CHAPTER 177

ARTICULATED CONCRETE MAT SLOPE PROTECTION

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ABSTRACT

This paper provides guidance for the design, fabrication, and installation of articulated concrete mat slope protection. Although articulated mat armor has been utilized for many years in low-energy wave environments, it has been extended recently to accommodate intermediate wave energies and severe ice loads. The development of the concept is discussed, after which hydraulic design considerations, material design considerations, and fabrication and installation techniques are presented. Prototype performance is reviewed. It is concluded that articulated concrete mat armor is capable of providing effective slope protection in intermediate-energy wave environments, and that additional research is required relating to hydraulic stability and failure modes under wave and ice loading.

INTRODUCTION

Articulated concrete mats, consisting of precast blocks connected by flexible linkages, have been used for many years as an alternative to rubble armor in low-energy wave environments. During the past decade, however, the technology has been extended to accommodate intermediate wave energies and severe ice loads in response to the slope protection requirements of artificial islands constructed in the Alaskan Beaufort Sea.

The mat armor system which has evolved, an example of which is depicted in Plate 1, incorporates the findings of conceptual design studies, large-scale model tests, and prototype test sections. Based upon its performance to date, the concept appears promising not only for arctic applications, but also for use as slope and toe protection in temperate environments.

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Plate 1. Concrete Mat Panel

This paper provides guidance for the design, fabrication, and installation of articulated concrete mat armor based on experience gained over the past eight years. The sections which follow present information on the development of the mat concept, a discussion of hydraulic and material design considerations, a discussion of mat fabrication and installation, a review of prototype performance, and recommendations for future applications and additional research.

CONCEPT DEVELOPMENT

The primary advantages of the articulated mat concept, when compared with discrete-unit armor systems such as quarrystone or individually-placed blocks, include:

- enhanced stability, by virtue of the interconnection between adjacent blocks;
- the ability to accommodate changes in the subgrade without permitting catastrophic fill losses; and
- suitability for rapid installation in preassembled, modular panels (Ref. Plate 1).

Additional benefits with more limited applicability include resistance to displacement by ice, and the potential for modular removal at the end of the project life.

A potential disadvantage of the mat concept is the critical function performed by the linkage system. If the linkages are weakened by abrasion, corrosion, or fatigue, the ability of the mat to withstand wave and/or ice forces is significantly reduced. Other drawbacks include the relatively high runup elevations which occur on the smooth surface of the mat, the need for mild sea conditions during placement, and the lack of well-established design procedures which are based on prior experience. It is noteworthy, however, that considerable research has been devoted to concrete block revetments in recent years (Bakker and Meijers, 1988; Bezuijen, et al., 1987; Bezuijen, et al., 1988; Galvin, 1988; Klein Breteler, et al., 1988; McDougal and Atkinson, 1987; Pilarczyk, 1988; Toyoshima, 1988). Although the majority of the research addresses placed block revetments, many of the findings are also relevant to the design of articulated mat armor.

The concept of articulated concrete mat armor dates back to the early 1900's (Hawkes, 1907). Prior to the 1980's, however, its use was confined primarily to low-energy environments such as rivers, lakes, and estuaries, in which the design wave height was on the order of 1 m. A number of proprietary and non-proprietary designs were developed to address this application, typically utilizing square or rectangular blocks ranging from 0.3 to 0.6 m in maximum horizontal dimension and 0.15 to 0.3 m in height. In keeping with the relatively modest design loads anticipated, the blocks were not reinforced. Linkages consisted of wire rope, synthetic rope, steel rods, or attachment to a geotextile.

The advent of offshore oil operations in the Alaskan Beaufort Sea engendered slope protection requirements which were significantly more demanding than those of previous articulated mat applications. To support oil exploration and production activities, gravel islands were constructed in water depths to 15 m. Key design considerations included significant wave heights of 3 to 6 m, impact loads from moving ice features, and an extremely short open-water season (typically 75 days) in which to install the slope protection system. Although large sand bags were used to protect many of the initial islands (Gadd, 1988), the need for a more resilient armor system was apparent from the outset (Leidersdorf, et al., 1982).

In view of the lack of quarrystone and high cost of importing non-native materials to northern Alaska, articulated concrete mats emerged as a promising candidate for island slope protection. The linkage concept was attractive from the dual standpoint of reducing the weight of the armor layer and improving resistance to ice forces.

