MANAGEMENT SOFTWARE FOR PROTECTION OF THE GREAT LAKES COASTAL NAVIGATION AREAS

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ABSTRACT

Protecting harbors or navigable areas requires evaluating maritime structures such as armor stones. Armor rocks are impacted by the natural deteriorating elements such as seasonal weather, and repeated cycles of temperature, flowing water, wetting and drying, wave action, and freeze and thaw cycles. The design process for the determination of armor stone sizes is complex and various factors must be considered to fully understand how the design parameters have effect on stone performance. The main objective of this study was to evaluate and quantify major factors affecting the armor stone durability. The effects of scaling on the test results of various samples of rock types used in Great Lakes coastal projects have been investigated. Field monitoring and laboratory testing have been conducted to evaluate the performance of stone subjected to both freezing and thawing and wetting and drying, and to quantify the combined effects of environmental stresses on armor stone. In addition, long-term performance or deterioration of armor stones have been quantitatively monitored and characterized by the changes in dimensions measured. We have developed stone deterioration software (ARMOR), which integrates field observations with numerical tools to provide an assessment of the local freeze-thaw and wet-dry on the stones. The ARMOR software has several numerical models, which can predict degradation of Armor Stone as rocks are impacted by the natural elements. The software includes a statistical technique (homogeneity index) to characterize rock heterogeneity. Two new numerical approaches have been developed to calculate freeze thaw cycles using long-term site weather data. The software also provides a model to estimate armor weight, minimum crest width, armor thickness, and the number of armor units per unit of area. The calculation uses varying values for the seaward slope and wave height by application of the Hudson formula. The degradation model relates the laboratory test results to the modification of the mass distribution and reduction at the project site. Innovative technologies such as geophysical techniques in stone selection and stonecutting (water saw) are examined for the field applications. This paper describes the latest research developments that improve our understanding of environmental impacts on armor stones in coastal areas with reference to breakage and integrity.

Keywords: hydrodynamic forces, response of structures, fluid dynamics, armor stone durability, Great Lakes, numerical modelling, laboratory testing

1. INTRODUCTION

Degradation of armor stone placed in coastal navigation areas in the United States Great Lakes has occurred as a result of a number of interacting and interrelated natural factors such as seasonal weather changes, and repeated cycles of temperature. This study was proposed to study various factors affecting the armor stone durability. The project results will be used to develop guidelines for the personnel involved in source of stone selection.
activities, which creates consistent operation across the organization. The research provides a better understanding of the relationship between the standard tests used in stone specifications and the performance of stone in the structures. Several investigations have developed standard field and laboratory procedures for careful comparisons of stone of similar, if not identical, properties.

Three sites, Burns Harbor, Cleveland Harbor and Keweenaw Waterway were selected for evaluation of armor stone performance. To consider the combined effects of environmental stresses on armor stone, testing were done to evaluate the performance of stone subjected to both freezing and thawing and wetting and drying. This testing was performed on the same samples rather than independently, as is more typically done. The combined testing realistically simulates the environmental conditions in the structure. In addition, by including stone of different rock types (i.e. igneous, metamorphic and sedimentary), the relative scaling effects can be evaluated to determine whether the scaling factors, if they exist, are constant or variable by rock type. After evaluating monitoring data, a determination was made as to the relative comparability of scaled laboratory test results and material durability in coastal projects in the Great Lakes, and recommendations made as to the appropriate laboratory tests for future stone specifications.

2. FIELD SAMPLING AND MONITORING
Several quarry sites that have historically supplied material for shoreline protection in and around the Great Lakes Region were visited. Samples from the Hayton Quarry identified as MCNP1, MCNP12, and MCNP13 were placed in the field for monitoring. Each sample consisted of two slabs, each approximately 4-ft by 6-ft by 1 ft, from the original. The smaller and thinner slabs are further identified as Slab A and the larger thicker and more massive slabs are further identified as Slab B (Figure 1). Samples identified as MCNP4 and MCNP5 are pieces from stones placed in the field from the Valders Quarry. These samples also consisted of two slabs, each approximately 4-ft by 6-ft by 1-ft.

