Confederation Bridge – An innovative approach to ice forces

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Abstract: Confederation Bridge was designed for a 100-year design life, and to a level of reliability previously not used for bridges. The increased level of reliability reflected the importance of the bridge as the principle transportation link to Prince Edward Island, and the commitment by the Federal Government to provide a continuous transportation link to the island. Prior to the contract award, potential impacts of the construction of the bridge on the ice regime in Northumberland Strait received considerable attention, and led to certain restrictions being placed on the bridge arrangement.

During the design process, ice forces became the primary lateral load effect on the piers, and the subject of both controversy and uncertainty. The final arrangement of the piers was designed to reduce the ice forces and thus meet the required reliability for lateral stability and to mitigate potential impacts on the ice regime. Nine years of observations and measurements have provided considerable evidence as to the efficacy of the design in both respects, and the design may be more effective than was considered initially. Since the bridge opened in 1997, a comprehensive monitoring programme has been in place to assess the bridge performance in a number of areas, including ice interactions and ice forces. The paper describes how the pier arrangement has been effective in reducing ice forces, the character of ice interactions with the piers, and the forces that have resulted from such interactions. The paper also summarizes the findings as to the impact of the bridge on the ice regime in Northumberland Strait.

Introduction

When opened in 1997, Confederation Bridge was the longest bridge in the world that crossed ice-covered waters, and is still the longest bridge in the world that is subject to ice forces every year. In the extensive planning and review process that led to the opening of the bridge, ice and the effects of ice, were a major influence, and received much emphasis. Initially this was in relation to potential environmental impacts associated with the construction of the bridge, and laterally in the assessment of the ice forces on the piers. At each stage, the engineered solution incorporated innovations introduced to mitigate first, the environmental impacts, and second, the forces resulting from interactions between ice and the piers. Throughout both stages, it was apparent that any issues associated with ice were subject to considerable uncertainty, and therefore any conclusions were also uncertain. Experience with the bridge and assessment of the performance of the bridge since it opened, has confirmed the efficacy of the design and also confirmed that the innovations have resulted in performance in relation to ice effects that may be better than was originally considered.

Prior to the contract award, potential impacts of the construction of the bridge on the ice regime in Northumberland Strait received considerable attention [1], and led to certain restrictions being placed on the bridge arrangement. The most of importance of these was that there should be a minimum spacing between centre-lines of piers, of 150 m. The second requirement was that the piers should be axially symmetric, in order that ice failure behaviour would be the same, regardless of the direction of travel of the ice with respect to the pier [2]. The impacts that were of primary concern were associated with the fishing industries in Northumberland Strait, and the potential deleterious impacts that the bridge might have on these industries. Specifically, there were concerns related to lobster growth in Northumberland Strait, and to spawning habitat due to increased ice scour [3]. The first of these resulted from potential delays in ice-out in Northumberland Strait due to the bridge restricting the movement of ice through the Strait, leading to a reduction in the water temperature in the Strait and a consequent reduction in the moulting behaviour of the lobster. The bridge could restrict movement of ice through the Strait if the forces that the drive the ice (wind and current drag) are less than the resisting forces required to break the ice against the piers. Subsequent analysis of the impacts confirmed that the bridge could be built and meet the requirement of a maximum delay in ice out of 2 days over the life of the bridge, subject to the restrictions discussed above.

The bridge was designed for a 100-year design life, and to a level of reliability previously not used for Canadian bridges. The overall reliability was defined by a β factor of 4, which corresponds to a probability of failure of 3.17×10^{-5}. For single path systems (as is the lateral behaviour of the piers), the reliability required corresponded to a probability of failure of 1.07×10^{-5}. This increased level of reliability reflected the importance of the bridge as the principle transportation link to Prince Edward Island, and the commitment by the Federal Government to provide a continuous transportation link to the island. However, it placed extremely onerous requirements on the design of the bridge and resulted in considerable effort expended to assure the design criteria, and, in particular, the ice load design criteria [4]. Concurrently, however, there was considerable effort placed on the design of the piers to mitigate ice forces, which, in turn, would also mitigate potential environmental impacts.

