Application of decision analysis to design of Arctic offshore structures

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Théorie de la décision et projet de structures en mer arctique

Entscheidungs-Theorie beim Entwurf von Offshore-Tragwerken in der Arktis

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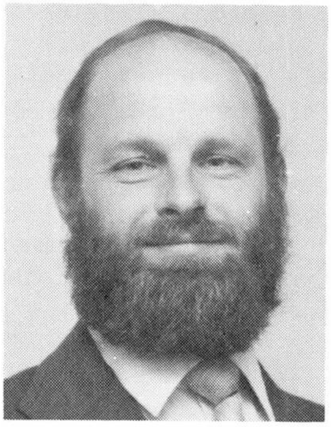

Peter Bein was involved in many aspects of civil engineering since graduation in 1970, and earned his doctorate in engineering systems analysis at the University of British Columbia. For the last six years he worked with two Canadian consulting firms prominent in the arctic offshore engineering, and now is a free-lance consultant.

SUMMARY

Application of decision analysis of the design of arctic offshore structures is discussed. The method proves useful in problems involving uncertain ice environment and multiple measures of merit of alternative solutions, and can help in selecting optimum design ice load criteria for structures.

RÉSUMÉ

La contribution présente une application de la théorie de la décision lors du projet de structures en mer arctique. La méthode est efficace et permet de résoudre des problèmes dans un environnement incertain de glace, en comparant diverses solutions selon leurs mérites. Elle permet également de déterminer les cas optimaux de charges de glace sur les structures.

ZUSAMMENFASSUNG

Die Anwendung von Entscheidungs-Theorien bei der Projektierung von Offshore-Tragwerken in der Arktis ist Thema dieses Beitrags. Die Methode hat sich als nützlich erwiesen in Fällen mit schwer abschätzbaren Eisverhältnissen und beim Vorliegen verschiedener brauchbarer Alternativen und gestattet die Festlegung optimaler Bemessungswerte für die Bemessung von Konstruktionen auf Eiswirkungen.

1. INTRODUCTION

Continued exploration, discovery and extraction of oil and gas from the arctic and sub-arctic frontiers is now becoming a reality. The development is taking place in an environment appreciably different from that encountered in offshore operations in more temperate climates. The presence of sea ice is the prominant factor that challenges the design, hampers the exploration, interfers with the installation and operation of drilling and production structures, and makes marine transportation of supplies, and later of the product to the markets, difficult and costly. Icebergs and sea ice intrude off the Canadian East Coast. Year-round ice up to 12 m thick covers waters between the islands of the Canadian Archipelago. Landfast ice develops along the coast in winter, and polar pack ice constantly moves in the Beaufort Sea. Every year drift ice proceeds southward in the Chukchi and Bering Seas. We cannot readily eliminate the problems created by nature in the arctic, and methods must be sought for dealing with them.

Since the beginning of arctic exploration a multitude of concepts have been proposed for structures capable of supporting all phases of development in each geographical area of the arctic offshore, but only the reasonably priced, reliable and safe technologies have been implemented. Among them are a number of exploration structures that have passed the tests of unusually severe ice conditions of the recent winters. These experiences add to the body of data being accummulated for use in designing more complex future production and transportation systems.

The new systems are necessarily costly because they have to meet the criteria of safe and uninterrupted operation. The designers are presently challenged to reduce the cost of structures, yet to assure safety and reliability at the same time. These are clearly conflicting objectives, and the uncertainties of the arctic further complicate decisions. This paper describes an application of decision analysis to the optimization of arctic offshore systems designed to operate in uncertain and random physical environment, and having conflicting decision criteria.

2. ARCTIC ICE AND STRUCTURES

The design of arctic offshore structures is dominated by lateral forces generated by sea ice. Wave conditions are less severe than in the more exposed sub-arctic waters because the fetch at most locations is limited by the presence of either ice or land. In the St. George Basin of the south Bering Sea, global wave and earthquake loads induced at the foundation level of a structure located in deep water may be comparable to loads produced by drifting ice in a severe winter, but further north, in the Navarin Basin ice loads will dominate design.

