CHAPTER 126

ARCTIC SLOPE PROTECTION METHODS

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ABSTRACT

This paper reviews knowledge acquired in the Alaskan Beaufort Sea pertaining to three methods of Arctic slope protection: (1) sacrificial beaches, (2) "soft" (geotextile based) armor, and (3) linked concrete mats. Design considerations and performance evaluations are presented for each method, along with recommendations for future use. It is concluded that the existing technology is capable of providing reliable protection for structures located in coastal and nearshore areas, and that more durable systems will be required to withstand the extreme wave and ice loads which can occur at exposed sites in deeper waters.

INTRODUCTION

Since 1976, more than twenty man-made islands, causeways, and coastal pads have been constructed in the Alaskan Beaufort Sea in response to the needs of the petroleum industry. The initial facilities were sited along the coast or at nearshore locations where wave heights and ice forces were limited by the water depth. By the mid-1980's, however, slope protection methods and construction techniques had advanced to the point where islands were installed in exposed locations with water depths to 15 m. Although the rate of new construction decreased in the 1980's with the decline in oil prices,

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performance monitoring of many of the facilities has continued through the present date.

The objective of this paper is to review the knowledge of Arctic slope protection which has been acquired from the past fifteen years' experience in the Alaskan Beaufort Sea. Emphasis will be placed upon the three methods which have been most widely employed: (1) sacrificial beaches, (2) "soft" (geotextile-based) armor, and (3) linked concrete mats.

SITE CONDITIONS

The most distinguishing feature of the Arctic offshore environment is the presence of sea ice. First-year ice typically attains a thickness approaching 2 m during the long winter season. When the ice is deformed by pressure, its thickness can increase to 30 m or more, and the resulting pressure ridge can often survive one or more summer melt seasons. Such multi-year floes pose a particular threat to offshore structures, not only because of their great mass, but also because of the drift velocities they can attain during the period of open-water.

Design ice loads generally are based on the crushing strength of the ice (American Petroleum Institute, 1988). Global loads in shallow water are of order 700 to 1000 kPA, while those in deeper water (to 15 m) are of order 1400 to 1700 kPA. Local loads, as might occur on piles or protruding armor units, can exceed the corresponding global load for the entire structure by a factor of three. Damage can also result from the shear forces exerted when ice moves up or along the structure slope, and from ice abrasion.

Hydraulic loads are moderate in the Beaufort Sea due to the limited fetch which results from the proximity of the polar ice pack. At an exposed, deep-water site, representative wave conditions for the 10-year return period storm might consist of a maximum significant wave height of 4-5 m and a peak period of 8-10 sec. Storm surges can significantly increase the water depths and the resulting depth-limited wave heights in nearshore areas.

Experience to date suggests that the most severe damage to slope protection systems often results from a combination of ice and wave loads. Drift ice impacts can damage and displace armor units below the waterline, for example, after which the slope is predisposed to rapid degradation under even moderate wave loads.

Conversely, deformations in the slope profile caused by wave impacts can create local protrusions which serve as focal points for ice forces.

In addition to ice and wave loads, the following factors must be considered in designing slope protection systems for Arctic service: (1) low temperatures (-50°C), (2) a brief open-water season during which construction can be performed (typically 60 to 90 days), (3) a lack of native construction materials (including quarrystone and cement in the Alaskan Beaufort Sea), (4) a paucity of environmental data from which to predict extreme events, (5) a lack of specialized construction equipment, and (6) the high cost of importing equipment and non-native construction materials. As a result of these limitations, the slope protection methods which have evolved in the Alaskan Arctic have tended to emphasize simple construction techniques, maximum use of locally available materials, and non-catastrophic modes of failure (in the event that the design conditions have been underestimated).

SACRIFICIAL BEACHES

Sacrificial beach slope protection consists of providing a buffer zone of expendable beach material around the area to be protected (Plate 1). The width of the buffer zone should be sufficient to accommodate the

Plate 1. Sacrificial Beach on Niakuk 4 Island

erosion anticipated from both daily conditions and design storm events. The obvious advantages of such an approach include a low capital cost, ease of construction, and low susceptibility to ice damage. The primary disadvantages are the need for frequent maintenance, and the fact that the degree of protection provided by the system depends not only upon the incident wave heights, but also upon storm duration. Because erosion rates tend to become unacceptably high in exposed locations, sacrificial beaches are most appropriate for coastal or nearshore sites in which the wave heights are depth-limited.

