CHAPTER 210

RECENT PERFORMANCE OF LINKED CONCRETE MAT ARMOR UNDER WAVE AND ICE IMPACT

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INTRODUCTION

Concrete mat slope armor has been used for many years to provide slope protection in mild inland and coastal wave environments. Presently, flexible block revetments are gaining popularity for application in moderate wave climates where more conventional types of slope protection are uneconomical or unavailable. European investigators have undertaken design and model testing of placed (non-linked) concrete block revetment systems (Burger, et al., 1990, for example). Systems requiring physical linkage of adjacent blocks have been designed and deployed as well (Hayley, et al., 1987; Leidersdorf, et al., 1988; Munday and Bricker, 1987).

Previous authors have described linked concrete mat systems in detail and suggest its promise for both Arctic and non-Arctic applications (Hayley, et al., 1987; Leidersdorf, et al., 1988; Munday and Bricker, 1987). The objective of this paper is to describe the results of on-going performance monitoring of linked concrete mat systems deployed upon a man-made island in the rigorous Arctic offshore environment. We wish to place particular emphasis upon recent observations that indicate performance limitations of existing concrete mat technology when subjected to the combined effects of severe Arctic wave and ice impacts at offshore deepwater sites.

LINKED CONCRETE MAT ARMOR

Concrete mat slope protection has been advanced by numerous investigators as an alternative to more conventional discrete-unit slope armor. Principal advantages to the concrete mat alternative are related to enhanced stability of light-weight armor units (by

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virtue of physical linkage), ability to accomodate changes in subgrade without loss of underlying gravel fill, and suitability for quick and economical modular placement. In addition, Arctic applications require ease of removal (for short-lived oil exploration structures) and resistance to ice abrasion and impact.

As indicated above, several large oil industry projects in Arctic Alaska that utilized the linked concrete mat concept have been described previously. The mat system under study is composed of individual blocks having plan dimensions of 1.2 m square. Block thickness can vary with application but has typically measured 0.23 m. Block linkage is provided by galvanized shackles and chain segments.

PERFORMANCE MONITORING OBSERVATIONS AT NORTHSTAR ISLAND

Northstar Island was constructed at an unprotected offshore location having a water depth of 13.7 m located approximately 25 km northwest of Prudhoe Bay, Alaska. This island has provided a unique setting in which environmental influences on the slope protection system have been carefully monitored annually since the completion of construction in 1985. The design of Northstar Island has been described previously (Hayley, et al., 1987; Leidersdorf, et al., 1988), and is summarized in Figure 1.

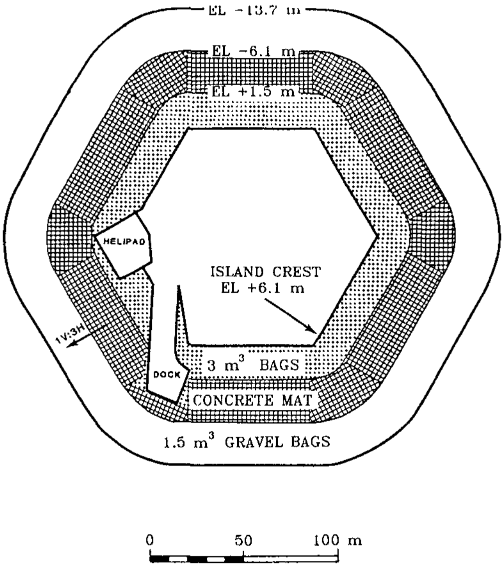

FIGURE 1: NORTHSTAR ISLAND DESIGN

The slope armor system is composed of linked concrete mat in the zone of primary wave and ice impact (El. +1.5 m to -6.1 m, MLLW) placed upon a slope of 1 (vertical) on 3 (horizontal). On the slopes up-slope and down-slope from the concrete mat, large (1.5 to 3.0 m^3 capacity) gravel-filled fabric bags are placed. The overlapped placement configuration of the gravel bags on the upper slope of the island reduces wave run-up elevation.

