the water, thickness of the ice cover and modulus of elasticity of the ice. If the speed of the vehicle coincides with that of the hydrodynamic wave, the deflection due to the load reinforces that associated with the wave".

Gold did not provide details of the physical processes associated with the formation and propagation of the hydrodynamic wave, nor did he provide conclusive evidence by way of field measurements to confirm the presence of a wave being set-up in the water.

Moreover, during the last 40 years a number of researchers have measured deformations in the ice cover under moving loads, but the presence of any form of energy being transferred to the water, or originating in the water, has never been measured and/or confirmed. Therefore, the hydrodynamic wave concept has remained a theory.

In 2012, AECOM and Northwest Hydraulic Consultants (NHC) carried out a field testing program to determine the physical processes that are at play when a loaded vehicle travels over an ice cover. The Governments of the Northwest Territories and Saskatchewan and Gouvernement du Québec provided financial support for the project. The Tibbitt to Contwoyto Winter Road Joint Venture and Nuna Logistics Ltd. provided support in kind.

The testing program was completed on the Tibbitt to Contwoyto winter road. The program involved measuring the response from the ice cover and water as a loaded vehicle passed by a measuring station at various speeds. Measurements were obtained in various water depths. This report presents the results of the testing program, AECOM's interpretation of the results, and recommendations for further studies.

In summary, when a load is placed on an ice cover, the ice cover sinks into the water like a raft until the weight of water displaced is equal to the weight of the load (*Archimedes principle*). Because the ice cover is flexible, it bends as it sinks to form a "deflection bowl" under the load.

As the vehicle begins to move the deflection bowl moves with it. As the deflection bowl advances it pushes water out of the way. Water is then drawn back after the deepest point of the bowl has passed, and the ice cover begins to rise to its original position.

The deflection bowl is effectively a "vessel" that carries the truck over the water surface. However, because of its flexibility, the shape of the deflection bowl will change as the forces acting on it change with velocity. The motion of a vessel in water is governed by the Bernoulli principle.

The results of the testing program indicate that in deep water (15.5 m) for vehicle speeds up to 17 kph, the response from the water is comparable to static conditions where the ice cover is supported by hydrostatic pressure.

As speed increases above 17 kph, the hydrodynamic response from the water starts to come into play, causing water pressure to diminish under the deflection bowl – as predicted by the Bernoulli principle. As this occurs, the deflection bowl sinks deeper into the water in search of support.

In the speed range we normally refer to as "critical" (38 to 44 kph for the test vehicle in deep water) the responses from the ice cover and from the water are in transition. In this speed range the deflection bowl reaches its maximum

depth and changes shape. A “spike” in water pressure develops just ahead of the deflection bowl and water pressure starts to oscillate behind the spike.

Above critical speed ice cover deflections decrease with speed and the deflection bowl becomes more elongated. However, the magnitude of the spike in water pressure increases with speed, as do the water pressure oscillations.

Drawing an analogy to marine vessels, it appears that critical speed could be compared to “hull speed” for a displacement hull, or the speed where a planing hull would have to “get-up-on-plane” in order to accelerate. Above critical speed the spike in water pressure appears to indicate that the leading portion of the bowl wants to be in planing mode, but the elongated shape that the bowl adopts indicates that its trailing portion remains under the effects of the water. In fact, it appears that the force causing that elongated shape may be compared to the force that pulls the stern (rear) of a displacement hull down when pushed above hull speed. Wild water pressure oscillations demonstrate the unsteady manner in which the hydrodynamic pressure within the spike dissipates.

In shallower water critical speed occurs at a much lower velocity than in deep water; 14.5 kph in 5.5 m of water depth, and 10 kph in 2 m of water depth. This appears to be due to interference from the lakebed amplifying the Bernoulli effect. It is interesting to note that ships travelling in shallow water are subject to the “squat effect”; a phenomenon which causes a ship to sink further when travelling in shallow water. The depth of influence may be related to the width of the deflection bowl, which was measured to be well in excess of 21 m wide.

Although variations in water pressure that occur under an ice cover as a truck passes are sufficient to alter the support provided to the ice cover, the magnitude of these pressure variations is very small: less than 0.89 kPa or 0.1 psi. Therefore, it appears that water pressure variations are of no consequence to the structural integrity of the ice cover.

Failure of an ice cover under a moving load will occur as a result of excessive bending stress within the ice sheet. Below critical speed, maximum bending appears to occur at the bottom of the deflection bowl. Above critical speed, maximum bending appears to occur just ahead of the bowl. Critical speed appears to present the worst of conditions as both the depth of the deflection bowl and the rise in the ice cover occurring just ahead of the bowl reach their maximum value. Therefore, failure of an ice cover could occur either under the load or ahead of it, depending on vehicle speed.

A common interpretation of the hydrodynamic wave concept suggests that a wave of “*substantial physical significance*” is set up in the water under a moving vehicle, and that this wave normally travels at a different speed than the vehicle. The concept attributes the increased deflections occurring at "*critical speed*" to a reinforcement effect that occurs when the speed of the wave coincides with the speed of the vehicle.

Results obtained during the testing program indicate that the deflection bowl behaves like a vessel and that the increased deflections occurring at critical speed are predicted by the Bernoulli principle. The results support Gold’s findings that water depth is a factor. However, although currents may be set-up as water is pushed out of the way and then drawn back after the passage of the bowl, there are no waves of physical significance set-up in the water, and the very small water pressures observed confirm that very little energy is transferred to the water. Moreover, the disturbances to the ice cover and to the water caused by the passage of the vehicle, travel with the vehicle at all speeds. Therefore, it appears that the hydrodynamic wave concept is not valid.

This study was undertaken to improve the understanding of the physical processes that come into play as a vehicle travels over an ice cover so that industry may exploit ice covers safely and cost effectively. Further study is required to better understand these physical processes and to assess whether current operations are properly aligned with these processes.

The current speed limit on ice covers along the Tibbitt to Contwoyto winter road is 25 kph, with a reduced speed of 10 kph when coming on and off ice covers. It appears that vehicles following these speed limits are travelling at or above critical speed where water depths are less than 5.5 m and when coming on and off ice covers. Therefore, the results of the study appear to indicate that current speed limits are not effective at keeping operations outside of the critical speed range.

Minimum deflections appear to occur when travelling either slower than approximately 0.5 of critical speed, or faster than 2 times the critical speed. Keeping operations below 0.5 of critical speed everywhere might not be practical from an operational aspect. This would require lowering speed limits that are already considered low and therefore, increase transportation costs. However, a feasibility study should be conducted to see whether speed limits could be increased instead.

This study supports the opinion that constructing a dogleg on the approach to shore to direct the hydrodynamic wave away from the path of the vehicle is not technically justifiable. This practice places the road over shallow water where trucks might be travelling within the critical speed range and should be abandoned.

The effect of longer vehicles, and closer vehicle spacing should be investigated. The effects of thermal expansion and contraction on the ability of an ice cover to support a moving load should be investigated. The effect of ambient temperature on critical speed should also be investigated.

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Appendices

1. Introduction

During the winter of 2012, AECOM, together with Northwest Hydraulics Consultants Ltd., completed a field testing program to measure the reaction from the ice cover and from the water under a loaded vehicle passing by a measuring station at various speeds. This report provides the results of the testing program, as well as AECOM's interpretation of the physical processes that are at play and recommendations for further study.

The testing program was completed on the Tibbitt to Contwoyto Winter Road. The field program was funded by:

- The Government of the Northwest Territories, Department of Transportation.
- The Government of Saskatchewan, Ministry of Highways and Infrastructure.
- Le Gouvernement du Québec, Ministère des Transports.

The following organizations provided in-kind contributions:

- The Tibbitt to Contwoyto Winter Road Joint Venture and Nuna Logistics Ltd. provided a loaded vehicle and various field support services.
- Northwest Hydraulic Consultants Ltd. provided technical reviews and advice during the project.
- AECOM Canada Ltd. led the research, development and execution of the project.

2. Testing Program

The field testing program consisted of measuring ice cover deflections and water pressure as a loaded vehicle passed by a measuring station at various speeds. The program was completed on the return lanes on Ross Lake (for deep water tests) and Waite Lake (for shallow water tests). The first round of tests was carried out on February 26 and 27, 2012 and the second round on March 20 and 21, 2012.

At the measuring station, a 200 mm diameter hole was drilled through the ice cover. The water depth and ice cover thickness were measured. A 25 mm diameter iron pipe was lowered in the hole through a centralizer and pushed into the lakebed to serve as a fixed reference, as illustrated in Figure A to the right.

A draw wire with ±1.0 mm accuracy was mounted between the pipe and the ice cover to measure ice cover deflections relative to the lakebed. A water pressure transducer with ±0.8 mm accuracy was secured to the pipe approximately 0.5 m below the surface of the ice cover to measure water pressure variations relative to the lakebed. Data from the draw wire and from the pressure transducer was sampled every 0.1 seconds (10 Hz) and recorded by a data logger with an internal clock.