Design Considerations

Of particular benefit in the design of sacrificial beach protection has been the availability of gravel and coarse sand in relict river deposits along the Alaskan coast. To date, all of the sacrificial beaches in the Alaskan Arctic have been constructed from this material rather than from the fine sands and silts found on the sea bottom. The median grain size (D_{50}) has typically ranged from 4 to 8 mm, with a maximum cobble size of 80 mm and a fines content ($D_{50} < 0.075$ mm) of less than 10%. As discussed below, the coarse nature of the sediment has resulted in lower longshore transport rates, and consequently more stable beaches, than those associated with the sand-sized material.

Both cross-shore and longshore transport must be taken into account in determining the required width of the sacrificial buffer zone. To obtain a first approximation of the former, successive profiles were obtained on the slopes of Niakuk 4, a man-made island located in a water depth of 1.4 m, during the three-year period between 1985 and 1988. The change in the configuration of the island which occurred during the monitoring period is illustrated in Fig. 1; representative profile data from the exposed northeast side are presented in Fig. 2.

The data suggest that the gravel tends to assume an equilibrium profile analogous to that reported for sand beaches by a number of investigators (for example, Bruun, 1954; Dean, 1977). The characteristic concave-upward shape of the below-water portion of the profile can be described by the relationship:

$$h = ax^m \qquad (1)$$

where h is the depth (m), x is the distance offshore (m), and a and m are empirical constants which provide a best fit to the data with values of 0.39 and 2/3, respectively.