Northstar Island is an oil exploration island having an intended design life of three years. The design storm event was expected to be accompanied by storm surge of 1.0 m and to exhibit a significant wave height of 3.7 m, and a significant wave period of 9.6 sec.

Prior to the construction of Northstar Island, shallow water installations of linked concrete mat slope armor in the Arctic in water depths of 2-4 m met with success. Owing to the mild wave and ice conditions at these locations, significant damage has not been noted to date. At Northstar Island, however, degradation of the mat revetment has been noteworthy, related to the alternating impacts of large storm waves and massive ice features.

In the 1987-1988 period, the performance of the mat system degraded following significant damage imposed by multiple episodes of large wave and ice impact. The discussions in this paper seek to describe the damage that has occurred on Northstar Island since its construction in 1985 and to offer insights that will improve the existing state of engineering knowledge concerning deployment of linked concrete mat slope protection in the Arctic offshore.

WAVE-INDUCED CONCRETE MAT DAMAGE

Effects of Angle of Wave Incidence

During a strong northwest storm accompanied by wave heights in the three to four meter range that occurred in late September 1986, significant uplift and undulation of the concrete mat at Northstar Island first occurred. It was clearly noted, however, that the extent of mat uplift was not uniform around the island circumference. Photo 1 is presented to show the condition of the island sector that received the incoming wave impact at a normal (i.e. wave ray approach = 90^{o} from waterline) angle of incidence. The undeformed nature of this slope suggests that mat uplift did not occur along this island sector.

Conversely, along the sides of the island which experienced wave passage at highly oblique angles of incidence, mat uplift and the resulting mat undulation was severe, as shown in Photo 2. Wave-induced mat instability was noted along the island slopes on the lee side of the island as well, where wave crests did not detach from the island slopes, but proceeded along the slopes at angles of incidence greater than 45^{o}.

PHOTO 1: POST-STORM CONDITION, NORMAL ANGLE OF WAVE INCIDENCE

PHOTO 2: POST-STORM CONDITION, OBLIQUE ANGLE OF WAVE INCIDENCE

We believe that the reasons for the destabilizing effect of oblique wave passage over the concrete mat at Northstar Island is based both on hydrodynamic effects that impose negative wave pressures on the mat, and as a consequence of asymmetrical mat linkage tension imposed during the construction process. The hydrodynamic effects that produce greater wave uplift for oblique angles of wave attack (relative to normal incidence) have been noted by researchers utilizing three-dimensional physical model studies at Delft Hydraulics, The Netherlands (Bezuijen, A., and A.M. Burger, personal communication).

Asymmetric block linkage tension within the mat was caused as a result of the construction process, undertaken during August-September, 1985. In placing the mat upon the island slopes, narrow mat segments were used incorporating 22 blocks in the upslope-downslope direction by two blocks across. As the placement crane lowered the mat to its above-water anchorage position and boomed the mat offshore, high tension was achieved in the upslope-downslope mat direction. Successive mat sections were placed closely side-to-side to allow divers to easily connect the mat beneath the water. Consequently, substantial slack resulted in the side-to-side block linkage. The resulting lack of side-to-side restraint in the mats surrounding the island promotes mat instability in response to oblique wave attack. Conversely, the lack of alongslope linkage tension would seem not to affect mat stability given a normal angle of wave incidence where side-to-side restraint would be less important. This indeed appears to be the case, given the visual observations of the effects of wave-induced uplift at Northstar Island.

Effects of Island Subsidence

Northstar Island is composed of approximately 800,000 m^3 of terrestrial gravel that was trucked to the offshore island site in winter over a floating ice road. Such an Arctic gravel placement project undertaken in winter typically results in the dumping of gravel having a temperature of -20^o to -40^o C. into ocean water exhibiting a temperature of -2^o C. As a result, ice forms in the interstitial spaces within the gravel fill. With time, summer thawing and long-term creep of the ice within the fill can result in island subsidence. Such subsidence has been noted continuously at Northstar Island within the 1985-1989 inspection period. Figure 2 shows the nature of the subsidence as evidenced at several benchmarks located on the island. The rate of subsidence is generally noted to be 10 cm annually, yielding a total subsidence of about 40-50 cm since the conclusion of construction in 1985.