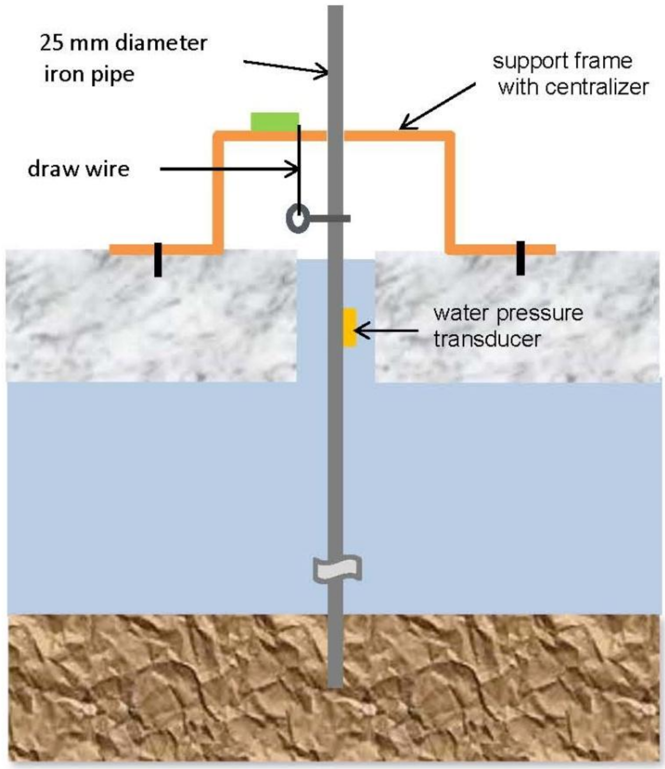

Figure A Equipment Set-up (NTS)

The measuring station was generally offset 3.5 m from the road centreline in order to have the test vehicle safely drive down the centre of the road. The lane was marked with cones to guide the truck so its centreline was consistently located 3.5 m away from the measuring station. On March 21st a series of tests were conducted with the driving lane offset 7 and 10.5 m away from the measuring station.

The vehicle position was tracked by GPS. A proximity sensor, which captured the truck passing by the measuring station, was used to synchronize the GPS clock to the data recorder clock.

Tests were generally carried out with the truck going in both directions in 5 kph speed increments. Speed on the graphs represents average speed calculated from the GPS positions.

The loaded vehicle originally consisted of a tandem axle water truck. On the last day of the second round of tests, the water truck was replaced with a gravel truck in order to have a heavier and more consistent weight (as the water truck continually let water out to keep the pump from freezing).

After the first round of tests, a preliminary review of the results indicated that water currents were being generated by the passage of the truck, and therefore, for the second round of tests, an Acoustic Doppler Current Profiler (ADCP) was also installed at the measuring station. The ADCP was installed in a second hole drilled through the ice cover 1 m away from the first towards the driving lane, and lowered so the sensor was positioned level with the bottom of the ice sheet.

3. Test Results

3.1 General

The results from the field testing program are presented in **Appendix A**. Figures 1 to 10 provide graphs of ice cover deflections and water pressure versus distance for a range of vehicle speeds.

The vertical axis on the graphs provides ice cover elevation and water pressure head in millimeters obtained at the measuring station, while the horizontal axis provides distance from the measuring station where the truck was located when the readings were obtained. These distances were obtained by transforming the measured time series data with the average speeds obtained from the GPS measurements.

For example, the deflection and water pressure readings indicated at –100 m on the horizontal scale were taken when the truck was 100 m before the measuring station. Deflection and water pressure readings indicated at 100 m on the horizontal scale were taken when the truck was 100 m past the measuring station.

The horizontal scale is set so the centreline of the truck is located at zero. Tests were carried out with the truck going in both directions. All results are oriented so the truck is travelling from right to left.

In deep water where the conditions are uniform along the test section, the graphs can be read as a “snap shot” of ice cover elevation and water pressure distribution along the test section taken when the truck was located at zero on the distance scale.

Near shore where site conditions are not consistent over the test section, the results cannot be read as indicated above. For example, 200 m shore side of the measuring station the ice cover appeared grounded. Therefore, the graphs should be considered as representing the responses from the ice cover and from the water only at the measuring station as the truck went by.

3.2 Results in Deep Water

In reference to the results obtained in 15.5 m of water (**Figure 1** in Appendix A), we note that for vehicle speeds up to 17 kph, the ice cover deflects 10 to 12 mm under the weight of the vehicle and water pressure remains relatively constant. The deflection bowl is relatively symmetrical about its centre. However, the centre of the truck is not located in the centre of the deflection bowl, but is slightly ahead of center. The passage of the truck disturbs the ice cover over a distance of 80 to 100 m.

Above 17 kph, water pressure begins to diminish under the deflection bowl, and at 25 kph ice cover deflections begin to increase.

At 38 kph, a “rise” appears in the ice cover at the trailing edge of the deflection bowl and water pressure starts to oscillate at that location.

At 44 kph, the rise at the rear of the deflection bowl has disappeared but one has appeared at the front, and water pressure oscillates for a longer distance along the trailing portion of the bowl. The leading portion of the deflection bowl is becoming steeper and the trailing portion more elongated. A noticeable “spike” in water pressure begins to develop just ahead of the deflection bowl. The water pressure curve follows the ice cover deflection curve quite closely. Variations in ice cover elevation reach a maximum of 22 mm.

Above 44 kph, the ice cover deflection and water pressure curves each adopt a clear pattern, and these patterns "mature" differently as speed continues to increase, as described below:

- Within the ice cover: the deflection bowl becomes more and more elongated, with its leading edge becoming much steeper than its trailing edge. The truck is definitely riding on the leading edge of the bowl. The rise in the ice cover just ahead of the deflection bowl becomes more prominent, and several smaller undulations occur ahead of it. As speed increases above 55 kph, deflections start to decrease overall and the deflection bowl becomes more elongated.

- Within the water: the spike in water pressure occurring just ahead of the deflection bowl becomes greater than the rise in the ice cover. At 49 kph, water pressure at that location rises twice as high as the ice cover. (At 79 kph it rises almost 5 times as high). The oscillations occurring along the trailing portion of the deflection bowl also become more important, and at 52 kph they have moved forward to follow immediately behind the spike in water pressure.

As speed increases, we note that the water pressure oscillations occurring ahead of the spike behave differently than those occurring behind it. Firstly, the frequency of the oscillations created ahead of the spike is lower than the frequency of the ones created behind it. Secondly, the magnitude of the oscillations occurring ahead of the spike remain relatively constant or decrease slightly as speed increases, while the water pressure oscillations occurring behind the spike continue to increase in size, and appear to grow at the same rate as the spike.

At speeds over 44 kph, the passage of the truck causes a disturbance in the ice cover, particularly in water pressure, over a distance in excess of 200m ahead of and behind the truck.

Figure 5 presents results obtained in 5.5 metres of water depth. The upper 2 rows of results were obtained using a water truck weighing 16,700 kg with the truck going in both directions. A full suite of tests could not be conducted; however, the response measured at 14.5 kph appears comparable to the response obtained at 38 kph in 15.5m of water depth (Figure 1). The response obtained at 20 kph appears comparable to the response obtained at 44 or 49 kph in 15.5m of water depth (Figure 1) – as evidenced by the spike in water pressure ahead of the deflection bowl.

The lower 2 graphs on Figure 5 present the results obtained under 2 commercial vehicles.

3.3 Results near Shore

Figure 2 presents the results obtained in 2.0m of water depth, using the water truck travelling from shore towards the center of the lake. These results indicate that maximum deflections of 20 mm at the measuring station were reached at 9 kph. Deflections decreased above this speed. Above 17 kph, deflections were less than 10mm.

Figure 3 shows results at the same site as Figure 2, travelling from the center of the lake towards shore. Maximum deflections reached 30mm at the measuring station at a speed of 12 kph. *(We note that the maximum deflection in 15.5 m of water depth under the same vehicle and comparable ice thickness was 22mm)*. At speeds higher than 20 kph, deflections were less than 10 mm.

Figure 4 presents results from four different commercial vehicles travelling from the center of the lake towards shore at 10 kph on the speedometer.

Figures 6 to 10 present the results obtained under a gravel truck with trailer weighing 31,120 kg. The measuring station was installed in 2.1m of water depth.

In **Figure 6** the truck is travelling from shore towards the center of the lake. Maximum deflections of 18 mm were obtained at 7.6 kph. At speeds higher than 20 kph, deflections were less than 10mm.

In **Figure 7** the truck is travelling from the center of the lake towards shore. Maximum deflections of 25 mm were obtained at 12 kph. At speeds higher than 17 kph, deflections were 10 mm or less. At 6.3 kph, water pressure had not changed.

In **Figure 8** the test lane centreline is offset 7 m away from the measuring station, and the truck is travelling from shore towards the center of the lake. In **Figure 9** the test lane centreline is offset 7 m away from the measuring station, and the truck is travelling from the center of the lake towards shore.

In the upper row of **Figure 10** the test lane centreline is offset 10.5 m away from the measuring station, and the truck is travelling from shore towards the center of the lake. In the lower row of **Figure 10** the test lane centreline is offset 10.5 m away from the measuring station, and the truck is travelling from the center of the lake towards shore.