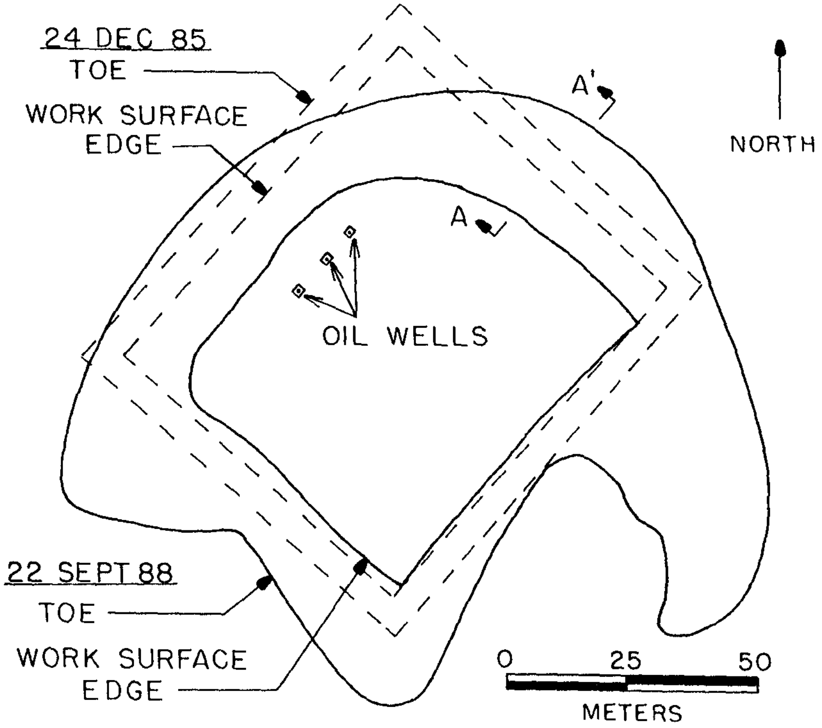


Figure 1. Evolution of Niakuk 4 Island, 1985-88

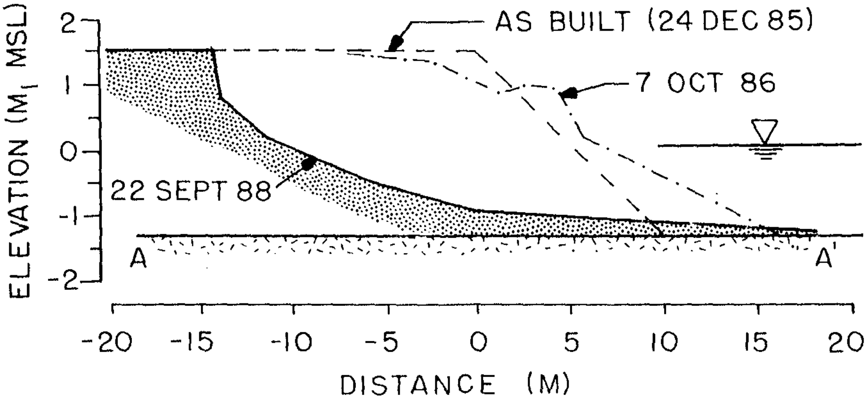


Figure 2. Beach Profiles on Niakuk 4 Island, 1985-88

As reported by Komar (1988), data regarding longshore transport rates for gravel-sized material are extremely sparse. To develop a first order predictive capability for the sacrificial beach material available in the Alaskan Arctic, the average annual net transport rates for the exposed northeast and northwest sides of Niakuk 4 Island (Fig. 1) were calculated from the survey data for the 1985-88 monitoring period. These results were combined with the wave measurements available from a single open-water season prior to the monitoring period (1982) to determine the transport coefficient K in the relationship proposed by Komar and Inman (1970):

$$I_s = KP_l \qquad (2)$$

where I_s is the immersed-weight transport rate and P_l is the longshore component of wave power based upon the root-mean-square wave height. Values of 0.08 and 0.12 were obtained for the transport coefficient on the northeast and northwest sides, respectively. In view of the limitations of the data set, this range is not surprising. The mean value of 0.10 was therefore adopted as a first approximation of the transport coefficient.

It is noteworthy that the foregoing result, obtained for material with a D_{50} of 4 mm, is substantially lower than the transport coefficient of 0.77 reported for sand (CERC, 1984; note that the value of K = 0.39 presented by CERC has been modified to 0.77 to reflect the use of the root-mean-square wave height rather than the significant wave height in calculating P_l in Eq. 2.) It therefore appears that the use of coarse sediment can significantly improve the performance of sacrificial beaches by reducing the rate of longshore transport.

Performance Evaluation

Four man-made islands and two shore-connected causeways using sacrificial beach slope protection have been constructed in the Alaskan Beaufort Sea to date. Water depths have ranged from 0 to 3 m. The most extensive application has been on the Endicott Oil Production Facility (Munday and Bricker, 1988), where 8 km of causeway in water depths to 2 m are protected by gravel beaches placed at an initial slope of 7H:1V. Fill losses and scarp formation have been modest, and no replenishment has been required since the facility was completed in 1986.

The most thorough documentation of beach performance has been obtained for Niakuk 4 Island (Plate 1; Fig. 1). Constructed in 1984 in 1.4 m of water as a 122 x

107 m rectangle, the island experienced moderate erosion during the 1985 open-water season. It was re-graded to its original configuration during the fall of 1985, at which time the monitoring program referred to previously was undertaken.

During the ensuing three open-water seasons (1986-88), the gravel losses from the exposed northeast and northwest sides of the island averaged only 2,200 m^3/yr. More than 75% of this material accumulated in spits which formed at the east and west corners (Fig. 1). During the 1989 open-water season, the spit material was excavated and used to restore the width of the buffer zone on the northeast and northwest beaches. Initial concerns that the gravel would remain frozen during the summer months proved to be unfounded, allowing the backpasing operation to proceed at a rate of 2,900 m^3/day.

In contrast to the relative stability evidenced by sacrificial beaches in water depths of 2 m or less, substantial erosion rates have been observed on beaches in deeper water. Such observations encompass islands from which the original armor has been removed (Anderson and Leidersdorf, 1988), as well as purpose-built beaches. Based upon both the rates of erosion and the cost of transporting gravel offshore for beach replenishment, it appears that the 2-m isobath represents a practical limit for the application of sacrificial beach slope protection methods in the Alaskan Arctic.

SOFT ARMOR

"Soft armor" refers the use of geotextile containers filled with sediment as a means of providing slope protection. Although the concept embodies a wide range of devices, the Alaskan experience has indicated that massive units such as tubes and mats are susceptible to rapid deflation when punctured by ice (Leidersdorf, et al., 1981). Large gravel-filled bags (Plate 2) have proven to be best-suited for Arctic service, and are therefore the focus of the discussion which follows.