The effect of island fill consolidation results in the inward relative motion of the individual concrete blocks within the mat surrounding the island. This subtle effect leads to a gradual decrease in the space that exists between adjacent blocks. As the block spacing decreases, relief of hydraulic pressures that build within the fill during the alternating action of wave run-up and wave run-down becomes increasingly more difficult to accomplish.

Originally, the design of Northstar Island specified a block spacing of 5.0 to 6.4 cm, yielding a "percent open area" (the area of open space within the mat relative to the total area) of 19%.

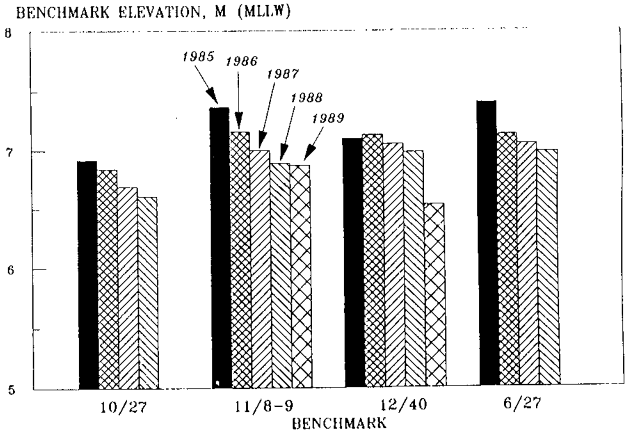

FIGURE 2: NORTHSTAR ISLAND SUBSIDENCE, 1985 - 1989

As a result of island subsidence/fill consolidation and a block fabrication process that yielded slightly oversized blocks, the existing "percent open area" is now estimated to be 11%, based on recent measurements of block spacing. This reduction in block open area will yield a propensity for mat uplift at lower wave height thresholds and also for greater vertical block uplift when wave-induced uplift does occur.

Effect of Mat Underlayer

A durable and permeable mat underlayer is important for the successful deployment of concrete mat armor over the granular fill material commonly used in the Alaskan Arctic offshore. At Northstar Island, a highly permeable non-woven polyester filter fabric was used for this three year design life application. The characteristics of the fabric are summarized as follows:

Fabric Weight = 510 gm/m^3
Tensile Strength = 525 N/cm
Permeability = 0.65 cm/sec.

In addition, the fabric readily sinks in seawater--an important detail that greatly aids the construction effort.

Successive mat uplift events can cause abrasion and parting of the underlying fabric, allowing the loss of gravel fill beneath the mat. Given the abrasive nature of concrete block slope armor relative to the underlying filter fabric, it is apparent that mat uplift must be eliminated if long-term survival of the fabric is to occur.

Inspection of the concrete armor at Northstar Island following large storm events indicates that uplift pressures beneath the filter fabric have been excessive. This has became evident at areas where gravel fill, completely encased in filter fabric, has been forced through block spaces to form outward pockets of gravel on the upper surface of the mat. An instance of this occurrence is shown in Photo 3.

