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# ICE ENCROACHMENT IN THE NORTH CASPIAN SEA

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## ABSTRACT

In the North Caspian Sea, ice rubble can encroach on gravel islands and other structures, and potentially damage the facilities contained thereon. For large footprint structures, design considerations include the necessary width of encroachment or buffer zones, island freeboard requirements and the need for protective walls. For drilling and other smaller structures, the height of protective walls and ice deflectors is an important design concern. Ice movement events can drive the ice onto a structure, riding directly up a sloping face or existing rubble accumulation, or piling up and tumbling onto the structure.

The paper deals with the collection of data on ice encroachment, indices that can be extracted from the data and the statistical characterization of these data. Special consideration is given to maximum rubble heights and their location relative to the structure, and the rubble slopes that have been observed. The paper also addresses some of the mechanisms that contribute to ride-up and pile-up, and potentially limit their extent and the resulting loads that the ice rubble can apply. A final objective is the establishment of design criteria that are consistent with the structural design philosophy and with the applicable standards.

## INTRODUCTION

### *Background*

Ice encroachment involves the action of ice moving onto the working surface of the platform. Low freeboard structures, such as islands, and those with a gently sloping face are particularly susceptible to this risk. There have been a number of encroachment events at structures in the North Caspian Sea over the last 10 years, see Figure 1.

There has also been some documentation of ice encroachment on beaches and structures in the Beaufort Sea. Over the years, a number of models have been developed for estimating the forces associated with various ride-up and pile-up mechanisms. In spite of this, there is considerable uncertainty in estimates of pile-up heights based on these mechanisms; and the processes are not easily predictable. A number of mechanisms acting at the waterline can potentially limit rubble height and ride-up loads, and these have been investigated as part of the present study.

Figure 1 Examples of ice encroachment at structures in the North Caspian Sea

Methods to counter ice encroachment include the use of high freeboard structures, the construction of ice deflector walls, the provision of an ice management strip around the island perimeter in which no equipment is placed, and the placement of protection structures around the main structure. All of these have been used effectively in the Caspian Sea. Because of the shallow water in the North Caspian Sea, it can be feasible and cost effective to include a multi-purpose perimeter strip in island designs.

The original design criteria for ice encroachment on Caspian Sea structures relied on estimates of the highest observed rubble piles and their occurrence at the edge of the structure. Since 2001, many ice rubble measurements have been made in the North Caspian Sea during on-ice field programs, by observers on the structures and from airborne surveys. Many rubble features, both stamukhi and pile-ups at structures, have been profiled in three dimensions using an airborne laser mirror scanner. The data are of sufficient quality and quantity to allow the development of probabilistic design criteria for ice encroachment.

### *Approach*

The first step in dealing with encroachment was to document actual events and try to determine the most important contributing parameters. To supplement this, a number of visual observations of the ride-up and pile-up processes were analyzed in an attempt to gain a better understanding of these contributing processes. Some key indices of rubble pile dimensions were identified and the laser mirror scanner data were processed accordingly to yield probability distributions that can be sampled from. Ice movement events based on hindcast winds were used to identify potential encroachment events and a probabilistic methodology was developed to sample corresponding rubble pile-up indices. Actual structure geometries were used to determine encroachment distances from which design values were estimated. In some circumstances, ice walls or barriers are required and design criteria can be established for them.

Both vertical and sloping offshore structures have been built in the North Caspian Sea, see Croasdale et al. (2011). As a result, the focus of this paper is on vertically-sided sheetpile-retained island structures as well as sloping-faced island structures.

## ENCROACHMENT PROCESSES

### *Overview*

When considering design requirements for ice encroachment on structures, two situations need to be considered. Ride-up is when ice rides up the face of a sloped structure or up the front of a pile of ice rubble formed in front of the structure and directly impacts facilities. Pile-up is when incoming ice breaks up into pieces and piles up against a structure, creating a bearing force or significant impacts from individual pieces of ice sliding down the back side of the pile. The two situations are shown in Figure 2 for vertical structures. For vertical structures, encroachment distance is measured from the outer wall of the structure. For sloping structures, encroachment distance can be defined from the waterline or from the edge of the working surface.