Along the coast of Labrador and Newfoundland particularly problematic are icebergs, which could still have a mass of some ten million tonnes on reaching the Hibernia oilfield on the Grand Banks. On the other end of the scale so-called "bergy bits" of the order of 50,000 tonnes and the even smaller "growlers" present great problems because of the difficulty of detecting them in the high seas and limited visibility common to the area. Accelerated by waves, they can produce impacts capable of damaging the mooring system or platform members at the water line [1]. Equally devastating can be the sea ice. Although it only appears at Hibernia every few years early in the year, sea ice is seasonal in the Beaufort and Labrador Seas. The bottom-founded mobile arctic caisson "Molikpaq", deployed in the Canadian Beaufort for exploratory drilling by Gulf Canada Resources in the summer of 1984, was designed for a 500 MN global lateral force from sea ice — compared to 110 MN wave and 180 MN earthquake load [6].

Given their magnitude, ice loads likely to be encountered in the lifetime of a structure must be accurately estimated. The early designs were understandably conservative and provided structural redundancy so that damage or failure would not lead to catastrophic consquences. As more is learned from the performance of already deployed structures, and from monitoring of the ice environment, the conservatism is gradually reduced. The continuing experience is central to efficient and economic design.

Exploration and production of hydrocarbons have different requirements for supporting structures. Exploration drilling is a temporary activity with the objective of obtaining definitive information about the geological structure, testing it for oil and gas producibility, and delineating the reservoir. The activity could last up to several months at one location. After the well is completed and tested, it is secured and abandoned. Because of the limited exposure, temporary or "disposable" structures are used for exploration in shallow water, such as sacrificial gravel islands, grounded ice islands, or floating artificial ice platforms. In deeper water, however, these systems are not feasible, and reusable mobile structures are used, such as ice-capable drill-ships and re-floatable caissons. The mobile structures can rapidly abandon the site in the event of extreme ice conditions.

Production, including storage and transportation of the product, is a longer-term activity, requiring more permanent and durable structures. Production systems can be artificial islands in shallow water, bottom-founded structures in intermediate water depths, or floating systems in deeper water. Both exploration and production structures dedicated to the development of a particular hydrocarbon field will function in the same physical environment, however the length of service expected from production structures is typically twenty years. The chance of experiencing extreme ice loading by the production structures is therefore larger. Also, the notion of extreme conditions is relative. The same ice load criteria that would be an extreme condition for a floating exploration platform, may well become an operating condition for a bottom- founded production structure.

The operating condition design ice loads are maximized using a number of design "tricks". Within the limits of practicality, structures are designed to have redundancy in the framing, so that ice loading exceeding the design values could be tolerated with local damage, but without catastrophic consequences. Some designs incorporate a sloping face with a low friction, low-adfreeze strength coating on the walls exposed to ice to promote flexural failure in the ice feature, and to obtain a vertically downward component from the load to assist in global stability. Foundations in clay seabeds are engineered to maximize tolerable base pressures and to mobilize shear strength of the seabed soil. This is accomplished by replacing the weak soils with sand or by placing a blanket layer of sand or gravel to increase the length of the failure surface, by using spud piles and by enlarging the structural base. Sand core structures, such as the caisson-retained islands and "Molikpaq", achieve stability against sliding largely through the resistance of the sand core. Other structures rely on their own mass plus ballast to develop sliding resistance through friction, and base keys (skirts) are used to ensure that the entire base area is mobilized even if the structure is set down directly on an unprepared, undulating bed. The CIDS (concrete island drilling system) and the new steel base mat for the SSDC (single steel drilling caisson) are examples of this application.

3. DEALING WITH EXTREME ICE LOADS

Although special gravity structures with massive fenders that would absorb the impact of a multi-million tonnes iceberg have been proposed, in most cases it would be uneconomic and impractical to design structures to withstand extreme ice loads likely to occur in the arctic waters. Instead, two general design philosophies have evolved to deal with the extreme conditions. The first one involves a careful monitoring of the ice conditions. The structure is moved out of the approaching extreme ice feature to avoid an impact, and returns to the site to continue operations after the ice has receded.

Gulf Canada's drilling system consisting of a conical drillship 'Kulluk', and a sophisticated ice management apparatus is an example of a successful application of this philosophy. 'Kulluk' is kept on station in the Beaufort Sea by twelve mooring lines, and is designed to withstand moving ice up to 1.2 m thick. Ice conditions in the vicinity of the vessel are monitored by marine radar and aerial reconnaissance. More severe ice is either deflected away or broken up by four ice-breaking vessels into smaller fragments which the mooring system and the hull can withstand. Shortly after its arrival in the summer of 1983, 'Kulluk' had to be towed off station because of an incursion of heavy ice. After the ice receded the vessel was able to return. Floatable production platforms that can take evasive action if necessary, require special solutions to allow rapid yet reliable disconnection of production riser and subsequent reconnection with minimum downtime. Without doubt the experience gained with floating exploration systems such as 'Kulluk' will be incorporated into their design.