One result of this uncertainty was a decision to install instrumentation on the bridge with the purpose of measuring ice forces and observing ice behaviour against the piers. This system was installed prior to the bridge opening and continues to operate to this day. The combination of ice force measurement and observation of the behaviour has resulted in considerable information related to the performance of the pier design in relation to ice interactions and provided some confidence that this performance has met both the design criteria and the conclusions regarding environmental impacts. The results have also suggested, however, that the design of the piers has resulted in some characteristics of ice interaction behaviour that were not previously predicted.

Ice Forces and Pier Design

Northumberland Strait is classified as a marginal ice zone, being the most southerly sea ice zone on Canada's east coast. As such, it is subject to ice for three to four months a year, from early January until mid-April, although ice has been present until late May [5]. The first-year ice cover consists of a combination of discrete floes of various sizes that range from a few 10's of meters to several kilometers in extent. First-year ice ridges are frequently embedded in these floes, and these ridges can reach a size that makes them the features that result in the highest loads on the piers. Figure 1 shows the profile of a typical first-year ridge, and the cross-sectional shape assumed in the design process. As may be seen, the cross-section is divided into three components but, of these, the above water sail is usually ignored. Both the consolidated layer and the keel can result in considerable load, depending on the geometric and mechanical properties of each component. These properties change with time, as the ridge consolidates and deforms as part of the ice cover. Consequently, the character of the interaction between any specific ridge and a bridge pier can vary significantly, depending on these properties, and the relative strengths of the two components.

The ice load applied to the structure depends on the nature of the failure mechanism induced in the ice feature, which depends on the shape of the structure. Generally, structures that are vertical, or close to vertical, will cause the ice to fail in crushing, while sloping structures will cause the ice to fail in flexure. The keel of a first-year ridge consists of randomly arranged blocks of ice that may be frozen together only at their points of contact. This ice rubble is often assumed to behave as a granular material that fails in shear according to the Mohr-Coulomb failure criterion. Thus, it is possible that the load resulting from failure of the keel material, does not depend on the shape of the pier.

Ice is considerable stronger in compression than in flexure, however, the ratio of the strengths varies considerably, depending on factors such as strain rate, ice temperature and salinity. However, for typical conditions in Northumberland Strait, the ratio is certainly greater than three. However, perhaps a more important reason for considering a conical structure over a cylindrical one is the potential for very significant cyclic ice loading at a frequency that may coincide with the natural frequency of the structure. This phenomenon has been observed with a number of structures varying from narrow lightpiers in the Baltic Sea to large caisson structures in the Beaufort Sea. As a consequence, the design of the piers focused on the design of conical structures, rather than cylindrical ones.

Tadros [6] has summarized the design and construction of the bridge and the associated load design criteria.

When an ice sheet interacts with a conical structure, the ice fails by sliding up the cone, resulting in a series of radial cracks and a circumferential crack. However, this behaviour is complicated by the rapid formation of a rubble pile that forms on the cone and is supported partly by the cone and partly by the incoming ice sheet. The forces need to lift and move this rubble pile can be greater than that necessary to fail the ice sheet. Figure 2 illustrates this rubble pile formation. The force required to fail the ice sheet reduces as the cone angle reduces but this is offset by an increase in the corresponding cone diameter, and an increase in the effect of the rubble pile. Figure 3 illustrates the effect of cone angle, and the coefficient of friction between ice and the surface of the cone. Design of the cone is therefore a balance between the benefits of lower cone angle against the other effects of increased size, including the added cost of requiring a larger structure. Figure 4 is similar to Figure 3 but now the cone waterline diameter has been increased to ensure the same neck diameter at the top of the cone, and the same freeboard at the neck of the cone. The benefits of reduced cone angle are not as apparent in Figure 4 as they are in Figure 3.

As was indicated earlier, the behaviour of the rubble in the ridge keel is quite different from that of the intact ice of sheet ice, or of the consolidated layer of a ridge. Two possible interaction modes for the rubble of the keel were considered: local interaction and failure, and global interaction and failure. Local failure occurs as the keel rubble is fully engaged by the pier and failure of the rubble occurs at the contact between the rubble and the pier. The important attribute of the pier is its cross-sectional area. Global failure occurs when there is sufficient force generated by the local behaviour to cause the keel to fail along shear planes that traverse the keel. Because the rubble is failing in shear along planes that are generally parallel to the direction of motion of the ice feature, again, the shape of the pier is not important. The need to cause the ice to fail in flexure is limited to the region of the waterline and immediately below. The actual depth required depends on the maximum thickness of the consolidated layer of the ridges, as this thickness is larger than the maximum thickness of the level ice. Thus a conical structure at the waterline provides the benefits of flexural failure of the intact ice of a consolidated layer, or of sheet ice, with the economies of being restricted to the waterline region.