Results from **Figures 6 to 10** indicate that the response from the ice cover and from the water 10.5 m away from the test lane centreline is generally similar to the response measured 3.5 m away from the test lane centreline, indicating that the deflection bowl is well in excess of 21 m wide.

4. Physical Processes in Play

The ice cover bends under the weight of the truck to form what is commonly called a “deflection bowl”, which moves along with the truck. The deflection bowl encounters resistance as it moves, as evidenced by the fact that the truck’s position is not in the center of the bowl but has shifted in the direction of travel – to the point where at higher speeds the truck is riding on the leading edge of the bowl. The elongated configuration that the bowl adopts as speed increases is further evidence that the deflection bowl is encountering resistance to movement and is reluctantly being pulled along.

In order for the deflection bowl to move, the ice cover must continually move and bend under the passage of the truck. Energy from the vehicle will be spent in overcoming the stiffness and inertia of the ice cover in order to make this happen.

As the deflection bowl advances it pushes water out of the way. Water is then drawn back after the deepest point of the bowl has passed and the ice cover begins to rise to its original position. Therefore, the deflection bowl is effectively a “vessel” that passes across the water surface. Energy from the vehicle will be spent in overcoming the inertia of the water, as well as the friction (drag) between the water and the ice cover.

The results indicate that in deep water up to a speed of 17 kph (see Figure 1 in Appendix A), except for the fact that the truck is located ahead of the centre of the bowl, the response from the ice cover and from the water is comparable to static conditions (i.e. *hydrostatic pressure*).

As speed increases above 17 kph, water pressure starts to diminish under the deflection bowl. As this occurs, the deflection bowl sinks deeper into the water in search of support.

This reduction in water pressure that occurs under the deflection bowl as speed increases above 17 kph is in keeping with Bernoulli’s principle which states: *“for an inviscid flow (i.e. an ideal fluid with no viscosity), an increase in the speed of the fluid occurs simultaneously with a decrease in* pressure.

The Bernoulli principle is illustrated in Figure B to the right. The velocity of the fluid (or air) flowing through the pipe increases as it goes through the narrow section of pipe, which results in reduced pressure.

Also shown in the illustration is the hull of a ship tucked into the top of the narrow section, and the wing of an airplane tucked into the bottom, to illustrate some applications of the principle.

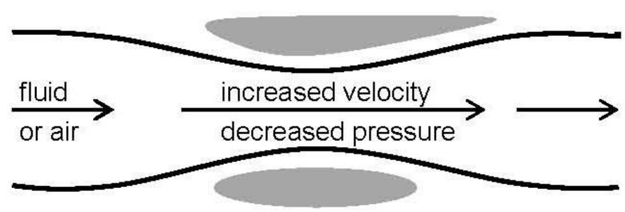

Figure B Bernoulli’s Principle

Between 38 and 44 kph, the responses from both the ice cover and from the water are in transition. In this speed range the deflections reach their maximum value, the deflection bowl is changing shape, and water pressure starts to oscillate. At 49 kph, both the deflection and water pressure curves have adopted a clear pattern that will change as speed increases.

The field of naval architecture offers insight into the processes that are occurring here. Two types of vessels are introduced below: the displacement hull and the planing hull.

Displacement Hull

A displacement hull is one that floats in the water. When under power, a displacement hull pushes water out of the way as it approaches, then water is drawn back after the largest section of the hull has passed.

To minimize resistance, a displacement hull is designed to cause as little disturbance to the water as possible. It typically has a sharp bow (front) to split the water apart, and smooth rounded curves that carry the water around its full body all the way up to the water line at the stern (rear).

A vessel with a displacement hull must work against two major processes: 1 - it must push water out of the way; and 2 - it must overcome the friction (drag) between the water and the hull. The disturbance caused to the water results in the formation of a complex system of waves that propagate in several directions. Of particular interest here are the waves propagating along the vessel hull.

As the speed of the vessel increases, the distance between the waves propagating along the vessel hull also increases, up to the point where the bow and the stern are supported on two successive wave crests, and the center of the vessel is located in a region of low pressure in the trough of the wave. This speed is known as "*hull speed*", illustrated below, and it varies with the square root of the vessel length.

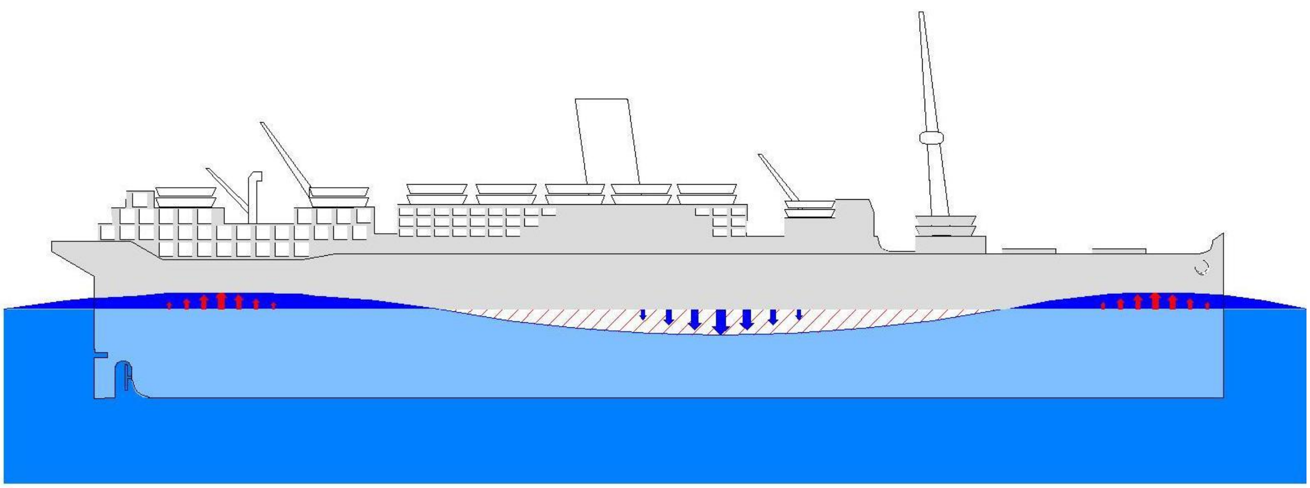

Figure C Hull Speed

When a displacement hull is pushed above hull speed, the bow wave remains under the bow, but the stern wave forms beyond the end of the vessel, placing the stern in the trough of the wave – a zone of lower pressure that pulls the stern further down as speed increases. This process limits the speed that a displacement hull can achieve “economically”. Therefore, because of its shape, a vessel with a displacement hull falls victim to its own wave system.

Planing Hull

A planing hull terminates with a vertical transom at the point where the hull penetrates deepest into the water. At displacement speeds, a planing hull performs terribly as the water lines try to follow the outline of the hull and rise up along the vertical transom. However, as speed increases above "planing speed", the water breaks away from the hull at the transom. This frees the hull from the influence of the water beyond that point, allowing it to rise to the surface.

Figure D illustrates the hydrodynamic pressure distribution under a planing surface.

The magnitude of the lift provided by the water is a function of the flatness of the surface, trim angle and velocity. Everything else being equal, the higher the velocity the higher the lift.

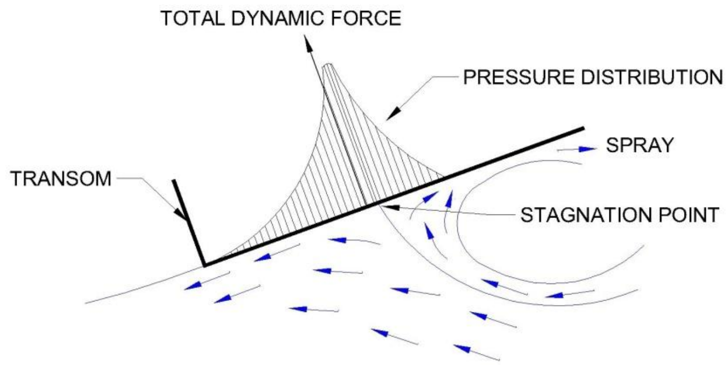

Figure D Hydrodynamic Pressure under a Planing Surface

Going back to the results for deep water, it appears that the zone of transition between 38 and 44 kph, the speed we would normally consider “critical”, could be compared to “hull speed” for a displacement hull, or the speed where a planing hull would have to “get up on plane” in order to accelerate.

Above critical speed, the spike in water pressure occurring just ahead of the deflection bowl appears comparable to the “hydrodynamic pressure” distribution under a planing surface, illustrated above. Because hydrodynamic pressure increases with speed, it is not surprising to see the amplitude of the spike in water pressure also increasing with speed, and the magnitude of the deflections diminishing. The wild water pressure oscillations demonstrate the unsteady manner in which the hydrodynamic pressure within the spike dissipates.

It appears that the force responsible for producing the elongated shape that develops along the trailing portion of the deflection bowl above critical speed could be compared to the force that pulls the stern of a displacement hull down when pushed above hull speed. The results indicate that the average water pressure is negative in this area.

Ahead of the spike, the frequency of the water pressure oscillations is different than the frequency of the oscillations occurring behind it, which indicates that these oscillations are generated by two different processes (as frequency is set by the wave generator).