The second design philosophy concerns bottom-founded platforms which can be surrounded by a subsea berm. If properly sized, the berm can stop approaching deep-draft features before they have a chance of making contact with the structure. The berm induces breakage of the moving ice canopy, with the eventual accumulation of grounded ice rubble. When fully developed the rubble pile-ups can effectively absorb kinetic energy of giant ice flows and ice islands, and dissipate it to the berm. One disadvantage is that grounded ice pads impede supply vessel traffic and docking ability at the structure. The other limitation is determined by the economics of submerged berm construction in deeper waters, since the volume of fill required increases drastically with the water depth, becoming prohibitive in areas where fill borrow is at a premium.

To circumvent these problems Exxon protected the CIDS on its first drill site in the Alaskan Beaufort Sea by spraying water directly on the stationary ice. Using large-capacity water monitors for two months from the onset of freezeup in late October 1984, enough water was dumped on the ice to ground it in 15 m water depth, creating a 2 million tonnes ice monolith with an average freeboard of 18 m along the crest. The barrier was horseshoe shaped to allow supply vessel access from one side. After drilling two wells, CIDS lifted off in the next summer and was towed away from the protective berm through its open side. Although very appealing for floating drilling and permanent production platforms alike, the method is limited to Beaufort Sea waters less than 20 m deep, which have the stationary natural ice required during initial stages of the spraying operation until the barrier grounds.

4. DECISION ANALYSIS MODEL

Because the design of arctic offshore structures is dominated by forces generated by sea ice, relatively more attention must be given to the estimation of ice loads likely to be encountered in the lifetime of a structure than to the other loads. The fundamental characteristics of ice loads is the magnitude vs. return period curve. It is not a simple matter to obtain it. Simulations play an important role in the derivation of the curves, but the results depend on the assumptions about the physics of load generating processes, and on the assumed probability distributions of input variables [1]. The curve is often defined by combining available data, knowledge of physical processes and parallels with other arctic regions [11]. The uncertainty of ice loads is caused not just by nature's randomness, but also by our imperfect knowledge of the arctic, and fragmentary data, sometimes with a dramatic impact on design. For example, recent full-scale tests at the Hans Island indicate that conventional theories overpredict ice forces on production structures by a factor of ten [12].

The ice load return period that is eventually selected for design has important consequences for operations. Extreme conditions occur infrequently in a structure's life, but the ice loads are high enough to displace and damage the structure, with the potential of oil spills from damaged storage and production facilities, well blow-out, and personnel casualties. Depending on the severity of damage, the structure could or could not be restored to an operable condition, but the repairs would be costly and time-consuming in the forbidding arctic environment. If the structure is lost, the capital investment is wasted and exploitation of the hydrocarbon reservoir delayed until the facility is replaced. Moreover, the current technology of oil spill countermeasures precludes an effective and environmentally acceptable clean-up of a major spill in ice-covered waters.

Shorter return periods imply smaller design loads and, consequently, smaller capital cost of the structure, but more frequent disruption of operations when the approaching ice features exceed the design limits. More extensive ice surveillance and more intensive control of ice feature size and movement by appropriate use of ice breakers and tugs are required to protect a structure designed to short return periods. If longer return periods are adopted the capital cost of the structure goes up, but the relative frequency of disruptions and the expected repair cost of damage decrease.

There is currently no accepted requirement for the level of environmental exposure used for arctic design -- largely due to the lack of experience in artic operations, and the poor data base. This paper proposes to use the decision analysis in defining ice load design criteria.

Many situations involving uncertain variables can be represented by a decision tree model [3]. The alternatives are a_i, and the system is described by a set of states s_j (Fig. 1). Uncertainty of states is quantified by probability distributions. When alternative a_i is selected and state s_j occurs, a consequence c_{ij} results. The consequence is measured by attributes derived at the problem definition step from the hierarchy of objectives of the decision maker and possibly other interest groups. The desirability of a consequence is expressed by a numerical measure u_{ij} termed utility. The theory prescribes the choice of an alternative with the highest expected utility to be the optimum criterion. The major data gathering task of decision analysis is to specify probability distributions and utility functions. Probability theory allows the analyst to make a maximum use of information available about uncertain states, while utility theory guarantees that the choice reflects the decision maker's true preferences.