Three major design modifications were implemented to adapt the articulated mat concept to its intended use in the arctic: the provision of high-strength, corrosion-resistant linkages, the introduction of reinforcing steel into the blocks, and the use of larger block sizes. A representative example of the resulting design is presented in Figure 1. Developed for use on Northstar Island, an oil exploration island constructed in 1985 (Hayley, et al., 1987), the mat is composed of 1.2 m square, precast concrete blocks which are reinforced with two layers of wire mesh. Linkage is provided by a combination of forged steel rods cast into each block, and interconnecting chains and shackles. Block thickness was adjusted in accordance with the design wave conditions; in this particular application, 230 mm was specified.

The selection of a 1.2 m square as the plan view outline of the block represents a compromise between the conflicting requirements of functional performance, fabrication, handling, and cost. Factors which favor a large block size include a reduced number of linkages per unit area, and an increased resistance to displacement by environmental forces. Factors which favor a reduced block size include ease of fabrication and handling, the ability to articulate into scour depressions rather than spanning across them, and a higher permeability to alleviate the hydraulic pressure differentials which may develop across the thickness of the mat and cause uplift.

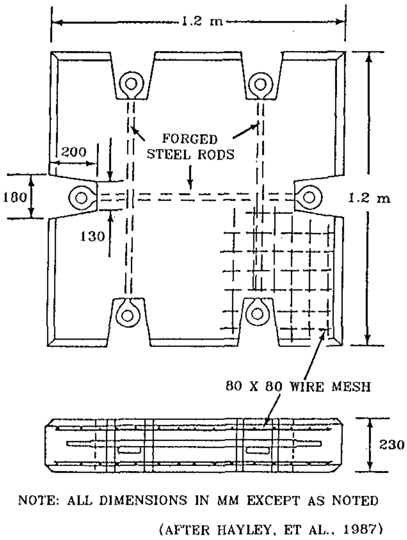

Figure 1. Concrete Block Design

Experience to date has indicated that the 1.2 m square block size approaches the upper bound for effective articulation. An additional benefit of this configuration is the fact that two blocks placed side-by-side are compatible with a standard 2.4-m (8-ft) wide truck bed. To improve the permeability of the mat system, as well as to protect the linkage components, recesses are provided in the perimeter of each block at the linkage points (Ref. Figure 1).

HYDRAULIC DESIGN

Stability

Although the current understanding of articulated mat stability is far from complete, significant insights have been gained from large-scale model testing. Based upon observations made at scales ranging from 1:6 to 1:3, the predominant hydraulic loads exerted on mat armor are as follows (Ref. Figure 2):

(1) The time-dependent wave pressure, which tends to induce uplift by creating a pressure differential between the top of the mat and the subgrade;

(2) The hydrostatic pressure head resulting from a setup of the water level in the structure core, which tends to induce uplift;

(3) The shock pressure from the breaking wave, which can produce uplift forces on the blocks adjacent to the plunge point;

(4) The shear forces from wave runup and especially wave rundown, which tend to displace the blocks in a downslope direction.

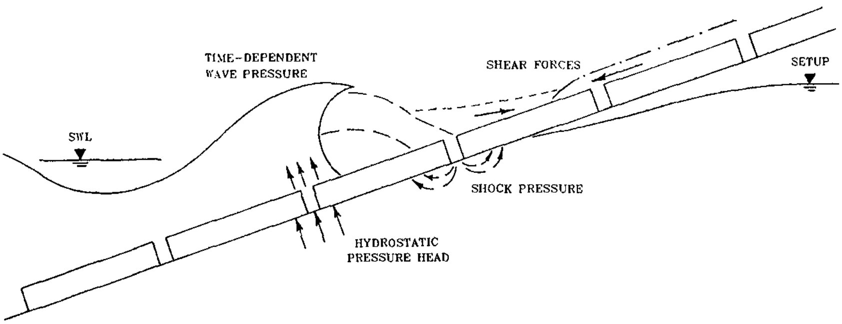

Figure 2. Hydraulic Loads on Articulated Mat Armor

The threshold wave height which initiates block uplift varies not only with the armor weight and slope steepness, but also with the wave period and the permeability of the mat and underlying filtration medium. The provision of adequate permeability is of particular importance in optimizing the performance of a selected mat thickness. In the absence of specific design guidelines, it is recommended that the permeability of each successive layer should increase from the structure core to the mat armor. For the artificial islands constructed to date in the Beaufort Sea, a minimum of 15% open area has been provided in the mat surface to accommodate the anticipated outflow from the permeable gravel core material.