Figure 5 shows the typical pier design for one of the piers of Confederation Bridge, and the instrumentation that was installed on pier P31. The waterline cone has a diameter of 14.2 m at the waterline and a cone angle of 52^o. This cone extends from -4m to +2.6 m where it transitions into a 78^o cone that subsequently transitions into the pier shaft at around +7 m. The second cone at the base is designed to provide the overturning and sliding resistance at the foundation level, and is not designed for ice interaction.

Ice Behaviour and Forces

The design ice forces resulted from interactions between first year ridges and the piers, with the consolidated layer failing in flexure and the keel failing in either the local or global mechanisms described above. The total load was obtained by summing these two load components. A rubble pile on the cone was assumed to occur but not with every interaction – it being argued that, because of the relatively high interaction speeds, there would be an effective clearing mechanism. The unfactored design ice forces, of the order of 16 MN, depended on the surface of the cone, being somewhat lower for steel cones than for concrete cones, due to the slightly lower coefficient of friction. This difference could have been greater but the bridge developer introduced a system that resulted in the concrete finish on the cones having a very dense, smooth, surface that resulted in a lower coefficient of friction than might otherwise have occurred. Because of the uncertainties associated with the ice force design criteria, the decision was made in 1996 to install an instrumentation system to measure ice forces and observe ice behaviour. This system, which includes a number of different sensors and sensor systems, has been described elsewhere [7]. Here, the results obtained from these systems are described and the benefits that have accrued as a result of the innovations built into the design of the piers.

Figure 6 shows a typical ice rubble pile formed against one of the piers. Rather than being an occasional occurrence, rubble piles are present during all interactions, forming immediately after the initial flexural failure of an interacting ice floe. However, what is also apparent from the observations is that the profile of the rubble pile, rather than being linear, is more often bi-linear. Based on the assumed profile used in the algorithms to determine the ice load, the actual profile would result in heavier rubble piles, and larger loads. During interactions with very thick consolidated layers, the rubble pile is replaced with what is termed ice ride-up in which a single layer of the thick ice rides up the slope. Although the algorithms assume that the complete slope is covered with ice, the experience with Confederation Bridge (Figure 7) is that the ice is generally too thick in relation to the cone diameter to result in this. In both Figures 6 and 7, the height of the ice build up on the pier is extreme, reaching to the transition between the upper cone and the pier shaft proper.

The observations of rubble pile and ride-up formation on the cones suggest that these formations are larger, and more frequent than was assumed in the design process. As a consequence, it would be reasonable to expect that the associated loads were also larger. This, however, is not the case; the measured load are lower than those predicted for the same interaction parameters. In addition, much has been learnt about the characteristics of rubble piles and the interaction variables, particularly ice thickness and velocity, which affect the rubble pile and ride-up heights.

The truly significant impact of the pier shape, leading to the benefits of the innovation, has been to interactions between first-year ridges and the bridge piers. Figure 8 illustrates the pressures against the pier that would be expected in a local failure mechanism involving the ridge keel. As the material is assumed to behave as a Mohr-Coulomb material, this pressure is a function of the buoyant stress in the keel, leading to the linear pressure distribution shown. If this mechanism was occurring regularly, one would expect that the panels that are attached to the pier shaft (Figure 5) below the cone, would be measuring pressures on a regular basis. Analysis of the data from these panels, and observation of marine growth on the pier shaft [8] has concluded that very few rubble interactions with the pier shaft take place. These observations are further supported by analysis of the relation between the total ice load on the pier and ridge keel depths (Figure 9). As may be seen, this figure indicates that there is no relation between load and keel depth, and yet, if Figure 8 is correct, there should be a very clear relation. The trend line does show a slight increasing trend with keel depth, but the reliability of this line is very low. The combination of the observations and the analysis of loads led to a re-assessment of the interactions between ridge keels and the Confederation Bridge piers [8]. However, as it is virtually impossible to view the interactions between the rubble of the keels and the piers, further corroboration of these findings had to be obtained in the laboratory.

