Harbor Protection through Construction of Artificial Submerged Reefs

Amarjit Singh, Vallam Sundar, Enrique Alvarez, Roberto Porro, Michael Foley

(www.hawaii.gov)
Outline

- Background of Artificial Reefs
- Multi-Purpose Artificial Submerged Reefs (MPASRs)
  - Coastline Protection
  - Harbor Protection
- MPASR Concept for Kahului Harbor, Maui
  - Situation
  - Proposed Solution
- Summary
Background

- **Uses**
  - Create Marine Habitat
  - Enhance Fishing
  - Recreational Diving Sites
  - Surfing Enhancement
  - Coastal Protection

- **Materials**
  - Rocks; Shells
  - Trees
  - Concrete Debris
  - Ships; Car bodies
  - Designed concrete modules
  - Geosynthetic Materials

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<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>First documented artificial reefs in U.S.</td>
<td>1830’s</td>
</tr>
<tr>
<td>First artificial reef in Hawaii</td>
<td>1961</td>
</tr>
<tr>
<td>First specifically designed artificial reefs in U.S.</td>
<td>1970’s</td>
</tr>
<tr>
<td>Artificial reefs in Hawaii – concrete Z-modules</td>
<td>1991- Present</td>
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</table>
Multi-Purpose Artificial Submerged Reefs (MPASRs)

Specifically designed artificial reef which can provide:

- **Coastline Protection or Harbor Protection**
  - Can help restore natural beach dynamics by preventing erosion
  - Can reduce wave energy transmitted to harbor entrances

- **Marine Habitat Enhancement**
  - Can provide environment for coral growth and habitat fish and other marine species.
  - Coral can be transplanted to initiate/accelerate coral growth

- **Recreational Uses**
  - Surfing enhancement: can provide surfable breaking waves where none exist
  - Diving/Snorkeling: can provide site for recreational diving and snorkeling
MPASRs as Coastal Protection

Wave Transmission:
MPASRs can reduce wave energy transmitted to shoreline.

\[ K_t = \frac{H_t}{H_i} \]

- \( K_t \) = wave transmission coefficient,
- \( H_t \) = transmitted wave height shoreward of structure
- \( H_i \) = incident wave height seaward of structure.

(Pilarczyk 2003)
MPASRs as Coastal Protection

- *Wave Refraction*: MPASR causes wave refraction around the reef, focusing wave energy in a different direction.

Dependent on local coastal dynamics, this can assist in stabilizing the coastline.
Yucatan Peninsula Beach Restoration, MEXICO

• **Description:**
  ▫ 4 km of geotextile tubes as submerged breakwaters
  ▫ Goal: restore *natural* coastal dynamic processes and provide a stabilized beach profile.

• **Project included:**
  ▫ Elimination of structures perpendicular to shore to restore natural *longshore* sediment transport
  ▫ Beach nourishment from inland material banks
  ▫ Sediment bypass techniques at harbors along coast
  ▫ Reducing hydraulic load on specific sections of coastline to stabilize longshore sediment transport. (i.e. reduce wave transmission)

**INITIAL SITE CONDITIONS**

(Alvarez 2006)
Initial Conditions on Yucatan Coast

Yucatan North Coast

- Progreso Beach timber groins
- 7km Progreso Pier
- Chicxulub Sandbags Groins
- Chelem rock-timber groins
- Chuburna Safe Port

(Alvarez, 2012)
Construction – Filling of Geotextile Tubes

- Sand-filled geosynthetic tubes
- Filled with sand
- Slurry pumps with 10-30% solids at 1000 gpm.
Sand Accretion After Tube Installation

**Results**

**a) Profile Before Restoration**

- Limit of construction
- Energy dissipation due to wave breaking on geotextile tube
- New profile after sand accumulation
- Geotextile tube
- Incident wave
- Scour apron
- Sand accumulation due energy reduction

**b) Conditions shortly after installation**

**c) Conditions 10 months after installation**

(Alvarez 2008)
Yucatan Project Results/Conclusions

**Shoreline Response**
- Geotextile tubes initiate wave breaking farther from shore, dissipating energy transmitted shoreward.
- Sand accumulation without interrupting littoral drift
- No change was observed in natural currents seaward of tubes.
- Upon stabilization, a vegetative dune should be implemented to act as natural defense.