In the absence of water current information, it is assumed that these are caused by water being pushed ahead by the blunt shape of the deflection bowl along its leading edge, which would tend to push water forward rather than sideways. We also note that the amplitude of the water pressure oscillations occurring ahead of the spike is much less than it is behind the spike, and appears to reach maximum value at 60 kph.

It appears that the rise in ice cover elevation occurring just ahead of the deflection bowl could be attributed to stiffness of the ice cover, which will tend to want to keep the ice cover from bending sharply at water level, thus causing the ice cover to rise ahead to ease the bend.

The results obtained in 2 m of water depth indicate that when travelling over shallow water, critical speed occurs at a much lower velocity – approximately 10 kph as opposed to 38 to 44 kph in deep water.

This situation can be modelled by suspending a curved object (like an empty 4 litre paint can) so it is allowed to swing freely about 40mm away from a wall. If you blow air (from an air compressor) between the object and the wall, you will notice that the object is sucked towards the wall.

If the curved object represents the deflection bowl and the wall represents the lakebed, you can imagine that the same suction effect will draw the deflection bowl downwards in shallow water. This phenomenon is in keeping with Bernoulli's principle.

It is interesting to note that ships are subject to the "squat effect"; a phenomenon which causes a ship travelling in shallow water to sink further into the water. The squat effect has caused numerous vessels to run aground in water depths that would have been sufficient for offshore drafts.

Squat effect is approximately proportional to the square of the speed of the ship. Thus, by reducing speed by half, the squat effect is reduced by a factor of four.

5. Discussion

The empirical approach developed by Gold (1971) to determine safe loads on ice covers made a substantial contribution to the safe use of winter accesses to remote sites. However, the hydrodynamic wave concept that he suggested to explain the physical processes involved does not appear to be valid.

The results of this study indicate that the deflection bowl formed in the ice cover under a loaded vehicle behaves like a vessel moving across the water surface. The motion of a vessel in water is governed by the Bernoulli principle.

Measurements obtained in 15.5 m of water depth indicate that the hydrodynamic response from the water is mobilized between 17 and 25 kph. The reduced water pressure that occurs under the deflection bowl as speed increases above 17 kph is predicted by the Bernoulli principle.

The speed limit on ice covers along the Tibbitt to Contwoyto winter road is 25 kph; 10 kph when coming on and off ice covers. At 25 kph the deflection bowl is in displacement mode when travelling over deep water. This speed coincides with the speed where the hydrodynamic response from the water begins to be mobilized and deflections begin to increase. Therefore, this is the ideal speed limit when travelling over deep water, particularly for heavy loads, because ice cover deflections below this speed are minimal.

However, measurements obtained in 5.5 m of water depth indicate that critical speed was 14.5 kph (Figure 5). In addition, results obtained near a shoreline in 2 m of water depth indicate that critical speed occurred at approximately 10 kph.

Therefore, it appears that:
1) The effect of the Bernoulli principle is very sensitive to water depth, and
2) Current speed limits are not effective at keeping operations below critical speed.

The depth of influence may be a function of the configuration of the deflection bowl; particularly its width. It was found during this study that the response from the ice cover and from the water 10.5 m away from the test lane centreline was similar to the response measured 3.5 m away from it, indicating that the deflection bowl is well in excess of 21 m wide.

Results indicate that variations in water pressure occurring under the deflection bowl are sufficient to alter the support provided to the ice cover, and thereby affect the magnitude of the deflections. However, given that the maximum range of water pressure variations measured was 70mm of head (equivalent to 0.68 kPa or 0.1 psi); these pressure variations appear too small to be of any consequence to the structural integrity of the ice cover.

Above critical speed it appears that ice cover deflections are not affected by peaks in water pressure, but respond to average pressures.

Failure of an ice cover under a moving load will occur as a result of excessive bending stress within the ice sheet. Because the ice cover is flexible, it will bend according to the forces that are acting on it, and these forces change with velocity.

Looking at the results obtained in deep water, it appears that for vehicle speeds up to 38 kph, maximum bending occurs at the bottom of the deflection bowl. Above 52 kph maximum bending occurs just ahead of the deflection bowl. The speed range from 38 to 52 kph appears to present the worst of conditions as both the depth of the deflection bowl and the rise in the ice cover just ahead of the bowl are at their maximum value. Therefore, failure of an ice cover could occur either under the load or ahead of it, depending on vehicle speed.

Below 25 kph in deep water deflections averaged approximately 11mm. Near critical speed deflections doubled at 22mm. Above 52 kph, deflections decreased with velocity, down to 11mm at 79 kph. Therefore, the magnitude of ice cover deflections measured at 79 kph, are equivalent to those measured at 25 kph.

Results near a shoreline in 2 m of water depth indicate that the magnitude of deflections was larger when travelling from the center of the lake towards shore, than when travelling in the other direction. However, deflections were less than 10mm when travelling over 20 kph in either direction.

It appears from the results that smaller deflections occur when travelling either slower than approximately 0.5 of critical speed or faster than 2 times the critical speed.

Keeping operations below 0.5 of critical speed may not be practical from an operational aspect. This would require operations personnel to have a thorough understanding of the bathymetry of all water bodies, to manage a large number of speed limit signs, and to reduce speed limits that are already quite low – which would increase transportation costs. However, if current operations have trucks travelling within the critical speed range and higher without problems, it may be feasible to raise speed limits without compromising safety. Further study is required before this can be implemented.

This study supports the opinion that constructing a dogleg on the approach to shore to direct the hydrodynamic wave away from the path of the vehicle is not technically justifiable and should be abandonned.

6. Recommendations for Further Studies

This study was undertaken to improve the understanding of the physical processes that come into play as a vehicle travels over an ice cover to help industry manage risk and optimize operations. Additional information is required to further understand these physical processes, and to assess whether current operations are properly aligned with these processes.

1) The relationship between water depth and critical speed should be studied. The Bernoulli effect appears to be amplified as water depth decreases.

2) It appears that the feasibility of increasing speed limits should be studied. If current operations have trucks travelling within the critical speed range as the results appear to indicate, this provides justification for studying the feasibility of increasing speed limits rather than lowering them.

3) The behaviour of the ice cover under longer vehicles, and closer vehicle spacing should be investigated.

4) Stiffness is a measure of an ice cover's ability to resist bending. Given that stiffness of ice varies with temperature, ambient temperature may have an impact on the behavior of an ice cover under a moving load. Tests to compare the behaviour of an ice cover between cold and warm temperatures were not part of this study. However, it is recommended that these be completed.

5) The effects of thermal expansion and contraction of the ice cover should be investigated. We know that when ambient temperature decreases the surface of the ice cover shrinks and develops tensile cracks. When ambient temperature increases the ice cover expands and pressure ridges form in the cover.

   However, given that the bottom of the ice sheet is continually at 0 ºC, it will not be subjected to thermal forces when ambient temperatures change. Thermal expansion and contraction of the top of the ice sheet will create tensile and compressive stresses at the bottom, which could affect the ability of an ice cover to support a moving load and should be investigated.

6) An attempt to measure water current direction and velocity was not successful because of equipment freezing problems. Further studies should include water current information to gain a better understanding of water movement in relation to the deflection bowl.