![Figure 1: Drawing of the cutting lines and test specimens.](image)

3. NUMERICAL MODELING AND SOFTWARE DEVELOPMENT
3.1. Estimation of degradation rate
Latham (1991) provided a simple technically sound approach to estimate weight reduction in armor rock as results of several environmental and other impacts. Factors affecting the degradation rate are the intrinsic material properties of the rock source, the production-influenced geometric properties of the armours, the environmental
boundary conditions at the coastal site, and the armour layer design concepts used. The parameters affecting stone degradation rates are provided in Table 1.

The technique requires that a sample of the material be tested in an abrasion mill simulating the wear process. This provides a graph of weight versus laboratory time. Laboratory time is converted to years in service of armor stone on site using an equivalent wear time factor which is derived from a product of nine weighted parameters (see Table 1). The effects of fracturing and spalling as well as abrasion are included.

Table 1: Degradation-rate factors for armor stone (post-construction)

<table>
<thead>
<tr>
<th>Type of factor</th>
<th>Controlling factor</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic material properties of the rock</td>
<td>Mineralogy</td>
<td>Rock fabric strength</td>
</tr>
<tr>
<td></td>
<td>Micro-texture</td>
<td>abrasion</td>
</tr>
<tr>
<td></td>
<td>Weathering grade</td>
<td>Type-II impact breakage</td>
</tr>
<tr>
<td>Block integrity block strength</td>
<td>Block strength due to existence of macro-flaws</td>
<td>Type-I impact breakage</td>
</tr>
<tr>
<td>Production influenced geometric properties</td>
<td>Block size ($W_{50}$)</td>
<td>$X_1$</td>
</tr>
<tr>
<td></td>
<td>Block grading ($W_{85}/W_{15}$)</td>
<td>$X_2$</td>
</tr>
<tr>
<td></td>
<td>Initial shape ($P_R$)</td>
<td>$X_3$</td>
</tr>
<tr>
<td>Environmental boundary conditions</td>
<td>Incident wave energy (e.g. $H_s T_m$ or $H_s$)</td>
<td>$X_4$</td>
</tr>
<tr>
<td></td>
<td>zone of structure</td>
<td>$X_5$</td>
</tr>
<tr>
<td></td>
<td>Meteorological effects</td>
<td>$X_6$</td>
</tr>
<tr>
<td></td>
<td>Water-borne attrition agents</td>
<td>$X_7$</td>
</tr>
<tr>
<td>Factors influenced by design of armor layer</td>
<td>Concentration of wave attack (slope angle+ tidal range)</td>
<td>$X_8$</td>
</tr>
<tr>
<td></td>
<td>Armor stone mobility in design concept (e.g. $H_s/\Delta D_{50}$)</td>
<td>$X_9$</td>
</tr>
</tbody>
</table>

$W_{50}$ is the median weight of blocks. $W_{85}$ and $W_{15}$ are the 85 and 15 percent lighter by weight values. PR is the Fourier Asperity Roughness parameter. $H_s$ and $T_m$ are the significant (i.e. average of the highest one third waves) wave height and mean wave period. $\Delta$ is the buoyant density of rock relative to sea water and $D_{50}$ is the nominal size of $W_{50}$ block.

Source: Latham (1991)
3.1.1. Example of degradation model

As an example to show the application of above technique, input parameters for two site situations are given in Table 2 (Latham, 1991): (i) for a 3 ton, basalt in tropical climate, medium grading, dynamic design, and (ii) for 4.5 ton, temperate climate, narrow grading, static design.

Table 2: Example data summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site Situation</th>
<th>(i)</th>
<th>(ii)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_1 )</td>
<td>size</td>
<td>0.72</td>
<td>0.84</td>
</tr>
<tr>
<td>( X_2 )</td>
<td>grading</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>( X_3 )</td>
<td>shape</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>( X_4 )</td>
<td>wave energy</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( X_5 )</td>
<td>zone</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( X_6 )</td>
<td>climate</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>( X_7 )</td>
<td>attrition</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( X_8 )</td>
<td>concentration of attack</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>( X_9 )</td>
<td>block mobility</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>equivalent wear time factor</td>
<td>0.6</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The rock samples were used in the abrasion mill to create plot of fractional weight loss versus revolutions (Figure 2). This graph gives the typical loss in asperity roughness observed in milling tests. The equivalent wear time factor, \( X \) is calculated as product of all ratings.

\[
X = \prod_{i=1}^{9} X_i
\]  

(1)

The value \( X \) is then used to convert number of years in service to thousands of revolutions in mill. The number of revolutions, \( W/W_0 \) (\( W = \) final stone weight; \( W_0 = \) initial stone weight) was estimated from Figure 2 and used to calculate the final reduction in stones weight.