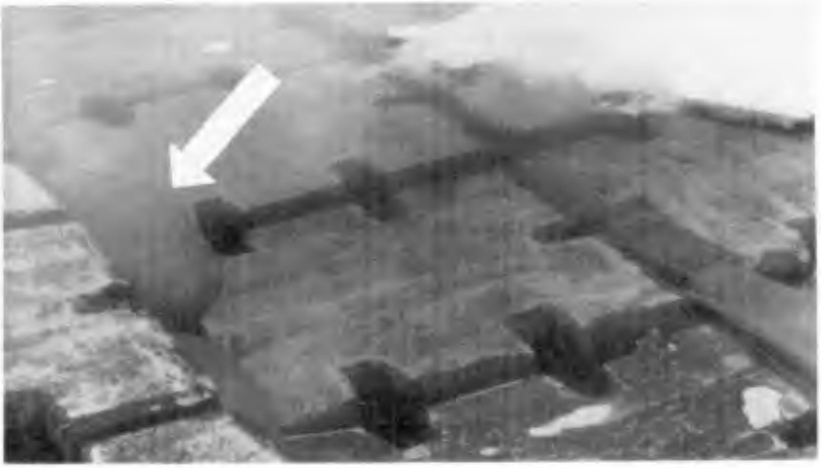

PHOTO 3: FILTER FABIC AND GRAVEL PROTRUSION BETWEEN BLOCK SPACES

Once these gravel bulges formed, ice or wave motion causes failure of the fabric pocket leading to filter fabric voids. Initially, the localized and infrequent nature of this occurrence did not render it of serious concern to the integrity of the slope protection system. However, the filter fabric shortcomings related to permeability were clearly indicated.

Repeated instances of wave-induced mat uplift at Northstar Island resulted in filter fabric abrasion and parting that caused loss of gravel fill beneath the mat. Major damage to the filter fabric in this regard occurred during the November 1987 storm event, when large waves and multi-year ice impacts heavily damaged the eastern side of Northstar Island. Repeated profiling of the island slope (as shown in Figure 3) shows the effect of the 1987 storm, and indicates the large volume of gravel lost from beneath the concrete mat due to filter fabric voids.

The damage sustained by the filter fabric at Northstar Island indicates that a more durable and permeable filter medium is vital in promoting improved performance of concrete block slope armor. Stronger, more permeable filter fabrics do exist in the geotextile industry and should be carefully considered for Arctic offshore applications.

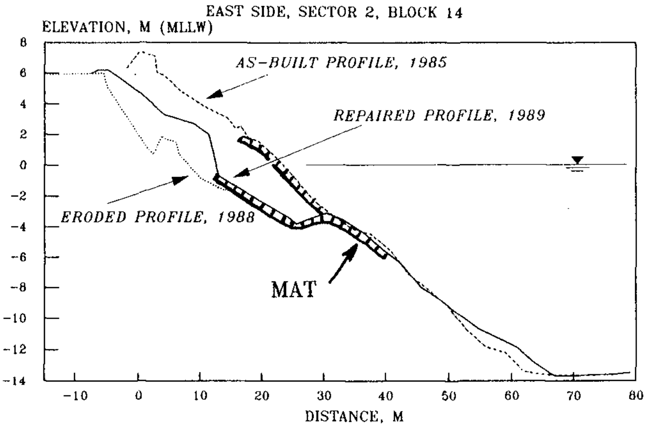

FIGURE 3: TYPICAL PROFILE CHANGES, EAST SIDE, 1985 -1989

For long-lived offshore production facilities, consideration has been given to the use of small quarrystone or concrete rubble as underlayer for concrete mat armor. The concrete alternative can be unreinforced and cast in shapes of the required size in a conventional concrete stamping procedure. These durable underlayers would benefit from their high permeability and abrasion resistance relative to fabric alternatives. Important issues related to construction placement and the effect on concrete block support must be resolved to render these materials viable for use as an underlayer/filtration medium.

ICE-INDUCED CONCRETE MAT DAMAGE

The concrete blocks used at Northstar Island were constructed at Prudhoe Bay, Alaska, using a highly mechanized "dry cast" block fabrication technique. The concrete mix exhibited low water:cement ratio (w/c = 0.32), high cement content (392 kg/m^3), air entrainment (5-7%), and use of fly ash pozzalon (10% by weight). The resulting concrete product exhibited an average compressive strength of 55 MPa (8,000 psi). By contrast, the expected compressive strength of ice impacting this site is 2.8 MPa.