7. References

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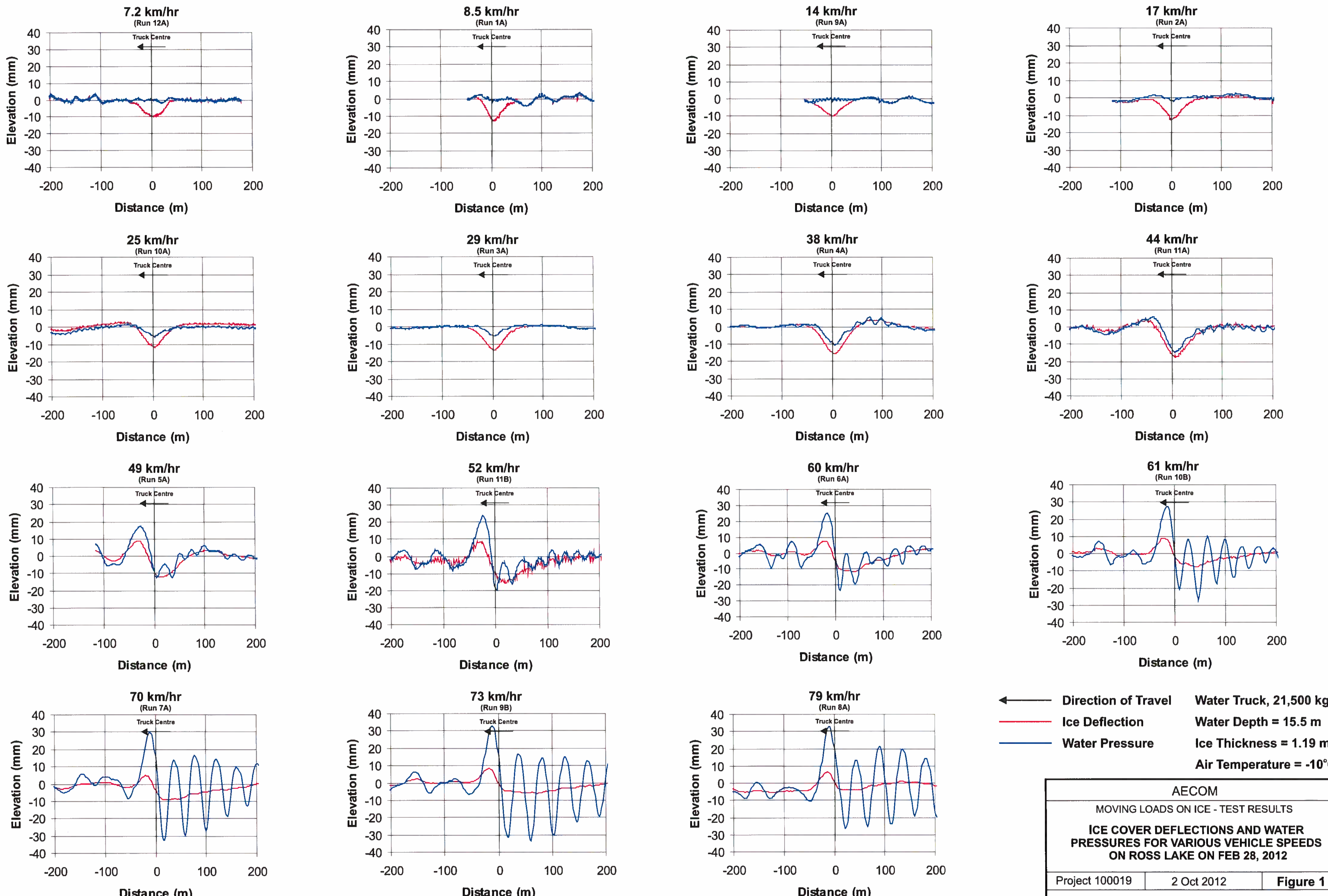
Appendix A

Field Testing Program – Test Results



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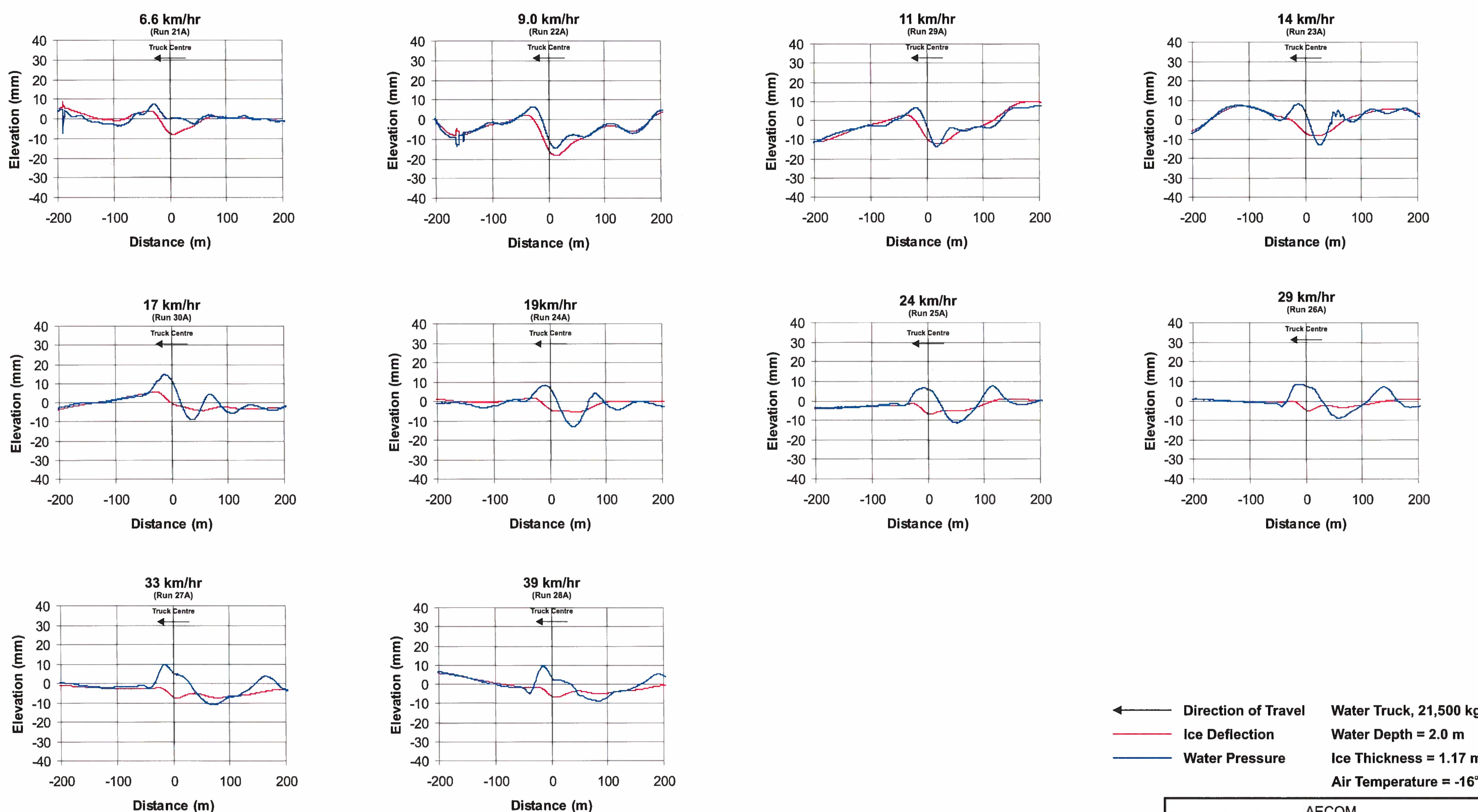
MOVING LOADS ON ICE - TEST RESULTS		
ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS ON ROSS LAKE ON FEB 28, 2012		
Project 100019	2 Oct 2012	**Figure 1**
northwest hydraulic consultants ltd.		



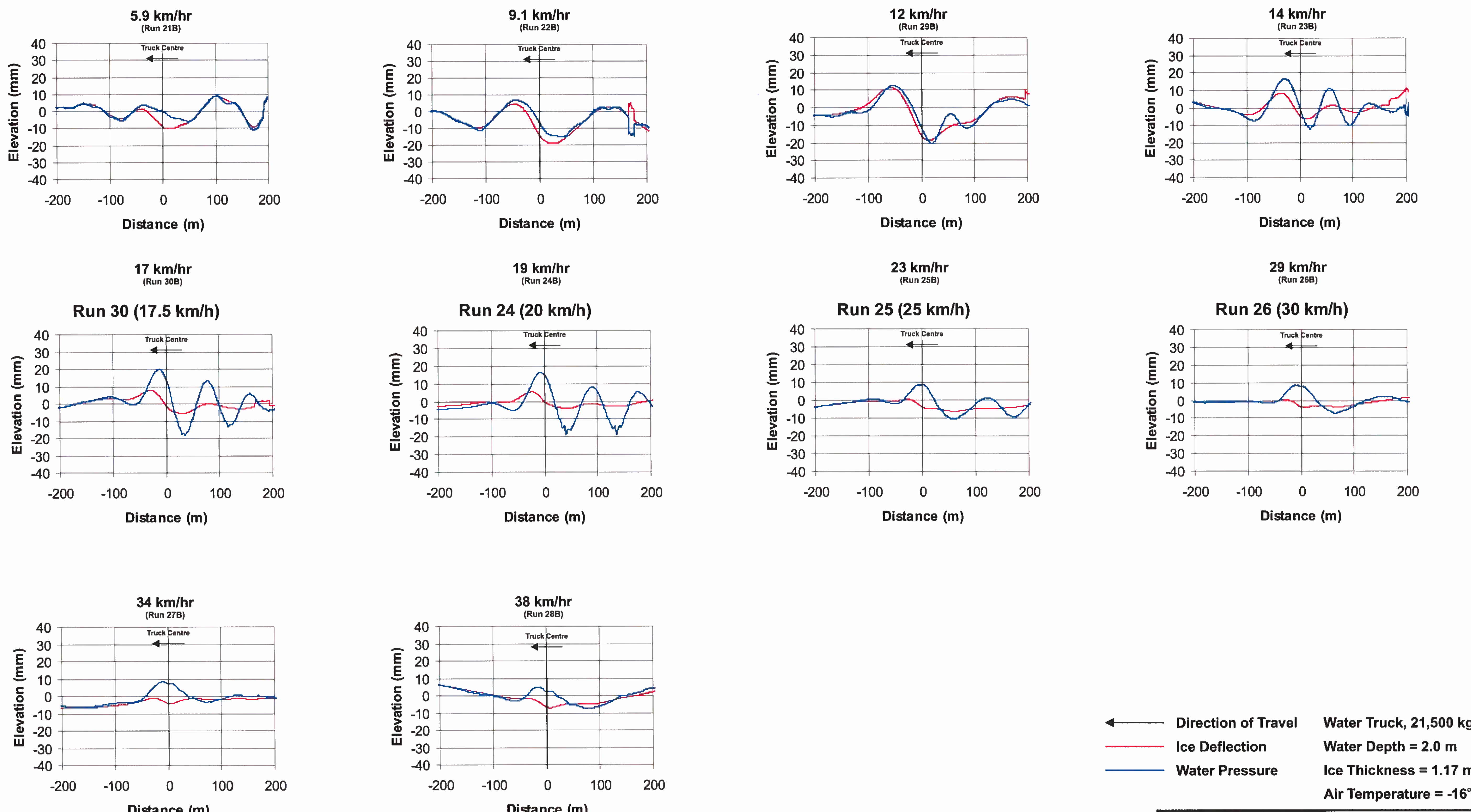
AECOM

MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM SHORE TO ICE ON WAITE LAKE ON FEB 29, 2012

Project 100019	2 Oct 2012	**Figure 2**

northwest hydraulic consultants ltd.