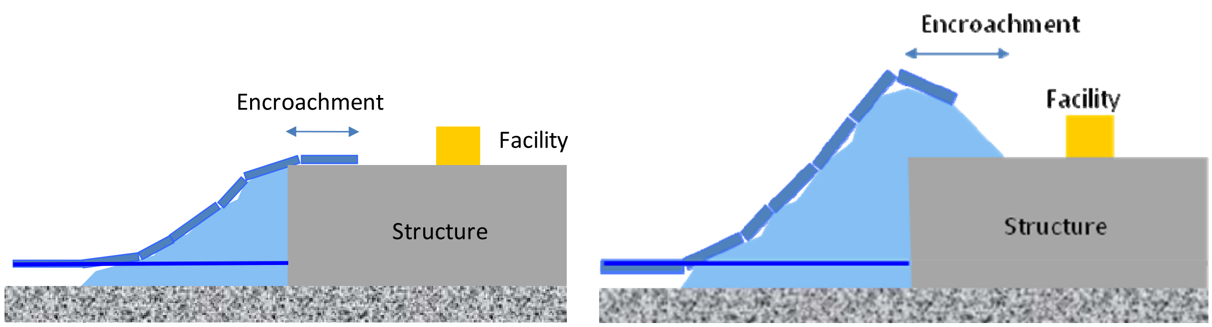


Figure 2. Encroachment from ride-up (left) and pile-up (right) against a vertical structure

### *Ride-up*

Ride-up against a vertical structure occurs when sufficient ice is piled up against the face of the structure to allow the advancing ice sheet to slide along the working surface. Because the necessary driving force from the surrounding ice sheet is not very large, ride-up distances can be considerable. While ride-up is not a common occurrence, potential sliding distances make it unfeasible to use an encroachment strip alone to prevent adverse consequences. The first line of defence against ride-up is having sufficient freeboard. If a high freeboard or an ice deflection wall is not present, potential damage to facilities as a result of ride-up can be avoided by providing some sort of obstruction to the ice sliding along the working surface. A wall set back some distance from the edge of the island or a step in the island surface can be used.

For sloping structures, ride-up tends to occur most often for shallow slopes of 1(vertical):4(horizontal) or less. In such cases, a barrier should be used to prevent encroachment.

### *Pile-up*

Pile-up occurs when incoming ice builds a large pile of rubble on the structure or at the base of the structure, rather than extending the rubble pile away from the structure. From observations, see Figure 3, this seems to occur when ice rides up the outside front of the pile (B) and deposits ice at the top and back side of the pile (C). Ride-up and pile-up therefore share some of the required conditions for occurrence. On the left side of Figure 3 is shown a case where there is a relatively shallow slope and the ice rides up the slope (B) without significant overburden and a relatively small vertical force component near the waterline (A). Also shown on the right is a case where there is a relatively steep slope resulting in development of more overburden and larger vertical force component near the waterline (A). In the second case, the development of a large pile is less likely. Once development of a pile is interrupted, it may be difficult for generation of the pile to be reinitiated and subsequent pile development may occur farther back from the structure. Several piles may build away from the structure or a profile through the rubble pile perpendicular to the face of the structure may have multiple peaks.

The probabilistic approach for design values illustrated in this paper focuses on the pile-up process.

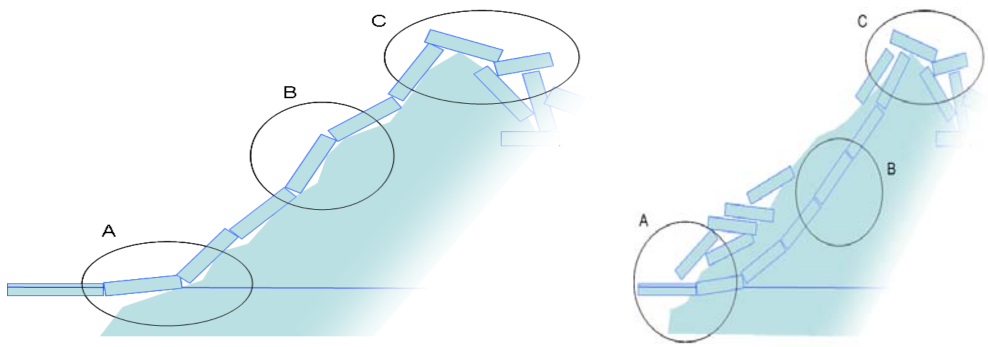


Figure 3. Growth of pile-up through (left) ride-up on the surface of the pile and (right) ride-up through the pile with a significant amount of overburden