A key feature of articulated mat armor is its ability to withstand wave conditions in excess of the threshold for block uplift. Although deformation of the subgrade will occur, catastrophic failure can be avoided provided that the linkage system and underlying filtration medium remain intact (Potter and Sun, 1983). Both model test and prototype experience have indicated that episodes of block uplift lead to the formation of an S-shaped slope profile, with flattening at the waterline and commensurate steepening above the limit of wave breaking and below the limit of wave rundown.

To resist the shear force exerted by wave rundown, as well as the tendency for blocks to migrate downslope during uplift episodes, the mat must be anchored at the top of the slope. Prototype experience has indicated that deadman anchors buried in the structure core material and linked to the upslope edge of the mat are an economical and effective means of fulfilling this requirement.

At present, there are no analytical models which accurately predict uplift thresholds and anchor loads for articulated mat armor. Large-scale model testing is therefore strongly recommended for the design of all major projects.

Wave Runup

The elevation of wave runup on concrete mat armor varies with the incident wave conditions, the structure slope, and the permeability of the mat and subgrade. In general, however, relatively high runup elevations are observed on the smooth surface of the mat.

Representative large-scale model test data reported by Gadd, *et al*. (1988), are reproduced in Figures 3 and 4. The data were acquired for breaking waves on a 3(H):1(V) gravel slope covered with a permeable geotextile and an articulated mat containing approximately 15% open area. Relative runup, R/H_o', is displayed as a function of wave steepness, H_o'/gT^2, for two values of relative water depth: $d_s/H_o' = 2$ in Figure 3, and $d_s/H_o' > 3$ in Figure 4. The notation is defined as follows:

R = runup elevation relative to the prevailing still water level;

H_o' = unrefracted deepwater wave height;

g = gravitational acceleration;

T = wave period; and

d_s = water depth at structure toe.

Runup predictions for concrete blocks derived from the U.S. Army Corps of Engineers' Shore Protection Manual ("SPM"; 1984) are included in each figure. Although the predictions evidence good agreement with the model test