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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM ICE TO SHORE ON WAITE LAKE ON FEB 29, 2012

Project 100019	2 Oct 2012	**Figure 3**

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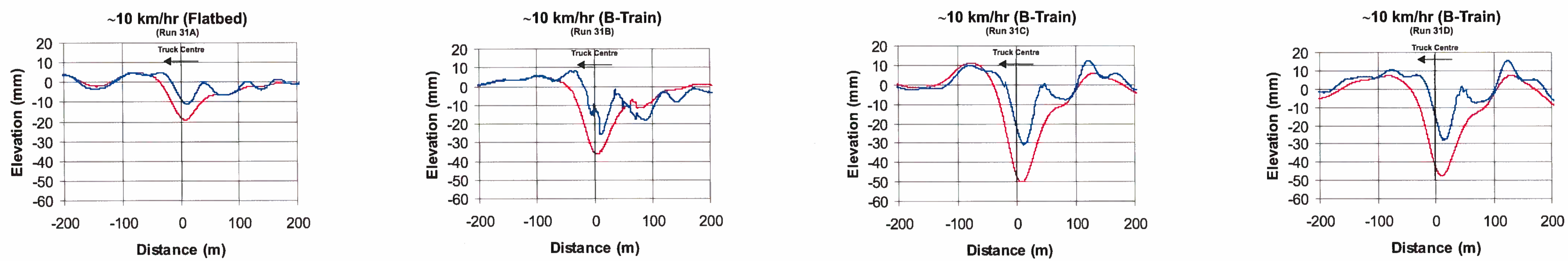

Direction of Travel
Ice Deflection
Water Pressure

Air Temperature = -16°C
Water Depth = 2.0 m
Ice Thickness = 1.17 m

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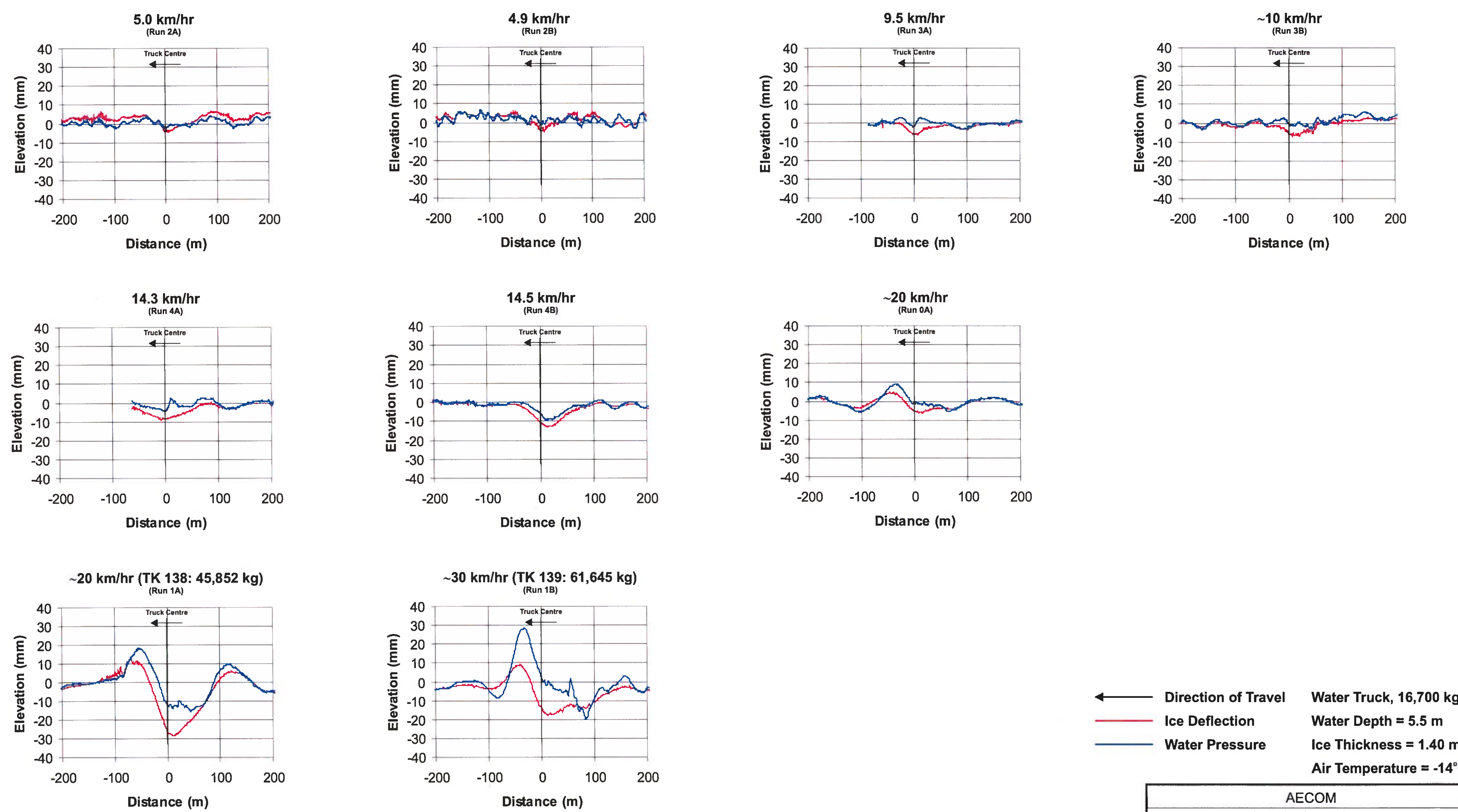
MOVING LOADS ON ICE		
ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS LOADED TRUCKS TRAVELING FROM ICE TO SHORE ON WAITE LAKE ON FEB 29, 2012		
Project 100019	2 Oct 2012	**Figure 4**
northwest hydraulic consultants ltd.		



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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS ON ROSS LAKE ON MAR 20, 2012

Project 100019	2 Oct 2012	**Figure 5**

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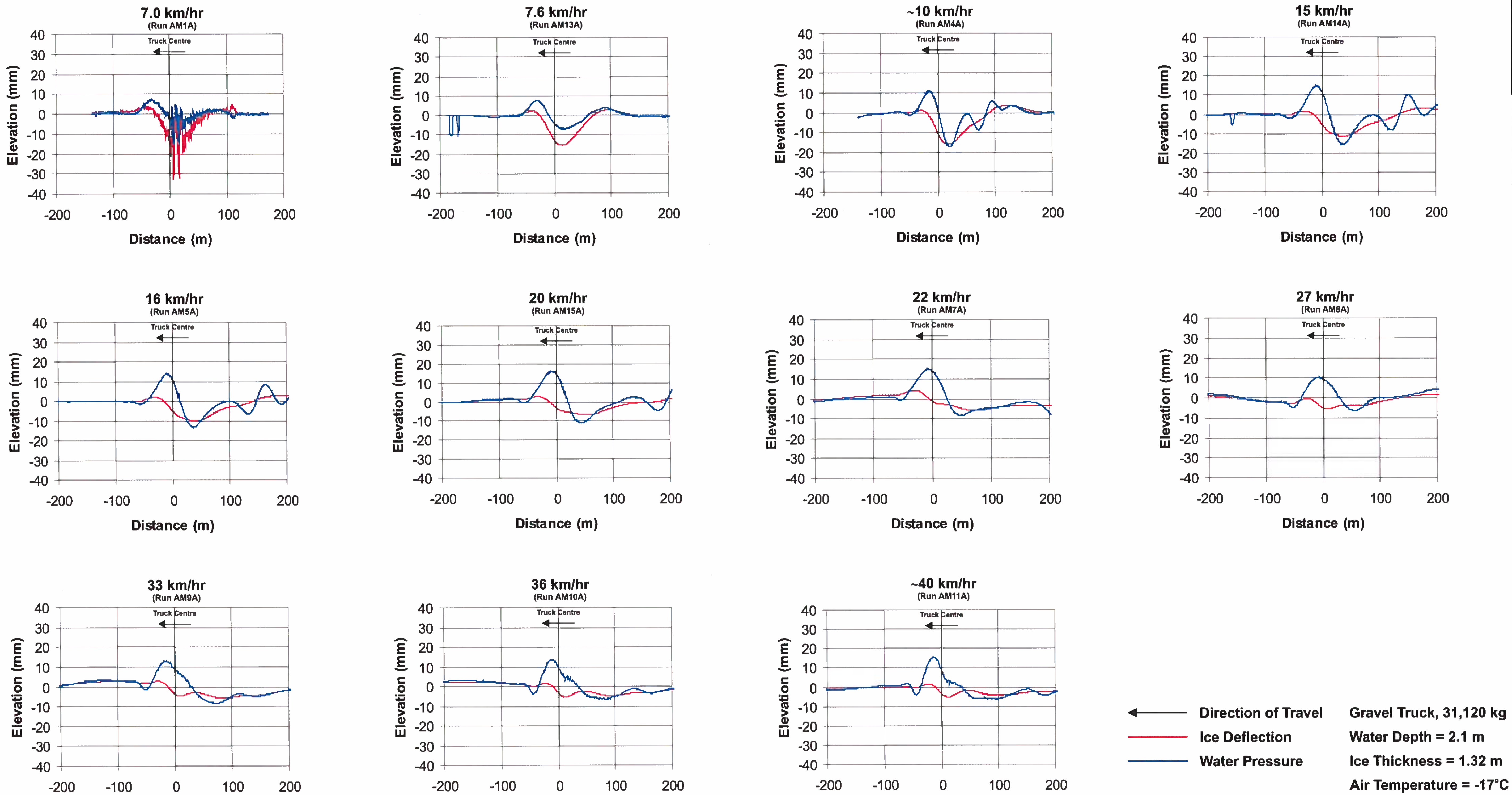