## DOCUMENTATION OF EVENTS

The process of documenting encroachment began with a recollection of significant events through the years at different structures, as observed and discussed by the on-board ice advisors and circulated in event reports. The nature of the encroachment event was strongly influenced by the profile shape of the structure, its orientation, and by the layout of auxiliary structures. Approximately 40 events were documented, focusing on the following parameters:

— ice (thickness, speed and direction, duration of movement);

— metocean (wind speed and direction, water depth);

— structure geometry and orientation; and

— details of the encroachment (principally distance inboard of edge and height above water surface).

Briefly, the following conclusions were drawn from the event data for vertical structures:

(a) the encroachment distance was positively correlated with the height of the rubble pile adjacent to the structure;

(b) there was a weak correlation indicating reduced encroachment with increasing freeboard;

(c) there was a positive correlation between ice thickness and maximum pile height;

(d) there was no discernable effect of water depth on pile height or encroachment distance; and

(e) there was little discernable relationship between the volume of incoming ice during an event and the rubble pile height.

Similar conclusions were drawn when sloping beach and sloping steel structures were considered, although the volume of incoming ice seemed to have an effect on the maximum pile height. While the effect of ice temperature or time of year was not considered, the effect of the ice properties on rubble height could potentially be addressed in future. Since many events tend to occur either early in the winter or as the ice is breaking up, it may be difficult to separate ice temperature and thickness effects.

When the Sunkar drilling barge was deployed, the bow and stern sections were generally exposed to ice actions, while the sides were protected using piles or steel barriers. The stern had a freeboard of 6 m to the top of the ice deflectors, while the bow had a freeboard of 7.5 m. Over nine deployment winters between 1999/2000 and 2008/2009, there were nine events where the ice reached or overtopped the deflectors, or one event per year.

Across all of the different structure types and water depths, some overall statistics can be ascertained. It is emphasized that, while water depths varied from about 2 m to 7.5 m, most of the structures were placed on berms such that effective water depths in the vicinity of the structures were 4 m or less. Since the structures have different plan dimensions and different levels of protection from berms and steel protection barriers, exposure was defined for an equivalent structure with a projected width of 100 m. Approximately 45 structure years of encroachment data exist for this equivalent structure for which there were 8 ride-up events and nearly 40 pile-up events.

While all attempts were made to document significant events during offshore operations, clear thresholds were not specified for the collection of field data. As a result, there may be some bias in the data in terms of what constitutes an event. Some of the events documented were significant, but did not actually result in ice reaching the working surface. Some events may also have occurred that were not documented. Nevertheless, the numbers reported should give a good general sense of the situation in the North Caspian Sea.

## ANALYSIS OF RUBBLE MORPHOLOGY DATA

### *Rubble height*

Based on data from 27 rubble building events against structures in the North Caspian Sea, the maximum height in a rubble field can be sampled from the average ice thickness in metres as

$$H_{max} = 4.32 + 9.80\,h + N(0,2.03) \tag{1}$$

where $N(0,2.03)$ is a normal distribution with a mean of zero and a standard deviation of 2.03 m. Other data, such as those reported by Barker and Croasdale (2004) substantiate this relationship. Although the peak rubble height in a rubble field is sometimes adjacent to the structure, in most cases it is not. A distribution for the ratio of peak height near the structure divided by the maximum height in the rubble field was established based on 136 rubble profiles against a variety of structures. The average ratio was 0.53 and the standard deviation was 0.23, over a range of 0.2 to 1.

### *Apex location*

Experience with ice rubble build-up in many areas suggest that the maximum height is usually at the point where the structure meets the waterline. When the location of the peak height is offshore of the structure, whether for vertical structures or rock slopes, the average distance from the structure was calculated to be 7 m (exponential distribution). For rock slopes, the apex is onshore about 60% of the time, in which case the average distance from the waterline is 5 m (exponential distribution).