In a series of tests conducted in 2003 [9], a model of the Confederation Bridge piers was deployed in a flume in the hydraulics laboratory of the University of Calgary and interactions with rubble ice features were observed. These tests clearly indicated that the leading edge of the cone was disturbing the equilibrium of the rubble in the keel to such an extent that the keel blocks, below the level of the underside of the cone, were being broken up before they contacted the pier shaft. Many of the individual rubble pieces were carried round the pier in the current, such that the number of pieces that actually hit the pier was extremely low. At low current speeds corresponding to periods of slack tide, it was shown that the entire keel could interact with the pier; however, these periods are also associated with reductions in driving force, such that there is insufficient force to cause the ice rubble to fail, and the corresponding loads are low.

One consequence of these findings is that only the top portion of the keel, which interacts with the cone, actually contributes to the total load, and hence there is only a weak relation between total load and keel depth, as suggested by the trend line of Figure 9. This result is in clear contradiction to the expected loads derived from the design criteria, and has nor been predicted by any of the ice ridge models that have and continue to be used for the prediction of ice loads on offshore structures. However, it is important to note that the benefit, as far as the Confederation Bridge piers are concerned, derives from having the cone truncated at some distance below mean water, creating the relatively sharp edge that causes disintegration of the rubble in the keel. This would not be the case for a cone that was carried all the way to the seabed as proposed for high arctic regions where structures would be susceptible to fully-consolidated multi-year ridges. For moderate ice regimes, such as the Gulf of St Lawrence, the Baltic Sea, the, Caspian Sea, and areas off the east coast of Russia and China, truncated water-line cones may provide a real benefit in reducing loads from first-year ridges.

Conclusions

The initial design of the piers for Confederation Bridge was driven by the pressures of the potential environmental impacts and the need to minimize the ice forces and avoid ice induced vibrations. These pressures resulted in the provision of ice breaking cones at the waterline that were continued to 4 m below mean sea level to ensure that flexural failure of the thickest possible consolidated layer could occur. The cones were truncated at that point because there was no ice-related requirement to continue them, and in order to control the overall costs of the piers.

The experience and knowledge acquired since the bridge opened has confirmed the efficacy of the design, but further, has also confirmed that the design is significantly more effective in mitigating loads from first-year ridges than was originally thought. The presence of the bottom edge of the cones effectively breaks up the portion of the keel below the level of the cone before it can interact with the keel, thus eliminating the load from this portion of the keel. This innovation is likely to be adopted in other regions where the design ice features are similar to those of Northumberland Strait.

Acknowledgement

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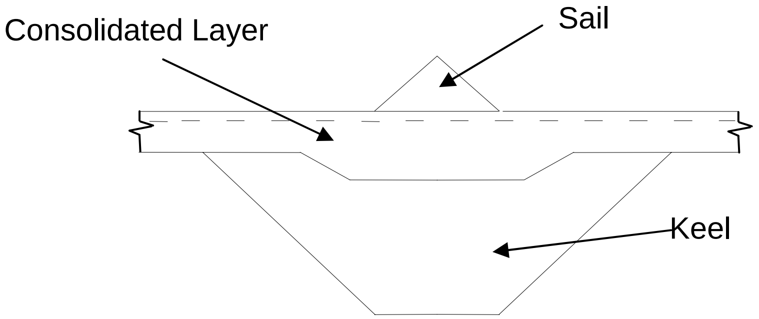