The advantages of gravel bag slope protection include a moderate capital cost, the ease of performing repairs, and the relative simplicity of the installation procedure. The primary disadvantages are a susceptibility to ice damage, resulting in the need for maintenance, and the environmental nuisance which is created when damaged bags drift away from the slope.

Plate 2. Gravel Bag Armor on Resolution Island

Design Considerations

The central issues to be addressed in the design of gravel bag slope protection are the characteristics of the bags themselves, the placement configuration, and the characteristics of the underlying filter fabric. In the case of the bag characteristics, two sizes, representing capacities of 1.5 and 3.0 m^3, have been adopted for most Arctic applications to date. The 3.0 m^3 size, with a weight of approximately 5.5 tonnes, has proven to be the largest unit which can be easily handled by conventional construction equipment. It is typically used in exposed locations with relatively energetic wave regimes, while the 1.5 m^3 size is applied in cases of more limited wave exposure.

Based on the performance of prototype test sections (Leidersdorf, et al., 1981), bags constructed of a single layer of high-strength fabric are more durable than those comprised of multiple layers of lower-strength material. Woven polypropylene with a grab tensile strength of 700 N/cm has been used to construct the majority of the bags in Arctic service; specifications for this material are provided by Gadd (1988).

Representative placement configurations for gravel bag armor are illustrated in Fig. 3. An inclination of 3H:1V has proven to be the steepest grade at which the

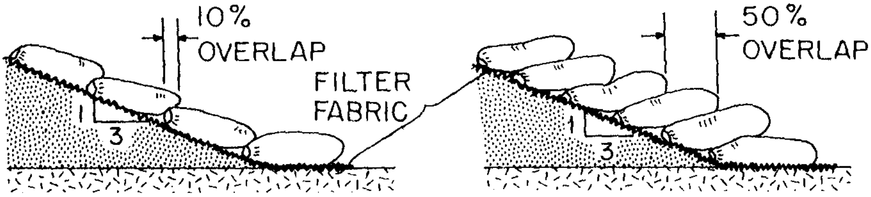


Figure 3. Gravel Bag Placement Configurations

bags are not prone to sliding failure, and has therefore been adopted for most gravel bag installations in Alaska. Maximum stability is achieved by orienting the longitudinal axis of each bag in the on-offshore direction, and by providing a measure of overlap between the bags. A minimum overlap of 10% of the bag length is recommended to insure that the closure end of the bag is protected from direct wave impact by the next bag upslope. Increasing the overlap to 50% requires additional bags, but offers the advantages of greater stability, redundant coverage in the event that bags are damaged, and reduced wave runup elevations.

Based on the results of large-scale model testing, the hydraulic stability of gravel bags in the 50% overlap configuration can be estimated using Hudson's Equation (CERC, 1984) with a stability coefficient K_D of 3.0 (Gadd, 1988). Fig. 4 displays the computed threshold wave heights for bag instability as a function of the cotangent of the slope angle. For the 3H:1V slopes in common use, instability is predicted to occur at a wave height of 1.9 m for 1.5 m^3 bags, and 2.4 m for 3.0 m^3 bags.

A permeable filter fabric must underlie the gravel bag armor layer to retain the slope fill material (Fig. 3). The experience to date indicates that if the slope is composed of coarse sand and gravel with a low fines content, non-woven material with a grab tensile strength of 525 N/cm provides acceptable performance.

Performance Evaluation

Gravel bags have been used as the primary means of slope protection on nine man-made islands and two coastal pads in the Alaskan Beaufort Sea. Four of the islands were constructed in exposed locations with water depths of 12 to 15 m; the remainder were located in partially sheltered sites with depths to 7 m.