### *Rubble slope*

The slope angle of the back face of ice rubble piles (facing toward the structure) influences ice encroachment distance. Ice rubble slope angles were derived from airborne laser mirror scanner surveys in 2002 for features ranging in maximum height from 6.2m to 11.8m. The steepest slope angle within each feature ranged from 30° to 40° from the horizontal with an average of about 35°. These are believed to estimate the angle of repose for ice rubble, and slopes upon which blocks could potentially tumble down. In general, back face slopes are steeper than front face slopes upon which the advancing ice rides up. In another study, back face slopes of numerous profiles for several rubble features up to 10 m high were calculated. It proved quite difficult to isolate slopes formed from repeated pile-ups and from individual large ones, and relationships with maximum rubble pile height were not obvious. While maximum slope values were in the range of the above values, minimum ones reached 10° to 15°. These shallow rubble angles were not associated with apex locations in close proximity to the structures.

On the basis of the above data, uniformly distributed rubble angles of between 25° and 35° were used in the probabilistic simulations in combination with the above distributions for apex location.

### *Effect of Structure width*

Since rubble height can vary significantly along the face of a structure, there is an increased probability of having a higher pile somewhere along a wider projected structure face. Many profiles from the laser mirror scanner data were analyzed to relate the peak rubble height adjacent to the structure to the maximum height in the rubble field. Since the profiles were all sampled at approximately 10m spacing, repeated sampling from the ratio distribution can be made to account for the effect of increased structure width. The pile height adjacent to the structure is equated to the sampled stamukha or rubble field height times the maximum of $n$ sampled rubble height ratios, where $n$ is the projected structure width divided by the profile spacing of 10m.

## PROCEDURE FOR CALCULATION OF DESIGN VALUES

### *Framework*

The framework for calculation of design values for rubble height adjacent to the structure and encroachment on the structure is given in Figure 4. Only the pile-up process is considered. In the probabilistic methodology, a large number of ice movement events is considered (see Jordaan et al., 2011), and for each one the maximum rubble height is sampled based on the ice thickness, a reduction factor is applied since the highest point may not be adjacent to the structure, the location of the apex is sampled, the rubble slope angle is sampled and multiple samples are taken according to the structure width. Based on the rubble height, location and rubble angle, encroachment is assessed relative to the structure geometry and the encroachment distance is calculated. If insufficient ice volume is available for the event, then the size of the rubble pile is scaled accordingly.