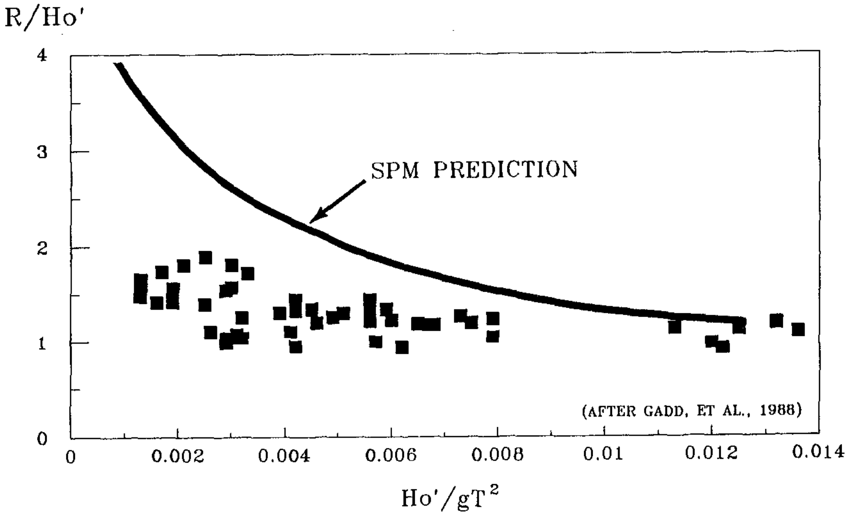

Figure 3. Wave Runup on 3(H):1(V) Slope, $d_s/H_o'=2$

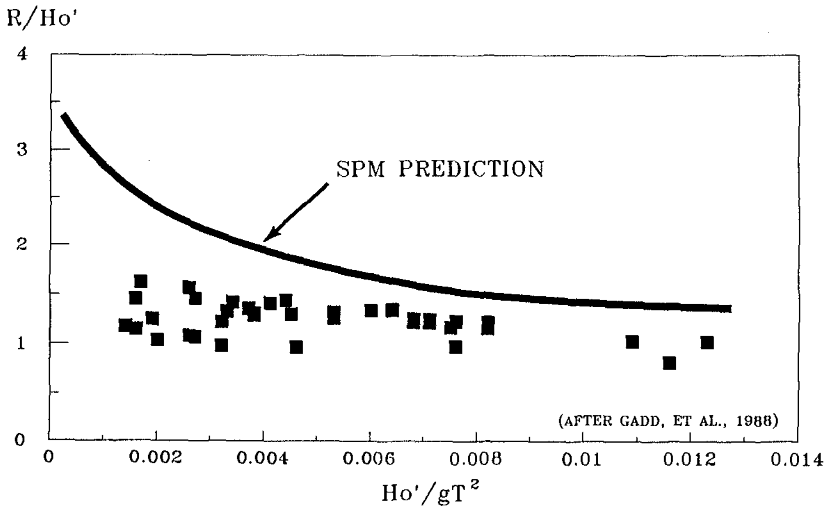

Figure 4. Wave Runup on 3(H):1(V) Slope, $d_s/H_o'\geq 3$

data at high values of wave steepness, they significantly overpredict the measured runup elevations at the lower steepness values. In consequence, the use of the SPM method to predict wave runup may be expected to yield conservative values in most instances. As in the case of hydraulic stability, large-scale model testing is recommended to evaluate the runup characteristics of all major projects.

Large-scale testing has also provided insight into measures which can reduce the runup elevations on articulated concrete mat armor. Increased roughness, as might be created by using blocks of different thicknesses, was found to have minimal effect in the region of wave breaking. If placed higher on the slope, however, in the zone of swash or sheet runup, the increased roughness significantly reduced the maximum runup elevation. Compound slope profiles which incorporated a bench near the waterline were also found to be effective. As reported in more detail by Leidersdorf, et al., (1984), a bench width of 12 m typically decreased the runup elevation by 30 to 40% relative to a straight 3(H):1(V) slope.

MATERIAL DESIGN

Concrete Blocks

Because the concrete blocks in an articulated concrete mat must withstand impacts with both the subgrade and each other during uplift episodes, they must be more durable than those used for unlinked revetments. Additional material design considerations may include abrasion from littoral sediments, corrosion and fatigue of exposed steel, and, in the case of cold climates, ice impacts, ice abrasion, and freeze-thaw cycling.

As discussed previously, steel reinforcement was incorporated into the block design when the mat technology was adapted to the more severe wave and ice conditions of the arctic. Prototype experience to date suggests that a steel content of approximately 0.5% of the block cross-section is sufficient to maintain structural integrity except in the case of impact loads exerted by very large ice features. The reinforcement should extend throughout the plan view outline of the block, including the arms between the linkage recesses (Ref. Figure 1), to insure that the block will remain intact even if the concrete is fractured. Hot-dip galvanization of all steel is recommended to reduce its susceptibility to corrosion.

The concrete should be of high strength to resist cracking. In the case of the block design presented in Figure 1, a 28-day compressive strength of 27 MPa was specified (Hayley, et al., 1987). Low permeability, which may be obtained through the use of a low water-cement ratio, a high cement factor, and the use of pozzolan or silica fume, is desirable to reduce chloride penetration.

Aggregate should be abrasion-resistant, especially when repeated exposure to littoral sediments and/or ice is anticipated. Additional design considerations for arctic service are presented by Leidersdorf (1988).

Linkage System

A properly designed linkage system will not only allow the mat to function under wave conditions which exceed the uplift threshold for individual blocks, but also facilitate rapid installation through the placement of large, pre-assembled panels. Both the placement loads and the in-place loads should be considered in determining the requisite strength of the linkage system. Additional design considerations include flexibility (to allow articulation), corrosion, abrasion, and fatigue over the design life of the armor system, and the ability to allow replacement of damaged blocks.

Kevlar rope, wire rope, and chain-and-shackle linkage systems have been tested at prototype scale with varying degrees of success. Although attractive from the standpoint of imperviousness to corrosion, Kevlar rope proved to be too elastic to permit accurate placement of large panels. Wire rope can be used for small panel sizes, but becomes difficult to handle at the large sizes required for heavy lifts. Additional disadvantages of wire rope include its susceptibility to corrosion (due to the large surface area of the component strands), and the difficulty associated with replacing individual blocks after the mat has been installed.