Resolution and Mukluk Islands illustrate the range of performance which has been observed for gravel bag armor systems. Resolution, located in a partially

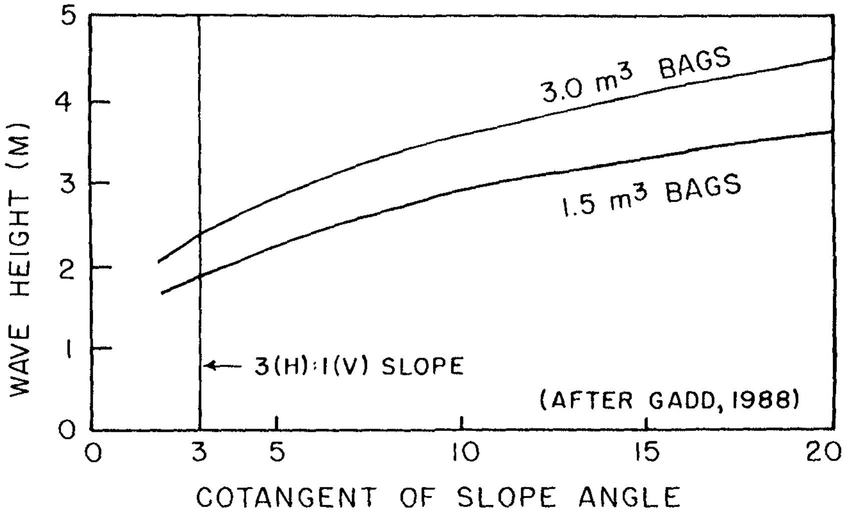


Figure 4. Threshold Wave Heights for Gravel Bag Instability

sheltered location with a water depth of 2.3 m, has sustained damage to its 3,140 1.5 m^3 gravel bags at an average rate of about 5% per year since it was constructed in 1980. The primary causes of the damage have been the impacts of drift ice during the summer months, and movements of the ice sheet during the winter months. Repairs have been performed on two occasions to restore the integrity of the armor.

Mukluk Island was constructed in 1983 at an exposed location in 14.6 m of water. During the following two open-water seasons, drift ice impacts ruptured a majority of the 3.0 m^3 bags from the waterline to a depth of 8 m. Because the island was no longer needed for oil exploration, the damage was not repaired, leading to an extensive failure of the armor and loss of island fill material in response to two severe storms in 1986 (Anderson and Leidersdorf, 1988).

The foregoing observations, as well as those from other facilities, suggest that gravel bag armor is best suited for applications in shallow and intermediate water depths where wave heights seldom exceed 3 m, and where frequent impacts from large, drifting ice floes are not anticipated. Because ice damage can predispose the armor to failure under wave conditions which are well below the threshold level for hydraulic instability, periodic inspections and repairs are essential to maintaining its functional effectiveness.

LINKED CONCRETE MATS

Linked concrete mat armor consists of concrete blocks which are joined by flexible linkages to form a continuous, articulated cover on the slope to be protected (Plate 3). Rather than depending upon mass alone, the mat derives a significant portion of its stability from the connections between adjacent blocks.

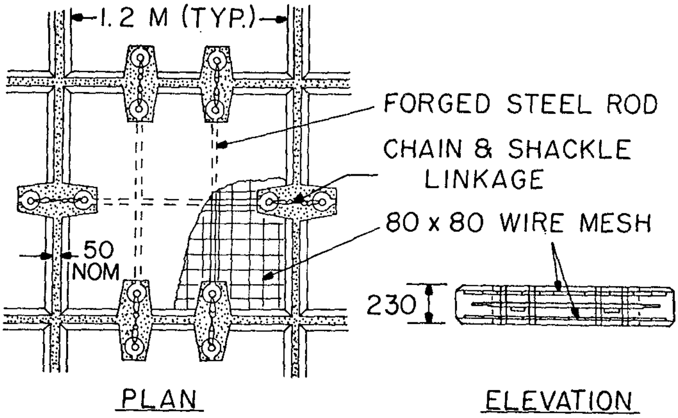
Plate 3. Concrete Mat Armor on the Endicott Project

The primary advantages of the mat concept are a reduced susceptibility to ice damage, a suitability for modular installation, and the ability to accommodate changes in the subgrade without permitting catastrophic fill losses. Disadvantages include a relatively high capital cost, and the difficulty in effecting repairs if significant damage is sustained.

Design Considerations

In recognition of the need to withstand both severe ice loads and the cyclic impact loads resulting from wave-induced uplift, relatively large, reinforced blocks with chain-and-shackle linkages have been selected for most Arctic offshore applications. A representative example of the block design, in which the blocks are 1.2 m square and 230 mm thick, is provided in Figure 5.