Despite the high strength characteristics indicated, isolated instances of concrete block breakage were noted during the summer of 1986, the year following island construction. Samples of broken concrete blocks were tested at that time to determine the characteristics of the failed blocks. Test results indicated that the broken blocks were not atypically weak blocks, but exhibited the same high compressive strength characteristics that were noted during the block fabrication period.

In November 1987, a high-energy easterly storm occurred along the northern coast of Alaska for a period of 14 days. The storm was accompanied by alternating periods of ice-free water (leading to large wave generation) and the incursion of large ice floes (leading to damaging ice impacts). Erosion of nearby islands protected solely by gravel bags was excessive during this storm period.

Damage to the slope protection at Northstar Island during this storm included major displacement of the concrete mat in response to wave-induced uplift and ice impact, breakage of concrete blocks due to direct ice impact and/or inter-block collision induced by ice impact, loss of underlying gravel fill material through filter fabric tears and voids induced by storm-related processes, and failure of steel chain/shackle linkages caused by ice impact forces.

During July of the following summer, large-scale damage to the concrete blocks occurred on the east and north sides of Northstar

PHOTO 4: BLOCK BREAKAGE CAUSED BY ICE IMPACT

Island as a result of the collision of massive ice features with the island during the open-water season. The nature of the damage included block breakage (as had been noted in rare instances in 1986), mat displacement caused by impacts of large ice features, and surface abrasion of the mat armor by ice impact.

Concrete mat breakage has proven to be impressive at Northstar Island, primarily affecting blocks located above an elevation of -3.7 m (MLLW). Block breakage has occurred, in which cracks propagate through the block without substantial loss of concrete volume. In addition, blocks have been stripped of concrete cover, leaving only the steel reinforcement where the concrete mass had once been. Photo 4 is presented to show an example of excessive block damage of this type.

When the slopes of Northstar Island were pristine and free from irregularities and undulations, the early winter ice would collide with the concrete and form ice piles that would build seaward from the waterline. These ice piles would form a barrier providing protection from the larger ice features that might impact the island later in the freeze-up period. Later, following the storm damage of September 1986, undulations in the concrete mat slope caused by wave-induced mat uplift, generated irregularities within the mat surface upon which incoming ice forces could act. As a result, deformation and displacement of the concrete mat armor occurred as large ice features collided with the irregular island slopes. With time, therefore, the ability of the island slopes to safely withstand large ice impacts degraded. Damaging mat displacements during both winter and summer were noted. Photo 5 shows the results to a particularly forceful ice collision with the north slope of Northstar Island during late July 1988. The nature of the concrete mat damage that occurred as a result of this incident is shown in Photo 6, following the natural ablation of the ice that caused the damage.

Figure 4 is presented to illustrate the sequence of the damage experienced as a joint result of both wave and ice processes at Northstar Island. Initially, wave-induced mat uplift occurred that led to deformation and undulation of the pristine "as-built" island slope. Subsequent to this event, incoming ice features, which had previously been ineffective in displacing the uniformly smooth mat, were capable of imparting force to the various mat irregularities, thereby inducing significant mat displacements. Such displacements further permitted filter fabric degradation and loss of underlying fill material. Therefore, elimination of concrete block uplift is of ultimate importance--to prevent abrasion of the underlying filter medium and subsequent loss of gravel fill, and to prevent the development of slope irregularities and deformations that allow large ice features to impart significant damage and displacement to the slope armor.

PHOTO 5: BLOCK DISPLACEMENT BY LARGE ICE IMPACT, AUGUST 1988

PHOTO 6: MAT DAMAGE OF PHOTO 4 FOLLOWING ICE REMOVAL, JULY 1989

CONCLUSIONS AND RECOMMENDATIONS

Recent experience at Northstar Island has allowed an evaluation of linked concrete mat performance when subjected to the harsh wave and ice environment of the Alaskan Arctic offshore. Observations have been made that could not be observed accurately in any other method of investigation. While performing as an oil exploration island, Northstar Island has also performed as a prototype laboratory in which the interaction of Arctic ice forces, three-dimensional wave impact, and the linked concrete slope