Chains and shackles, in conjunction with forged steel rods cast into the blocks, have emerged as the preferred linkage alternative (Ref. Plate 2). Connections between adjacent blocks are readily made, damaged blocks can be removed and replaced as needed, and corrosion is less problematical than with wire rope due to the reduced surface area. If the corrosion rate in the project area can be estimated, the linkage components can be oversized accordingly to provide for sufficient strength at the end of the design life. Hot-dip galvanization of all linkage hardware is also recommended.

Filtration Medium

The performance of an articulated mat armor system depends not only upon the characteristics of the mat itself, but also upon those of the underlying filtration medium. In addition to providing adequate permeability to relieve pore pressures in the structure core, the filter must be capable of retaining the core material during episodes of mat uplift.

The absence of suitable granular fill material has necessitated the use of geotextiles for filtration on all articulated mat armor installed in the Beaufort Sea to date. The advantages of fabric include the ability to

Plate 2. Chain-and-Shackle Linkage System

achieve a specified permeability, ease of installation, and low cost. The primary disadvantages relate to long-term performance: a susceptibility to abrasion by the concrete blocks, and progressive deterioration from exposure to the ultraviolet (UV) component of sunlight. Measures taken to ameliorate these effects have included the specification of UV-stabilized fabrics, the application of an abrasion-resistant resin coating, and the use of an overstrength fabric in anticipation of deterioration over the project life (Munday and Bricker, 1987). Although performance has been satisfactory to date, longer periods of service will be required to evaluate their long-term effectiveness.

In the absence of conclusive evidence regarding the long-term durability of geotextiles, their use is recommended for projects with a limited design life, or at which frequent mat uplift is not anticipated. When severe wave conditions and/or exposure to intense sunlight are expected, particularly over an extended design life, the use of graded stone or manufactured concrete rubble is recommended. Although rubble has not been used as a filtration medium for articulated mat armor at prototype scale, large-scale model tests have yielded satisfactory results (Leidersdorf, et al., 1984). To prevent washout, the filter layer immediately beneath the mat should consist of rubble which is larger than the largest openings in the mat surface.

FABRICATION AND INSTALLATION

Both wet and dry casting techniques have been used to fabricate the individual concrete blocks which comprise the mat. In the case of dry casting, a block molding machine is utilized to inject concrete with a low water-cement ratio into the forms. Although set-up of the molding machine and adjustment of the concrete mix can be time-consuming, the semi-automated block production process which results appears warranted for large projects. Fabrication rates of up to 20 blocks per machine-hour have been reported (Munday and Bricker, 1987).

When the blocks have cured sufficiently to be handled, they can be assembled into large panels in preparation for placement by crane. To minimize the number of underwater linkages required between panels, it is recommended that each panel extend from the lower terminus of the armor to the waterline. The width of the panel can be adjusted in accordance with the lifting capacity of the crane.

To insure that proper alignment is maintained during placement, the centerline position of each panel is monitored continuously using a theodolite. Any adjustments which are required are relayed to the crane operator. Once the panel has been lowered into position, a diver verifies that the desired side-by-side relation with the preceding panel has been achieved before releasing the mat from the crane. The diver then shackles the new panel to its predecessor, and the cycle is repeated. Based upon prototype experience to date, the underwater shackling is relatively straightforward, and is typically completed before the next panel has been lifted by the crane.

Continuous coverage of non-planar surfaces, such as island corners, can be achieved through the use of trapezoidally-shaped blocks (Ref. Plate 3). Fabrication and placement procedures are analogous to those for square blocks, although survey control of the placement operation assumes greater importance in maintaining proper alignment.

The maximum permissible wave height for mat installation depends not only upon the tolerance of the divers, but also upon the extent to which unevenness can be accepted in the finished grade. Because the mat represents a relatively thin veneer on the structure, any wave-cut scarps which develop prior to mat placement will be reflected in the mat surface.

Placement rates for articulated mat armor vary with crane capacity, wave conditions, water depth, and structure geometry. Reported rates have ranged from 44 m^2/h for an exposed location with a maximum placement depth of 6 m (Hayley, et al., 1987), to 110 m^2/h for a more sheltered location with a maximum placement depth of 3 m (Munday and Bricker, 1987).