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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM SHORE TO ICE ON WAITE LAKE ON MAR 21, 2012

Project 100019	2 Oct 2012	**Figure 6**

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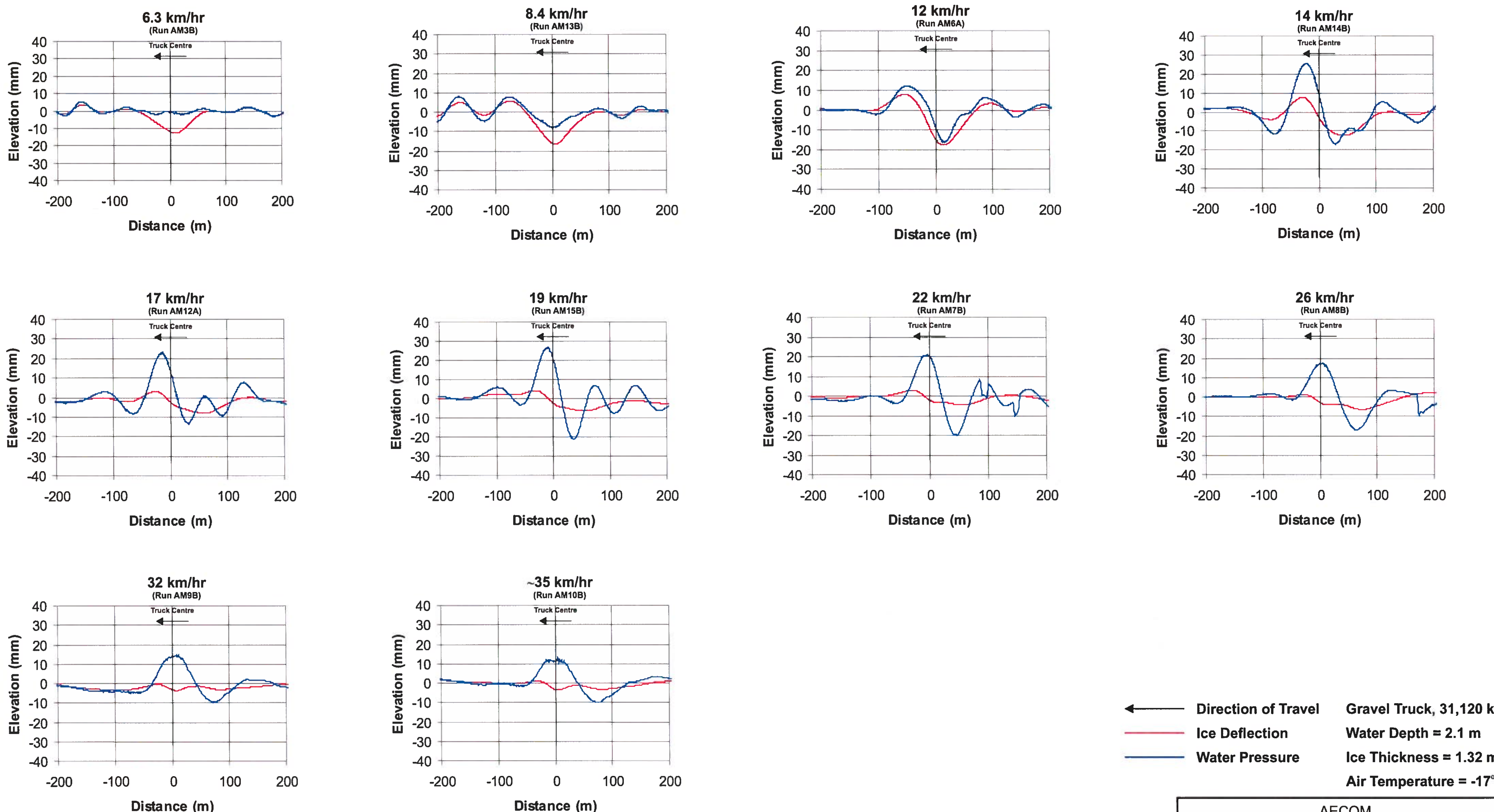

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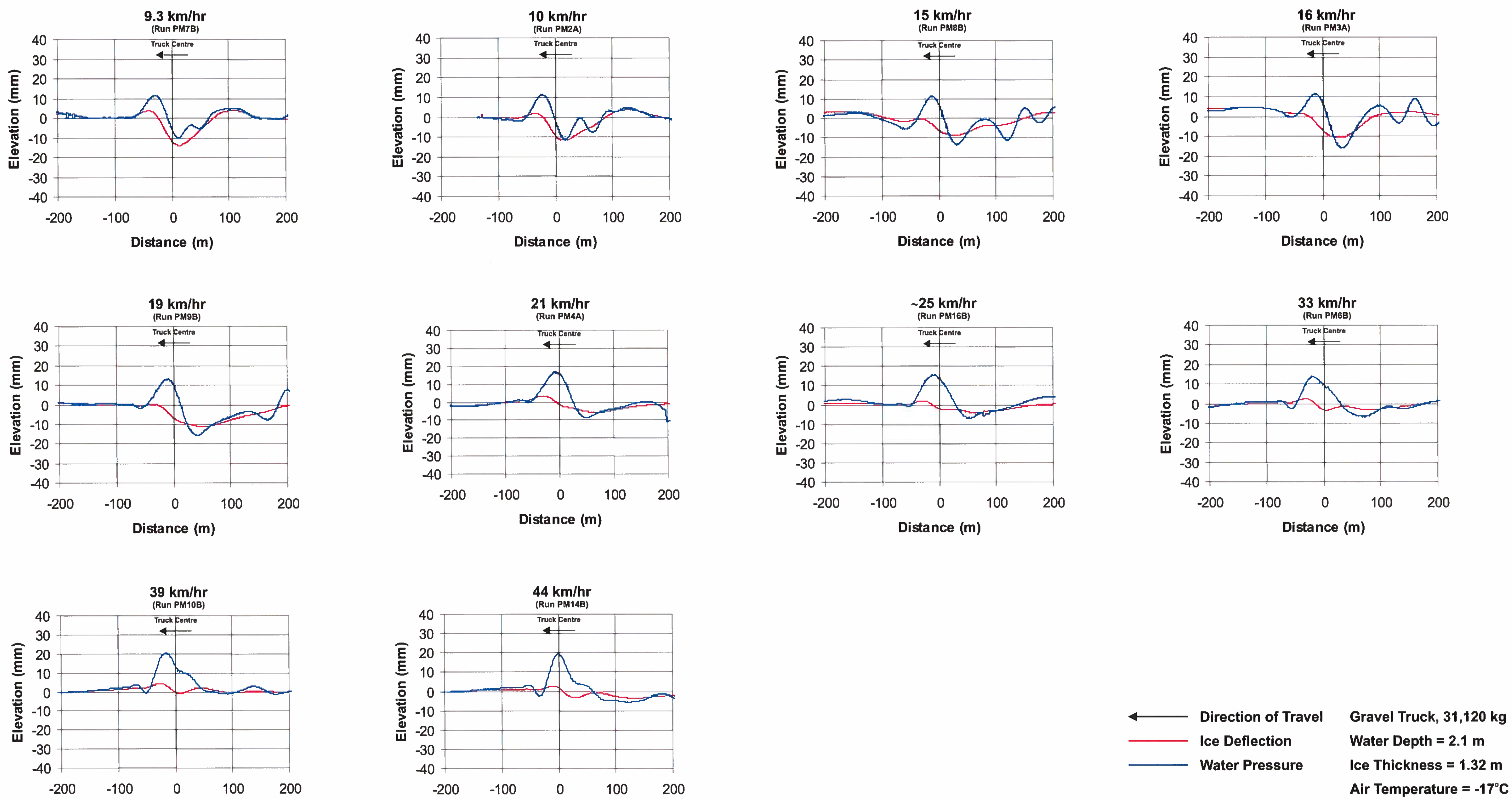
MOVING LOADS ON ICE		
ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM ICE TO SHORE ON WAITE LAKE ON MAR 21, 2012		
Project 100019	2 Oct 2012	**Figure 7**
northwest hydraulic consultants ltd.		