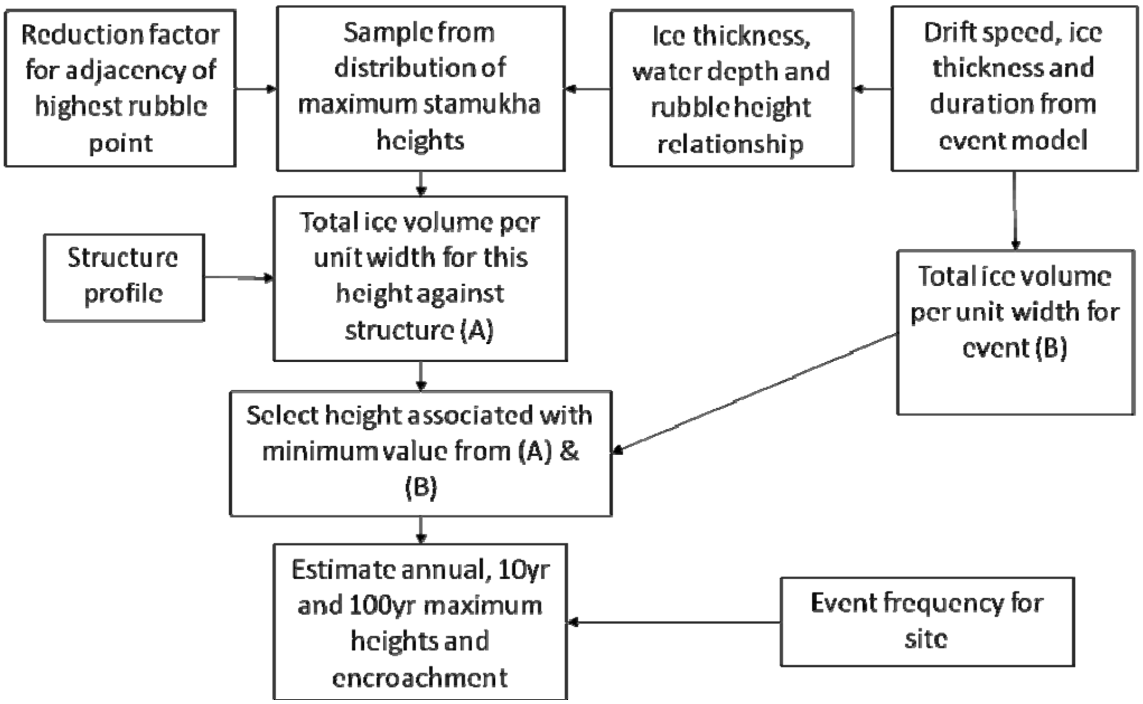


Figure 4. Framework for calculating design values of ice encroachment

### *Structure representation*

For island structures in the Caspian Sea, different designs can be used for different faces, depending on function. The perimeter can be used for vessel and barge access, EER, storage or helicopter landing facilities, and each area may have different encroachment considerations. Some structures can also be protected by satellite berms or steel barriers. As with the rubble modelling methodology (see McKenna et al., 2011), the structure layout can be represented on a grid, with different parts of the perimeter identified using separate indices. In this way, projected widths for particular structure segments or faces can be estimated with due consideration for protection structures.

Generally, the encroachment calculations are made for individual faces and all faces combined. An example of when the "all faces combined" situation might be relevant is when ice encroaching on either of two adjacent faces could impact a particular facility.

## CALCULATION OF DESIGN VALUES

### *Design example*

Using the procedures outlined above, a design example has been worked for a 100 m vertically-sided structure to illustrate the effects of structure freeboard and ice event frequency. In presenting the following results, it is emphasized that this structure does not correspond to any of the structures presently in the North Caspian Sea, nor of any proposed for future construction.

Furthermore, the parameters and events used in the analysis do not represent those for the present development sites.

### *Effect of freeboard*

Design values of encroachment distances have been calculated for freeboards of 4 m, 5 m and 6 m, as shown in Figure 5. Changing the freeboard by 1 m changes the encroachment distance by about 2 m, which is consistent with the rubble slope angles.

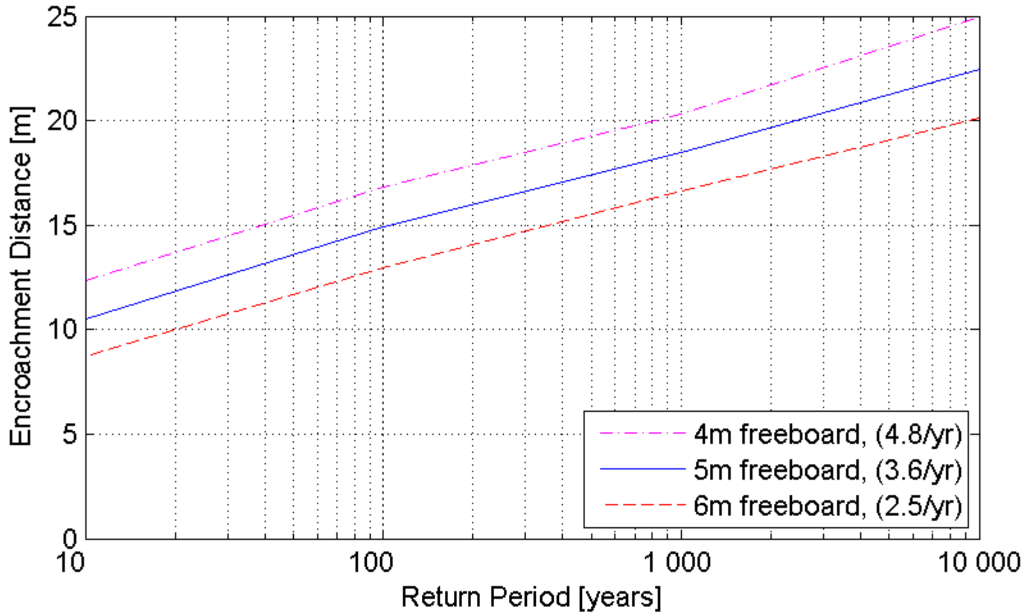


Figure 5. Effect of freeboard on encroachment distances for design example (the estimated number of encroachment events per year is shown in parentheses)