PERFORMANCE ASSESSMENT

Articulated concrete mat armor was first installed in the Alaskan Beaufort Sea in 1980 (Leidersdorf, et al.,

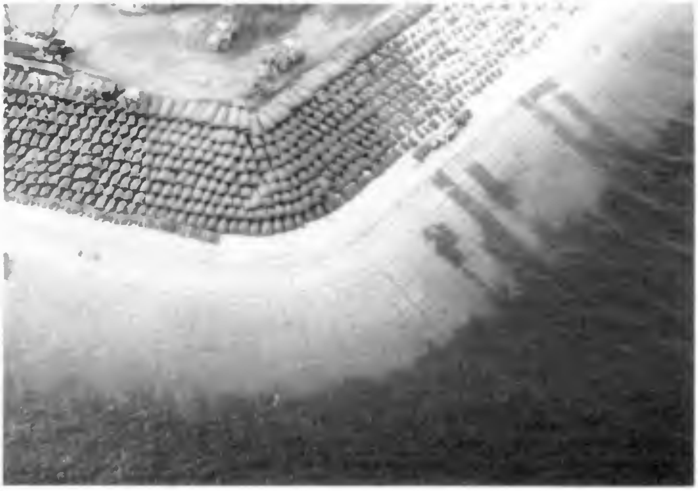

Plate 3. Island Corner Armored with Trapezoidal Blocks

Plate 4. Articulated Concrete Mat on the Endicott Project

1982). Subsequent projects have utilized more than 57,000 m^2 of mat armor in coastal and offshore locations. The primary application has been as slope protection for gravel islands, although mats have also been used as toe protection for seawall structures.

The most noteworthy projects to date which employ mat armor are the Endicott Project, an oil production facility consisting of two islands and a causeway in a maximum depth of 3.7 m, and Northstar Island, an oil exploration island located in a depth of 13.7 m. On the Endicott islands, approximately 40,000 m^2 of mat were installed from just above the waterline to the sea floor (Ref. Plate 4). To accommodate the anticipated design life of 25 years, a woven polyester filter fabric with an extremely high tensile strength of 2.1 kN/cm was specified (Munday and Bricker, 1987). Installation of the slope protection system was completed in 1986, one year ahead of schedule. Since that time, the mat has remained in sound condition.

Northstar Island, designed for a minimum service life of three years, is distinguished by its exposure to more extreme environmental conditions than the Endicott Project. A band of concrete mat was installed around the circumference of the hexagonal island from +1.5 to -6.1 m, the region most subject to wave and ice impacts (Hayley, et al., 1987). In September, 1986, one year after the island was completed, it was exposed to a severe storm with estimated wave heights of 3 to 4.5 m. Although the mat experienced uplift, no significant adverse effects were noted. Damage was inflicted, however, by a late-1987 storm which drove large, deep-keeled multi-year ice features against the island. The damage consisted of block fractures and displacements in areas which received direct impacts from the ice.

CONCLUSIONS AND RECOMMENDATIONS

Based upon the experience gained to date, articulated concrete mat armor is capable of providing effective slope protection in intermediate-energy wave environments. Promising applications include not only the arctic projects for which it was developed, but also selected non-arctic uses such as:

1. Long-term slope protection against waves and ice in low-corrosion environments (such as the Great Lakes);

2. Rapidly-deployed emergency protection for coastal areas threatened by storm erosion; and

3. "Last Line of Defense" protection, in which the mat and an underlying geotextile are buried behind the beach face and exposed only during major storm events.

In the case of the last suggested application, the relatively thin nature of mat armor will facilitate its concealment in the backshore. If relocation becomes necessary to accommodate a moving shoreline (occasioned, for example, by long-term erosion or beach renourishment), the mat can be moved in modular panels.

Despite the promise demonstrated by the mat technology, additional research is required before a standardized design methodology can be elucidated. Areas which warrant further investigation include failure modes under wave and ice loading, quantification of hydraulic stability in terms of the primary design parameters, hydraulic stability on non-planar surfaces such as island corners, and geotextile performance over an extended design life or when frequent uplift is experienced. Until a more comprehensive understanding of mat performance is achieved, the final design process for all major projects should include large-scale hydraulic model testing, and, when feasible, observation of existing prototype structures.

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