Figure 1 Typical First-Year Ridge Cross-section

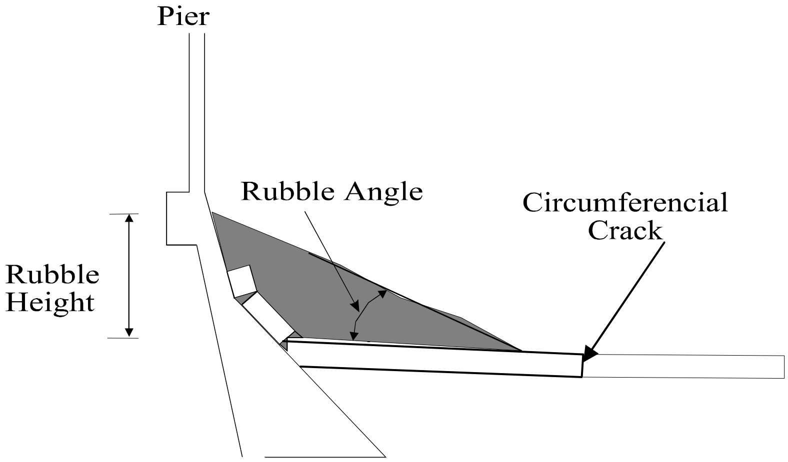

Figure 2 Ice Sheet interaction with Sloping Structure and Rubble Pile

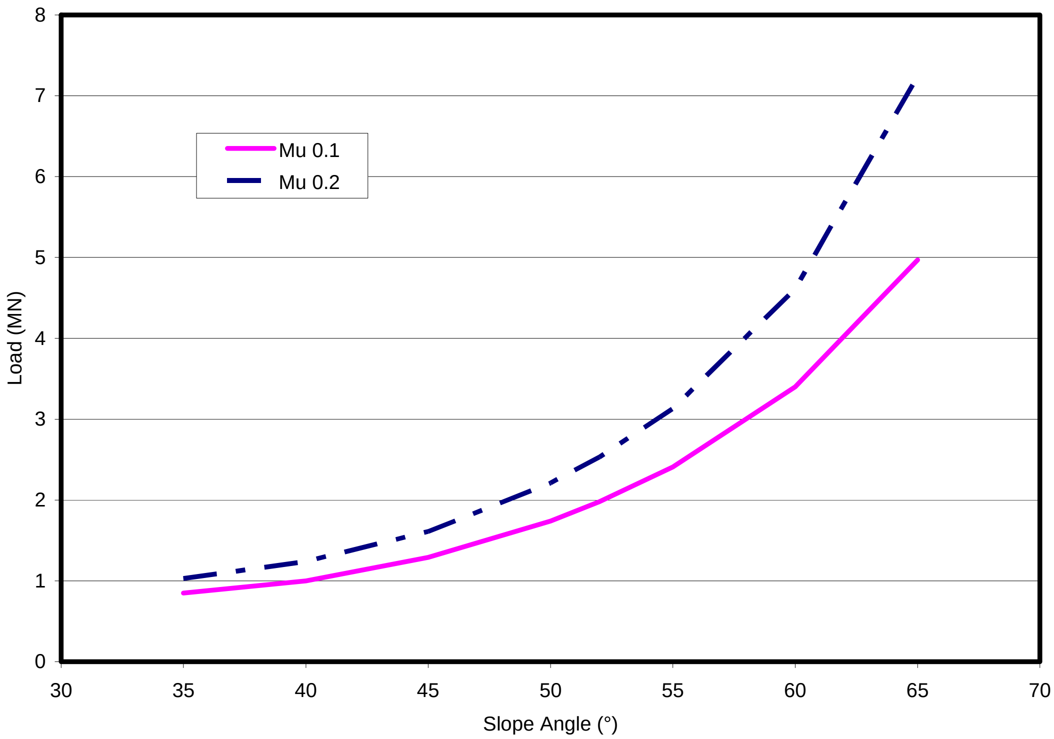

Figure 3 Influence of Slope Angle and Friction on Ice Sheet Load – Constant Diameter