A filtration medium is required under the blocks to retain the slope fill material. Permeable geotextiles



(AFTER HAYLEY ET AL., 1987)

Figure 5. Representative Concrete Block Design

have been used for the Arctic projects to date, but graded stone or manufactured concrete rubble may be warranted for projects with a long design life or at exposed locations where the fabric might be damaged by uplift-related abrasion.

Although a semi-analytical model has recently been developed for evaluating the hydraulic stability of unlinked mat systems (Burger, et al., 1990), a comparable design tool for linked mats does not presently exist. Hydraulic model testing is therefore recommended as the most reliable means of refining and confirming the design of linked mat systems for major projects.

The relatively smooth surface of concrete mat armor, although advantageous from the standpoint of reducing ice forces, is ineffective in deterring wave runup. As illustrated in Plate 3, this potential problem can be addressed by restricting the use of the mat to the zone of severe ice and wave impacts, and placing overlapped gravel bags on the upper portion of the slope.

Performance Evaluation

Linked concrete mat armor was tested on a limited scale on two nearshore islands in the early 1980's. Based on the successful performance of these prototype test sections, it has been selected for use in a coastal revetment, and as the primary means of protection for three islands: Northstar, constructed in 1985 in a water depth of 13.7 m (Hayley, et al., 1987), and the two islands of the Endicott Project, constructed in 1985-6 in depths of 1.8 to 3.6 m (Munday and Bricker, 1987).

At the Endicott site, where the wave and ice conditions are moderated by the water depth, the mat has sustained no significant damage and required no maintenance since it was installed. It is noteworthy that this performance has been achieved despite the occurrence of wave and ice events with sufficient energies to displace 4 m^3 gravel bags on the upper slopes.

Wave and ice conditions have been more extreme at the Northstar Island site, and have included storm waves with heights of 3 to 4 m, and numerous impacts from large multi-year ice floes. Although the mat performed significantly better than the gravel bag armor systems on nearby islands, it nevertheless sustained appreciable damage. As discussed by Gadd and Leidersdorf (1990), wave-induced uplift was of a sufficient magnitude to cause deformation of the subgrade, abrasion of the filter fabric, and localized fill losses. These irregularities in the slope served to intensify the loads imparted by ice impacts, resulting in the breakage of both concrete blocks and steel linkages, and the displacement of groups of blocks in the vicinity of the waterline.

The foregoing observations suggest that the mat systems currently in use are capable of withstanding the wave and ice forces in partially sheltered environments with little or no damage. They are particularly appropriate for projects in such locations with extended service lives, in that their relatively high capital cost will be offset by low maintenance costs. In exposed locations, the existing mat technology is susceptible to damage from the wave and ice forces associated with extreme events. Possible alternatives for improving the armor performance in this regard include increasing the thickness of the blocks and the strength of the linkage system in the vicinity of the waterline, and providing a near-horizontal bench in the slope just below the waterline to dissipate the energy of arriving waves and ice floes (Leidersdorf, et al., 1894).

SUMMARY AND CONCLUSIONS

The experience of the past 15 years indicates that the existing slope protection methods are capable of resisting the hydraulic and ice forces encountered in the coastal and nearshore waters of the Alaskan Arctic. The most cost-effective method of protection for a particular project depends upon the water depth, the degree of exposure to wave and ice impacts, and the project design life. Sacrificial beaches are well-suited for applications in depths of 2 m or less. Gravel bag armor can withstand more severe wave conditions, but is susceptible to ice damage and requires regular maintenance. Linked concrete mat armor is capable of resisting both the ice and wave impacts commonly encountered in nearshore areas, and is therefore recommended for projects requiring secure protection over an extended period.

Gravel bags and linked concrete mats have also demonstrated the ability to protect facilities at exposed sites in deeper water, but have sustained damage from extreme wave and ice events. Frequent inspection and repair activities are necessary at such locations to prevent catastrophic slope failures.

In order to develop more durable slope protection systems suitable for long-term service at exposed sites, it will be necessary to provide an improved resistance to the impacts of large ice floes, and to the combined effects of wave and ice loads. At the present time, the most promising approach appears to be through modifications to the existing mat technology.

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