![Figure 2: Abrasion mill test results for specific type of armor stone.](image-url)

3.2. Characterization of rock heterogeneity

Liu et al. (2004) describes a statistical approach (homogeneity index) to characterize the heterogeneity in rock. According to the article, the Weibull distribution equation (Weibull,
1951; Hudson and Fairhurst, 1969) fits very well the experimental data for the distribution of microstructures within rock. Therefore, the Weibull statistical distribution is used to characterize the rock heterogeneity. The Weibull distribution may be simplified as:

\[
Q(\sigma) = \int_0^\sigma P(x)dx = 1 - \exp \left[ -\left( \frac{\sigma}{\sigma_0} \right)^m \right]
\]

(2)

where \( Q \) is a simplified form of Weibull distribution, \( \sigma \) is the elemental parameter (unit is megapascal or MPa), \( P \) is the Weibull probability density function, \( m \) is the shape parameter describing the scatter of \( \sigma \) and describes the heterogeneity of rock, and \( \sigma_0 \) is the mean value of the physical-mechanical parameters of the specimen (elemental parameter).

The most recommended method for calculating the homogeneous index \( m \) (Curtis and Juszczyk, 1988; Davies, 2001) is to rank strength (\( \sigma \)) data from smallest to largest and the assignment of respective \( Q (\sigma) \) values according to the following:

\[
Q(\sigma) = \frac{i}{N+1}
\]

(3)

Where \( i \) is the rank and \( N \) is the total number of specimens. According to Equation 3, the Weibull distribution can be linearized into the following form:

\[
y = \ln \left[ \ln \left( \frac{1}{1 - Q(\sigma)} \right) \right] = m \ln \sigma - m \ln \sigma_0 = A x + B
\]

(4)

where \( y = \ln \left[ \ln \left( \frac{1}{1 - Q(\sigma)} \right) \right] \), \( A = m \), \( x = \ln \sigma \), and \( B = -m \ln \sigma_0 \). With reference to this equation, a plot of \( \ln \sigma \) against \( \ln \left[ \ln \left( \frac{1}{1 - Q(\sigma)} \right) \right] \) gives the line-relationship and the slope of the line is the homogeneous index \( m \). The best estimate of the homogeneous \( m \) may be obtained using the linear least squares (LLS) techniques (Davies, 2001):

\[
m = A = \frac{n \sum xy - \sum x \sum y}{n \sum x^2 - (\sum x)^2}
\]

(5)

where \( \sum, x \) and \( y \) in the equations are abbreviations for \( \sum_{i=1}^n x_i \) and \( y_i \), respectively.

One of the attractive aspects of the Weibull distribution is the presence of the shape parameter, which allows this function to take a wide variety of shapes. For \( m = 1 \); this distribution is exponential; at about \( m = 1.5 \); the distribution is nearly log-normal; and at about \( m = 4 \), it closely approximates a normal distribution. Since the shape parameter \( m \) is a measure of the element parameter variability, it can be considered as a homogeneity index. The larger the index \( m \) is, the more homogeneous is the rock. When \( m \) tends to infinity, the variance tends to zero and an ideal homogeneous rock is obtained.

3.3. Estimation of freeze-thaw intensity

The intensity of freezing and thawing depends on the freezing temperature, the duration of the freezing cycle, the available moisture, the slope direction (geographic area properties), degree of saturation, and permeability (rock properties) (Lienhart, 1988). The first four of these parameters depend on geographic area and the last two factors are...
merely rock properties. Lienhart (1988) describes the calculation of some terms that can be used to calculate intensity and frequency of freeze-thaw cycles.

The National Oceanic and Atmospheric Administration (NOAA) climate data were used to calculate mean number of freezing cycle days for each month. These monthly freezing cycle days could then be added to find the mean number of freezing cycle days per year. Since the presence of moisture is significant in the freeze-thaw durability environment, it was decided to multiply the percent days of precipitation of 0.01 inch or more during the freezing cycle month by mean number of freezing cycle days per year and the product was termed moist freeze-thaw index. Figure 3 shows isoline map of the moist freeze-thaw index for the United States using Lienhart method. The software developed for this project, ARMOR can calculate the freeze-thaw intensity.