### *Effect of ice event frequency*

The above results assume that each ice movement event results in rubble build-up adjacent to the structure. A number of factors can influence whether a reduced frequency should be considered:

- if rubble is cleared routinely from a jetty or EER access area, the frequency should not be reduced;
- if grounded rubble is allowed to build up over the course of the winter, a reduction factor equal to the proportion of time grounded rubble is present can be used; or
- partial shielding by a berm or an ice protection structure can be represented, with substantiation, using a reduced frequency

Reducing the frequency has a significant effect on design encroachment distance. If the frequency of ice movement events is reduced by factors of 0.5, 0.25 and 0.125, the 100 year encroachment distance is reduced from 16.7 m to 11.8 m, 9.4 m and 7.1 m.

## ICE LOADS ON WALLS

While beyond the scope of this paper, ice actions resulting from ride-up and pile-up processes have been estimated for ice walls and barriers in the Caspian Sea. For ride-up, a key mechanism that limits the actions on a facility (see Figure 2) is when the ice riding up the surface of the rubble or the working surface is lifted from the surface and can no longer transfer the in-plane load. For pile-ups against ice walls, rubble pressures often can be calculated using geotechnical methods for locations above the waterline.

## DESIGN REQUIREMENTS WITH RESPECT TO ICE ENCROACHMENT

In most circumstances, ice encroachment can be considered as a local design issue in the context of the ISO 19906 standard for arctic offshore structures (ISO, 2010). This means that a particular portion of the structure can be designed separately from the rest as long as its failure does not lead to failure or adverse consequences in other parts of the structure. Because of this, design values can often be calculated separately for individual faces of the structure.

For structural design, the ultimate limit state (ULS) criteria apply and the ice encroachment event or action is specified at the $10^{-2}$ annual probability of exceedance level. Such actions should be factored by 1.35 according to ISO 19906. For accidental or abnormal limit states (ALS) where the consequence is catastrophic damage, encroachment events should be specified at the $10^{-4}$ annual probability of exceedance level.

Non-critical parts of the structure can be considered in terms of serviceability limit states (SLS). In the absence of other requirements, ISO 19906 suggests that actions or events can be specified at the $10^{-1}$ annual probability of exceedance level. An example of this would be encroachment on a normally unoccupied storage building or an area that does not contain hydrocarbons or other polluting substances.

## CONCLUSIONS AND RECOMMENDATIONS

While very few published data exist with respect to ice encroachment, the scope of the issue has been demonstrated in this paper.

Some uncertainties remain in the specification of design values of encroachment distance for ice management strips at the edge of island structures in the Caspian Sea. Key parameters that could be refined through further field studies include maximum rubble heights, the location of the apex of the rubble pile-ups adjacent to the structure and the angle from the horizontal of the rubble as it piles up against structures.

Experience has shown that plan geometry and structure profile can influence ice encroachment. Because of the variety of existing structural configurations, water depths, freeboards and ice conditions, it is difficult to extract clear functional relationships from the field data. Numerical investigations are ongoing using the methods outlined in Barker and Croasdale (2004) in an effort to establish these.

## REFERENCES


Barker, A. and Croasdale, K., 2004. Numerical Modelling of Ice Interaction with Rubble Mound Berms in the Caspian Sea, in *Proceedings of 17th International IAHR Symposium on Ice*, Saint Petersburg, Russia.

Croasdale, K., Jordaan, I. and Verlaan, P., 2011. Offshore Platforms and Deterministic Ice Actions: Kashagan Phase 2 Development: North Caspian Sea, in *Proceedings of POAC 2011*, Montréal, Canada, this volume.

ISO, 2010. ISO 19906 Standard, Petroleum and natural gas industries — arctic offshore structures, 2010

Jordaan, I., Stuckey, P., Bruce, J., Croasdale, K. and Verlaan, P., 2011. Probabilistic Modelling of the Ice Environment in the NE Caspian Sea and Associated Structural Loads, in *Proceedings of POAC 2011*, Montréal, Canada, this volume.

McKenna, R., McGonigal, D., Stuckey, P., Crocker, G., Marcellus, R., Croasdale, K., Verlaan, P. and Abuova, A., 2011. Modelling of Rubble Accumulations in the North Caspian Sea, in *Proceedings of POAC 2011*, Montréal, Canada, this volume.