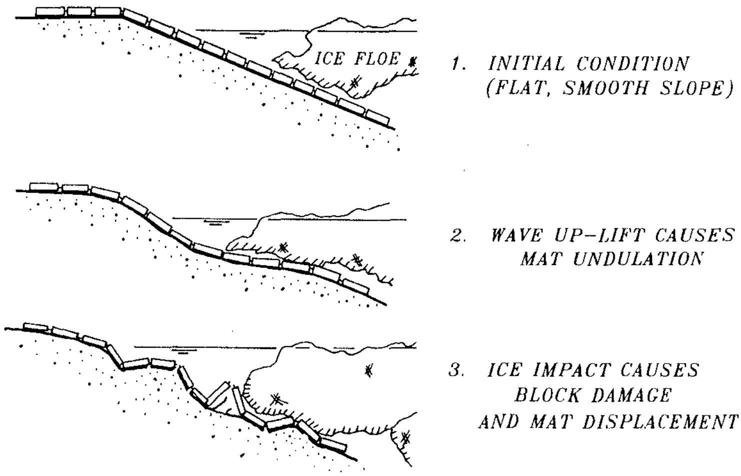

FIGURE 4: NORTHSTAR ISLAND MAT DAMAGE SEQUENCE, 1985 - 1989

protection system could be observed. The valuable lessons learned from this experience are ongoing. To date the following conclusions are worthy of note:

- <u>Oblique Wave Impact</u>: Wave impact arriving at high angles of wave incidence to the slope effectively induce mat uplift more readily than the same wave conditions arriving at a normal incident angle. This is due both to hydrodynamic effects yielding higher negative wave pressures from oblique wave attack, and also to the lack of side-to-side tension in the linkages of the Northstar Island mat system.

- <u>Reduction of Mat "Open Area"</u>: The void space within the mat system ("open area") allows relief of hydraulic pressures that are created within the island fill during periods of wave run-up. This "open area" must be sufficient to allow adequate hydraulic relief initially, and must be maintained with time if mat performance is to continually achieve the design intent. One factor that has caused a reduction in the "open area" at Northstar Island is island subsidence. Due principally to thermal effects within the gravel fill, the elevation of the island has decreased approximately 40-50 cm since 1985. This subtle effect has contributed to a decrease in the "percent open area" of the mat from the designed value of 19% to the present (summer 1990) measured value of 11%.

- Underlayer Characteristics: Important factors related to the proper performance of an underlayer for the concrete mat are high permeability and durability. While the filter fabric selected for use at Northstar Island exhibited excellent performance in both of these areas relative to other fabrics, it is clear that improvement of underlayer performance is vital to future concrete mat installations in this environment. Should fabric permeability be lacking leading to creation of excessive uplift pressures beneath the fabric, mat uplift may occur. Once the concrete blocks uplift periodically in response to wave passage, failure of the fabric though block abrasion will follow. Fabric voids caused by mat abrasion will lead to loss of gravel fill from beneath the fabric and subsequent slope deformations. For long-lived offshore structures, concrete or quarrystone rubble may provide more suitable underlayer characteristics for concrete block revetments. An expensive alternative to a highly permeable underlayer is the utilization of heavier concrete blocks that can adequately withstand the wave-induced uplift pressures.

- Side Slope Configuration: Improvements in linked concrete mat performance will result from consideration of slope alterations that include the incorporation of milder slopes and/or horizontal benches having a width of perhaps 10-20 meters in the zone of wave impact. Previous physical modelling efforts (Potter, et al., 1983) have noted that such slopes reduce block uplift, lower wave run-up, reduce ice impact forces, and improve overall block stability against wave impact relative to the straight smooth 1 (vertical) on 3 (horizontal) slopes utilized on Northstar Island. In addition, the inclusion of a flat bench of significant width near the waterline will provide a safety buffer to restrict any damage that may occur to areas of the slope that are distant from the island work surface.

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