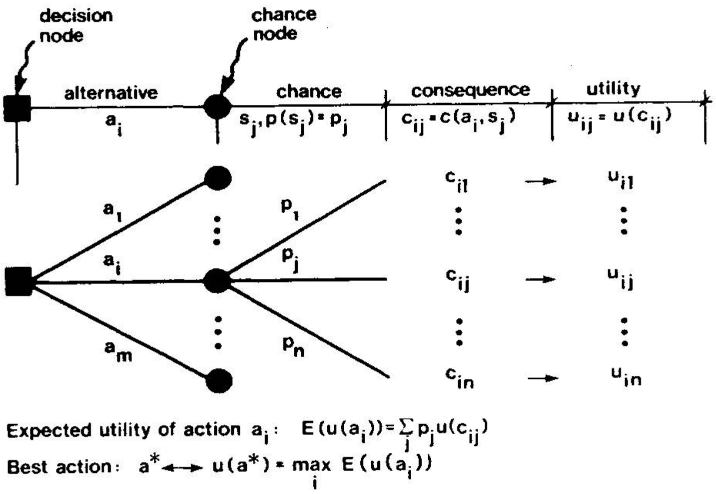

Fig. 1 Decision model

The model requires that a complex problem be divided into parts allocated to specialists. When re-assembled all parts fit into a clear structure facilitating meaningful sensitivity analyses and new insights into the problem, with a potential for reduction of costly experimentation in the arctic. Although past experience has shown that our knowledge cannot improve markedly until the structures are in actual service, supplementary analyses such as sensitivity or value of improved information can provide insights with a great potential for improving decisions prior to deployment of arctic structures.

The model is modified depending on a particular problem [8]. There are typically vectors of attributes in multiple criteria arctic decision problems. Alternative a_i can denote a sequence of decisions over a period. State s_j becomes then a sequence of states that can occur with joint probability p_{ij}. The utility function can be a decision maker's or it can represent a compromise between conflicting preferences of multiple interest groups. If the decision maker is risk neutral and chooses to minimize expected cost, the utility function can be measured in monetary units.

In solving engineering problems for the arctic, the ability to quantify vagueness is at least as important as the facility of probability theory. This ability is now possible with the development of the theory of fuzzy sets. The theory has matured to the point of practical applications in decision analysis [9] and the first attempts have been made in arctic offshore engineering to apply it to imperfect knowledge of sea bottom scour by ice [13]. The marriage of the two approaches proves the decision model's flexibility and opens new avenues for a rigorous treatment of imperfect knowledge within the scheme of decision analysis.

The Committee on Reliability of Offshore Structures [4] have recognized the potential of decision analysis in selecting tolerable risk levels in the conventional offshore platform design. Maximization of expected utility has been identified among available methods to be the most flexible for dealing with multi-attribute consequences of structural failures, such as capital and operating costs, environmental contamination, life loss and injury.

The overwhelming uncertainty of the ice environment has led to an emphasis on the formulation of probability inputs into arctic technology evaluations, and only a few references apply the complete decision method. A decision tree approach has been employed to select the most preferred development plan, consisting of a chain of decisions on drilling, production, and transportation systems, on the basis of the highest net present worth and the lowest economic risk [5]. Jordaan [7] recommends decision analysis for risk assessment of systems, and for planning of operations in ice-infested waters. Bein [3] applies decision approach to screening of alternative production structures in the Beaufort Sea, and to optimization of arctic tanker terminal configurations.

5. APPLICATION

Since there is always a chance of disruption of operations and structure damage by ice loads higher than those adopted for design, the selection of their return periods shall be based on a calculated risk, which simultaneously optimzes:
- capital cost of the structure,
- operating cost of ice management required for the protection of the structure,
- downtime when operations are suspended as a precaution against ice hazards,
- costs of damage (time lost, repair, cleanup and well re-drilling),
- exposure to casualties of personnel engaged in evacuation, countermeasures, and restoration of operations, and
- impact of oil spills on the arctic habitat.

These are the consequences c_{ij} in the sense of Fig. 1.