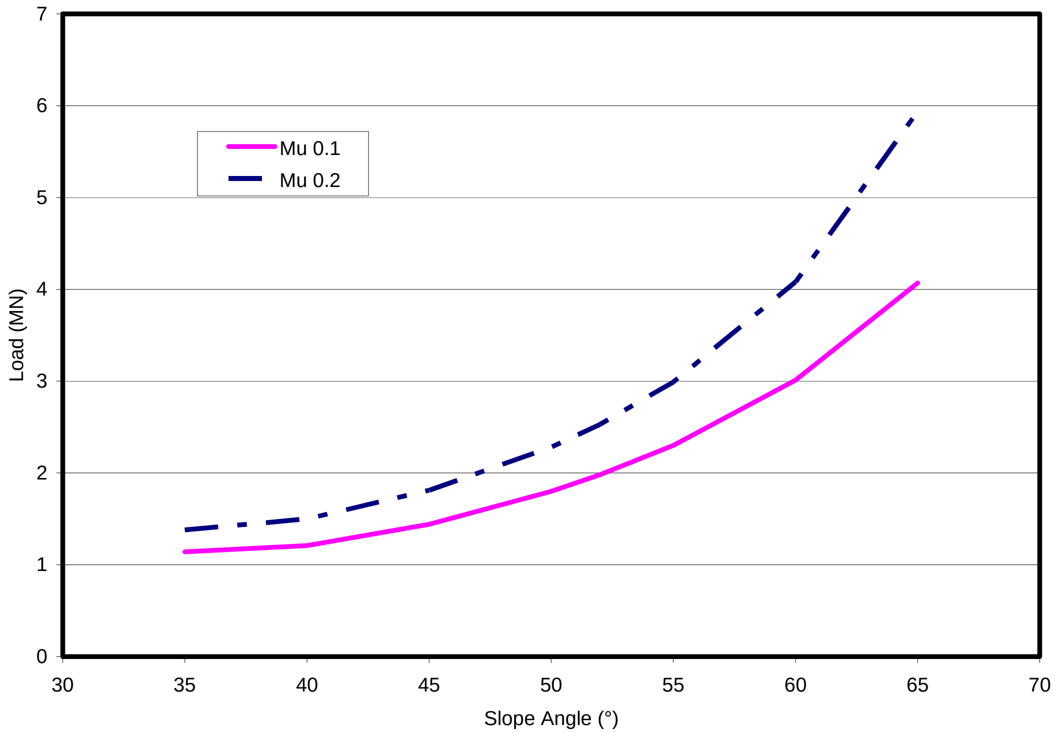

Figure 4 Influence of Slope Angle and Friction on Ice Sheet Load – Constant Neck Diameter