![Isoline map of the moist freeze-thaw index for the United States](image)

**Figure 3**: Isoline map of the moist freeze-thaw index for the United States.

### 3.4. Design
Various factors must be considered in order to fully understand how the design parameters have an indirect effect on stone performance.

Hudson (1969) developed the best known of the design equations for determination of acceptable armor stone size to resist damage from a given wave system based on hydraulic modeling studies. The equation is as follows:

$$ W = \frac{H^3 w_r}{K_d (S_r - 1) \cot \theta} $$

where $W$ is the weight of the armor unit, $H$ is the average wave height of the highest 10 percent of all waves, $w_r$ is the unit mass of the stone, $K_d$ is a damage coefficient, $S_r$ is the specific gravity of the stone, and $\theta$ is the angle of the slope of the armor stone.

Hudson (1969) presents the results of an extensive series of experiments conducted to obtain basic information on the stability, $K_d$ of rubble-mound breakwaters. These equations have been programmed in the software ARMOR.
4. OVERVIEW OF KEWEENAW WATERWAY
The Keweenaw waterway is located on Michigan’s Upper Peninsula, USA. The waterway is being used by shipping companies to transport copper and other goods. The waterway experiences some of the harshest weather conditions in the great Lakes region with large fluctuations in temperature and high wind and wave action due to large fetch. The local weather has led to stones deteriorating faster than laboratory testing indicates.

Freeze-thaw effects have the potential to increase rates of deterioration. Water gets into natural and man-made cracks of the stones. When water freezes in these cracks, it causes them to expand, increasing its size and exerting more pressure on surrounding areas. Subsequent thawing leaves larger areas for the process to repeat itself. Two published methods of freeze-thaw cycle techniques were used for this study. The first method is described by Lienhart (1988) and the second one is modified from Arnold et al. (1996).

The maximum number of freeze-thaw events generally occurs during seasonal changes, such as the late fall and early spring. The most intense periods occurred in the winter and month of November. Preliminary analysis indicates the freeze-thaw cycles had little correction with the overall rate of the stone degradation.

Waves impacting the structure can cause stone to move around, potentially increasing the rate of deterioration. The Hudson (1969) equation was used to determine the minimum weight of an armor stone to ensure structure stability for a given wave condition. Field observations indicate that wave heights had a strong correlation with the degradation of the cast concrete block.

5. SUMMARY
The project described here is a multi-year research effort. The results presented here are not conclusive. The reader should look for future publications of this research project. Currently, ten index stones have been placed at Keweenaw Waterway and eight index stones at Cleveland Harbour. The Keweenaw samples consist of ten stones, five lime stones, two quartzites, two granites and one cast concrete block. All Keweenaw index stones (except the cast concrete) were cut into roughly rectangular shapes producing a 5-6 ton stone. The concrete block was cast into approximately the same dimensions as the other cut stones. Cleveland Harbour’s index stones consist four cut stones; two sandstones and two limestones and four cast concrete blocks (with varying concrete mixtures). These stones also rectangular in shape average about 9 tones in weight. The index stones placed in Keweenaw Waterway and Cleveland Harbor are currently being monitored for rock mass-loss and degradation. Additionally, specific macroscopic features being monitored include vugs, stylolites and fossils in the limestones and fractures, joints and cracks in the quartzite and granites. Petrographic analysis of various microscopic features is continuing as part of the laboratory efforts.

Field observations on the collected samples indicate that in general the armor stones are weathering from the edges inward towards the center of the stone. The cast concrete block has shown the most weathering with measurable deterioration and mass-loss beginning along its edges (and some corners) that is progressing towards the center of the stone. This trend is less evident in the other index stones, but four rounds of observations indicate that although stone deterioration and mass-loss is less than for the concrete block, it is still progressing in a similar manner.

The field observations and laboratory testing were used to construct a “stone durability index model” that will be useful in determining the life cycle of large (type A) armor stone. The software developed by this project may be used to integrate field observations and
laboratory testing into a common index that will predict percent rock mass-loss and deterioration rate.

REFERENCES