Fig. 2 models a situation where a structure can be damaged with probability r in

$$r = 1 - (1 - 1/t)^n$$

t = return period of ice load
1/t = annual probability of damage
n = design life of structure
r = n-year probability of damage

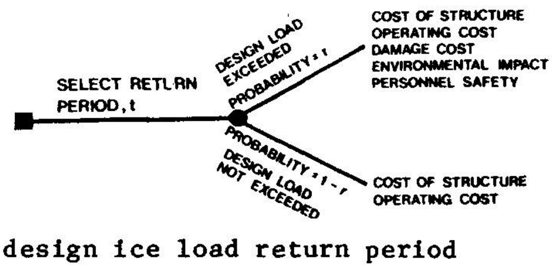

Fig. 2 Decision model for selecting design ice load return period

its lifespan. With probability (1-r) damage will not occur, and the consequences will be only the capital and operating costs. To find the optimum return period, the consequences are evaluated using a utility function. It can facilitate trade-offs between the conflicting consequences, and account for risks posed by consequences and by their probabilities and timing [8]. The decision maker's relative disliking of negative impacts associated with a return period is measured by a quantity termed disutility corresponding to u_{ij} in Fig. 1. The statistical expectation of disutility is the relative measure of merit of selecting return period t and having damage probability r in Fig. 2. For a range of return periods a graph (Fig. 3) can identify the optimum. If it happened to exceed the period required by codes, it would be the value for design, otherwise the code requirement would govern.

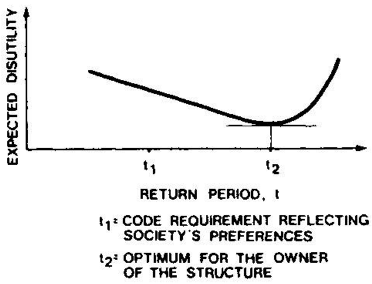

Fig. 3 Optimization of ice load return period

The acceptable return periods must be established by an engineer in consultation with the owner of the structure, but from the standpoint of public well-being it would be inappropriate for either of them to make value judgements concerning personnel and environmental safety. The usual way of encoding the public values necessary to consider in design is through the code stipulations. Lower bound return periods would be specified for arctic structures classified by design life, function, manning requirements, and environmental hazard. The owner would use return periods required by the code, unless longer periods would be more economical. No such guidelines are presently available for the arctic operators. One recommended practice states in too simple terms that the selection of design loads should be the prerogative of the owner [2], but a reported case demonstrates that the owner requires clear guidelines [6].

In the artic developments, where often no basis exists for comparing new designs with existing practice, the degree of conservatism in design may be unbalanced. It can be excessive and costly if the engineer derives design criteria with only rough guidelines [10]. If on the other hand the owner has the prerogative of selecting ice load criteria, the public concerns may tend to be overlooked, with possible adverse impacts following after project implementation.

CONCLUSIONS

Arctic ice is the major environmental load in the design of arctic offshore structures, yet its characterization is subject to considerable uncertainty caused by the natural randomness, poor data and insufficient knowledge. Although the uncertainty is being continuously reduced as more is learned both from the performance of structures placed in service and from improved observations of the ice environment, the choice of ice loads for design of structures must be based on a probabilistic basis because of the randomness. The costs and the reliability of structures strongly depend on the ice loads assumed for design. Success of the hydrocarbon development plans hinges on our ability to devise inexpensive technological solutions that are safe, reliable and bring us closer to energy self-sufficiency in spite of the extremities and variability of the arctic offshore environment.

Decision analysis can address those engineering, planning and design problems of arctic offshore systems that arise from conflicting decision criteria, and uncertain physical environment. From problem definition to decision maker's use of the results, the analysis provides a sound basis for improving current planning and design pratices. It can help define problems in code formulations, feasibility studies, and preliminary design; it is a flexible analytical technique for systems design optimization; and finally, it is useful in relating engineering design to the overall development planning. This paper addresses selection of ice load design criteria as an example application.

Although the merit of decision analysis in prospecting for oil and gas, and in offshore engineering, has been established, more work is required to make it a credible tool for arctic offshore engineering. Data bases must be enlarged in order for probabilistic descriptions of ice characteristics to become more trustworthy. Ice-structures and ice-soil interaction mechanisms need better understanding to allow reliable simulations from fundamental data. The effects of structural damage on operations delay, habitat, personnel safety, and costs of repair under arctic conditions must be assessed for a range of structure types and materials, damage severity, mitigating measures, and contingency plans.

ACKNOWLEDGEMENTS

This paper is based in part on the author's work with Swan Wooster Engineering Co. Ltd. and DF Dickins Associates Ltd., both of Vancouver, Canada.

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