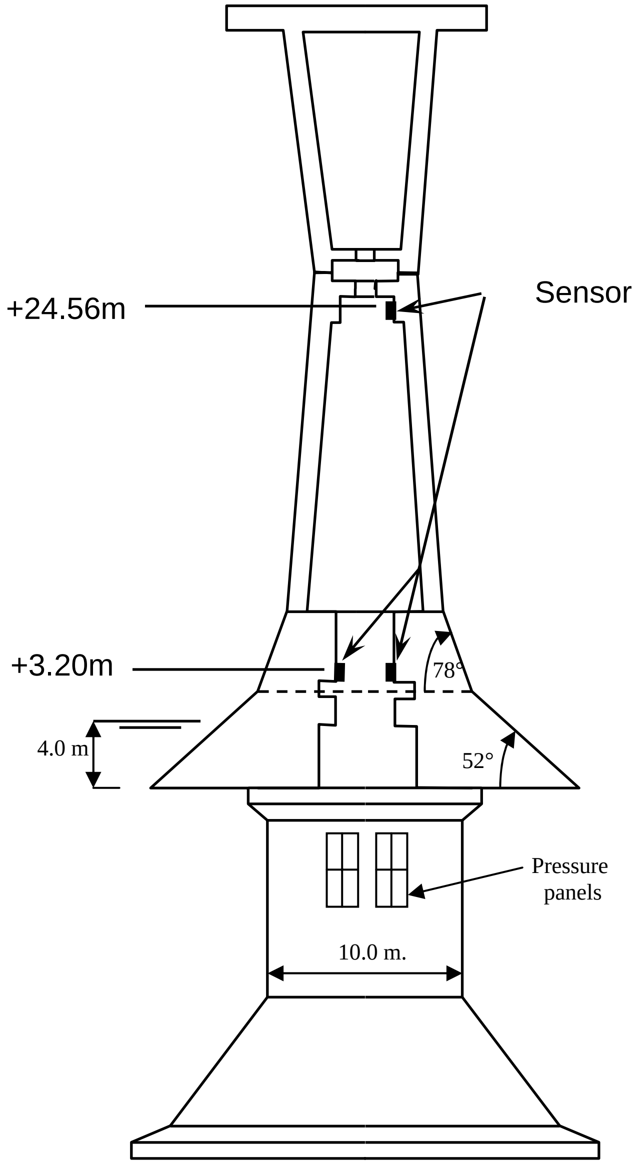

Figure 5 Typical Pier Arrangement Showing Instrumentation

Figure 6 Typical Rubble Pile

Figure 7 Typical Ice Ride-Up

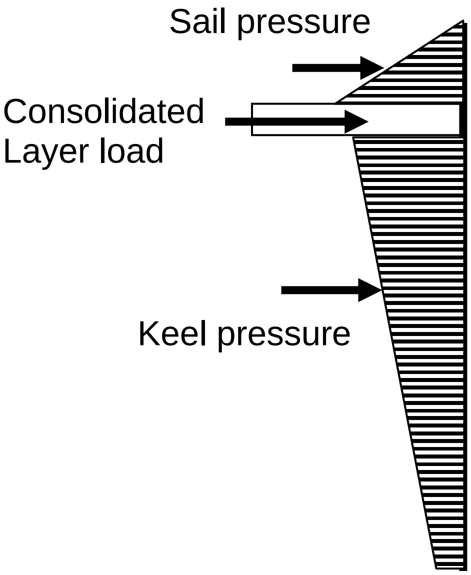

Figure 8 Assumed pressure Distribution in First Year Ridge Interactions

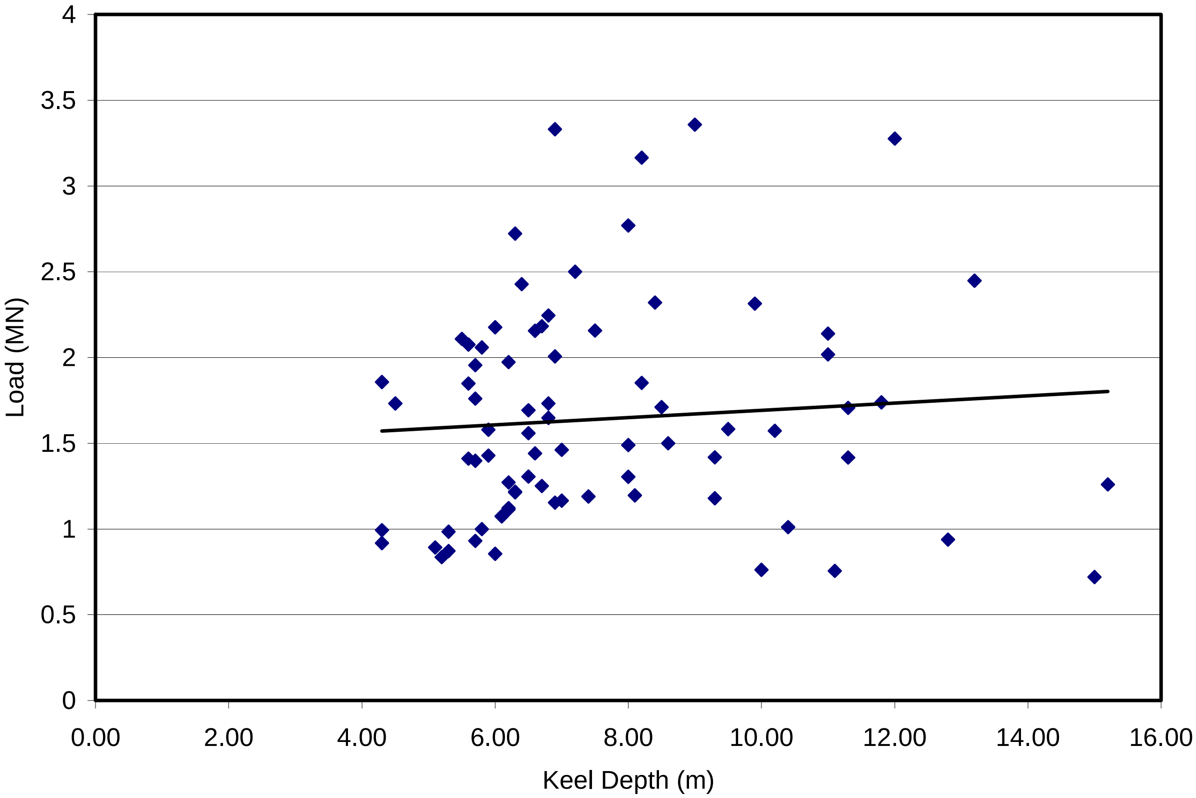

Figure 9 Relation Between Load and Ridge Keel Depth