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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM SHORE TO ICE 7 m FROM TEST HOLE ON WAITE LAKE ON MAR 21, 2012

Project 100019	2 Oct 2012	**Figure 8**

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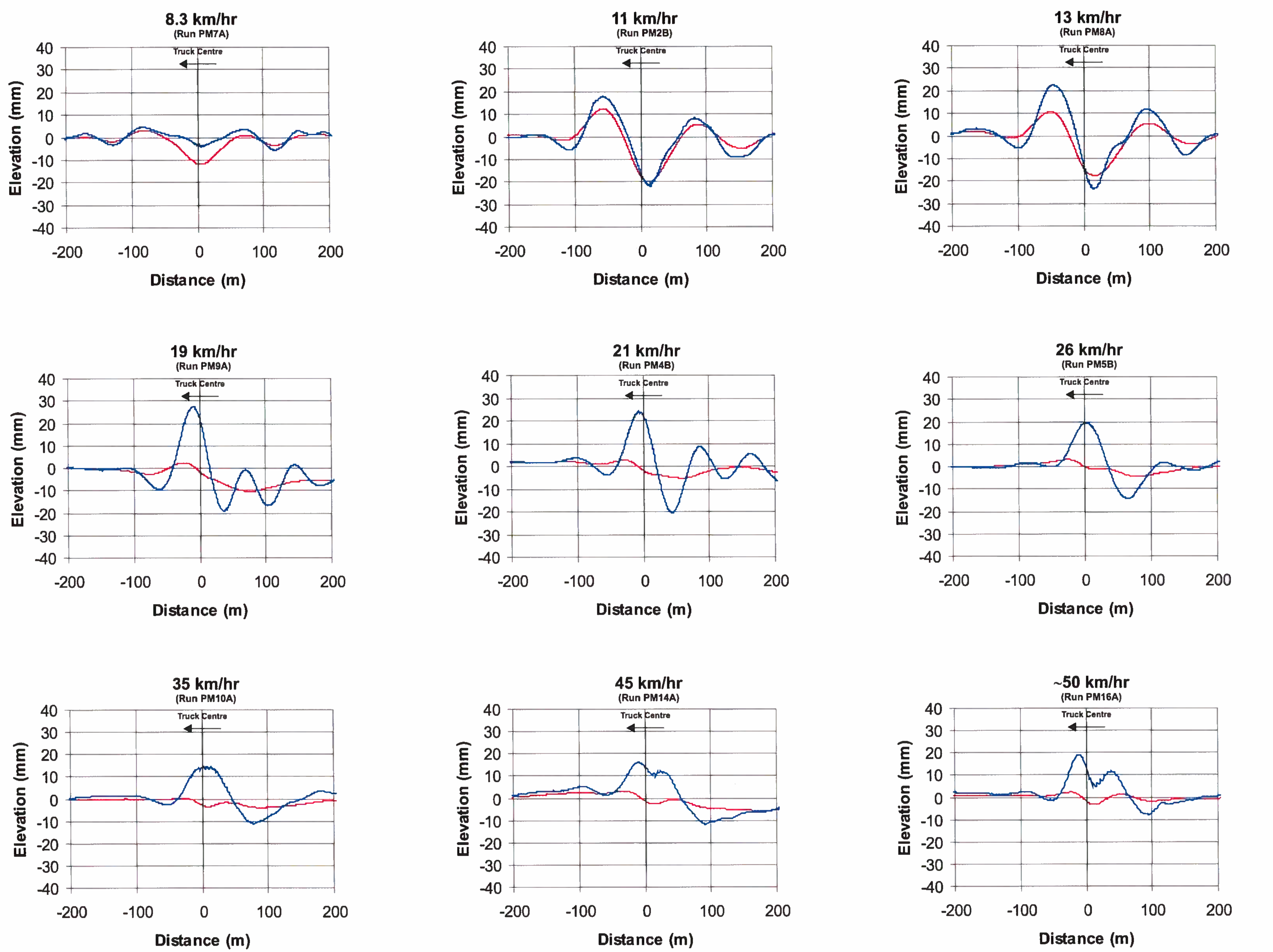

Gravel Truck, 31,120 kg
Water Depth = 2.1 m
Ice Thickness = 1.32 m
Air Temperature = -17°C

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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS TRAVELING FROM ICE TO SHORE OFFSET 7 m FROM TEST HOLE ON WAITE LAKE ON MAR 21, 2012

Project 100019	2 Oct 2012	**Figure 9**

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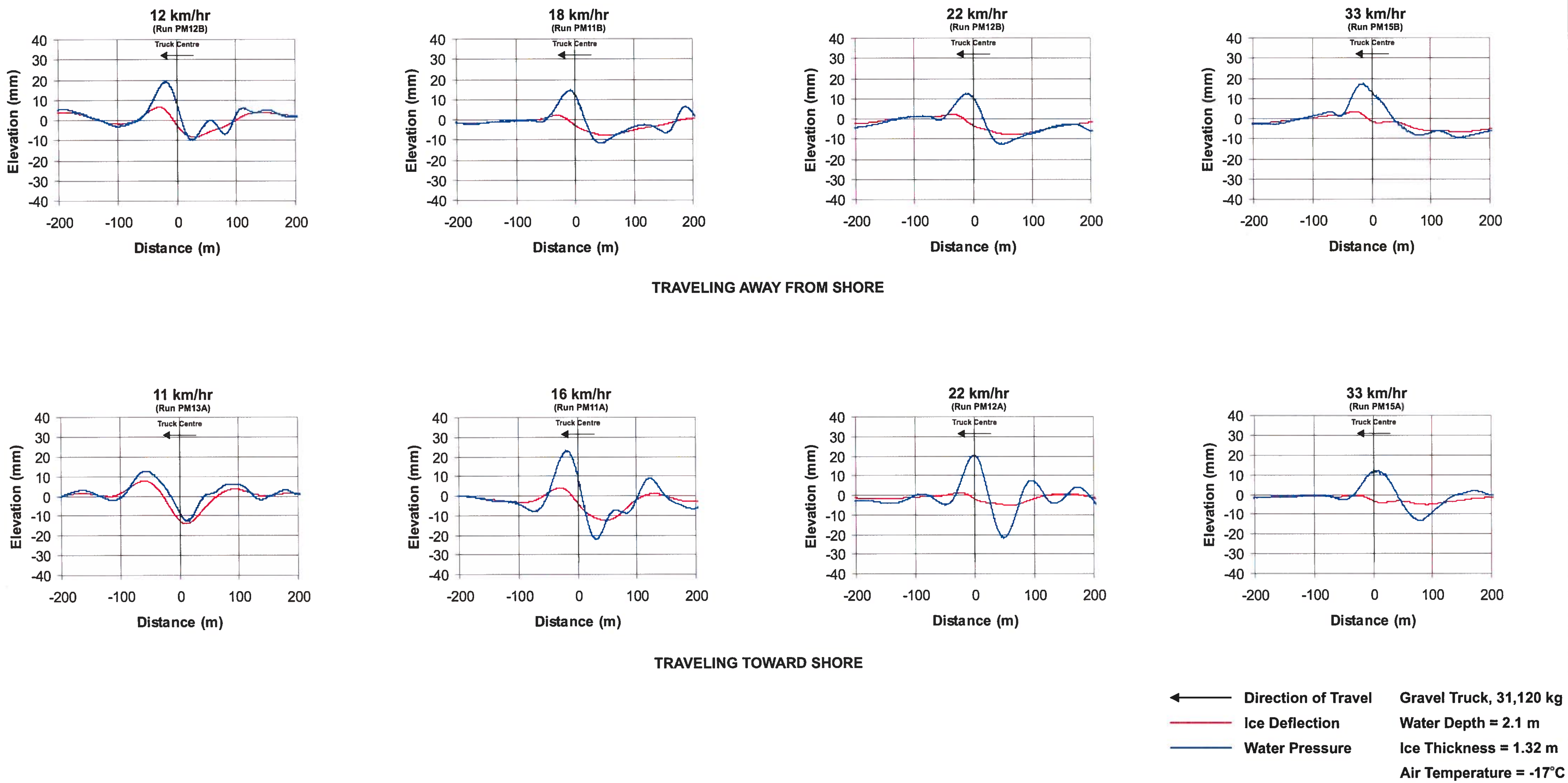

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MOVING LOADS ON ICE

ICE COVER DEFLECTIONS AND WATER PRESSURES FOR VARIOUS VEHICLE SPEEDS OFFSET 10.5 m FROM TEST HOLE ON WAITE LAKE ON MAR 21, 2012

Project 100019	2 Oct 2012	**Figure 10**

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