**Geotextile Material Response**
- No damage to materials due to pumping pressure or installation.
- Period of observation too short to determine long term durability of tubes.
Reef Ball™ Units as Submerged Breakwater, Grand Dominicus, Dominican Republic

Pre-Cast Reef Ball™ Units

Reef Ball™ Units as Submerged Breakwater

Conditions Shortly after Installation

Conditions 3 years after Installation

(Harris, 2006)
## MPASR Examples

<table>
<thead>
<tr>
<th>Reef</th>
<th>Cables Station - Western Australia</th>
<th>Narrowneck – Queensland, Australia</th>
<th>Pratte’s Reef – Los Angeles, CA</th>
<th>Mt. Maunganui – New Zealand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Functions</strong></td>
<td>Surfing Enhancement</td>
<td>Coastal Protection, Surfing and Ecological Enhancement</td>
<td>Surfing Enhancement and mitigation</td>
<td>Surfing and Ecological Enhancement</td>
</tr>
<tr>
<td><strong>Construction Material</strong></td>
<td>Granite Rocks</td>
<td>Geotextile Sand Filled Containers</td>
<td>Geotextile Sand Filled Containers</td>
<td>Geotextile Sand Filled Containers</td>
</tr>
<tr>
<td><strong>Construction Method</strong></td>
<td>Barge and Crane</td>
<td>Split-Hull Barge</td>
<td>Barge and Crane</td>
<td>Rapid Accurate Deployment</td>
</tr>
<tr>
<td><strong>Total Volume (cu.m.)</strong></td>
<td>5,000</td>
<td>60,000</td>
<td>1,600</td>
<td>6,500</td>
</tr>
<tr>
<td><strong>Cost per unit Volume (US$/cu.m.)</strong></td>
<td>303</td>
<td>50</td>
<td>312</td>
<td>160</td>
</tr>
</tbody>
</table>
Harbors typically formed/protected by breakwaters
- Formation of artificial harbors
- Protect an area inside against waves
- Reduce dredging at harbor entrance
- Serve as quay facility
- Guide currents
- Provide tranquility conditions inside harbor

Types
- Type S: sloping breakwater
- Type V: vertical breakwater
- Type C: composite breakwater (combination of sloping & vertical)

Submerged Breakwaters
- Where complete wave protection is *not required nor necessary*, can use submerged breakwaters.
- Submerged structure reduces wave energy shoreward of the structure.
- MPASRs focus and reduce wave energy and provide recreational and ecological benefits.

(Sundar 2012)
Construction Materials

- Geosynthetic Materials present a possible cost-effective alternative to conventional concrete/rock/rubble-mound structures.
- Can combine with use of conventional construction material for durability/armor.
Examples of Use of Geosynthetics in Coastal Protection

**Seawall - Uppada, India**

- Gabion Armor Layer
- Geotube Core
- Geobag Layer

(Sundar 2012)
Seawall - Uppada, India

(Sundar 2012)
Seawall – Shankarpur, India: Cross Section

(Sundar 2012)
Seawall – Shankarpur, India

(Sundar 2012)
Barge mounted crane individually stacks relatively small geotextile units into the designed shape
- $312/m^3 (Pratte’s Reef, Los Angeles, CA)

Dropping much larger sand-filled units onto the ocean floor using a spilt-hull hopper barge
- $50/m^3 (Narrowneck Reef, Gold Coast, Aus)

Inflating empty geotextile containers with pumped sand after they have been secured on the seabed in the desired layout (Rapid Accurate Deployment)
- $160/m^3 (Mt. Maunganui Reef, New Zealand)
Geotextile bags are filled with sand and dropped on the ocean floor.

- Cost: $50/m

Draw Back: Inaccuracies

(ASR Marine Consulting and Research, 2002)
Rapid Accurate Deployment (RAD)

- Geotextile bags are filled with sand after being secured to ocean floor.
- Cost: $160/m³
- Advantage: Accuracy

Construction of Mount Maunganui Reef, New Zealand using RAD method. (ASR Limited)
MPASR Solution for Kahului Harbor, Maui

Oceanit Laboratories, 2008

Hawaiian Islands

Kahului Harbor, Maui

(Oceanit Laboratories, 2008)
Situation (Maui)

Maui’s largest Harbor

The majority of Maui’s imports and exports travel through the harbor

Berthing demand from cargo and passenger shipments is steadily increasing.

Shipping operations at the harbor face operational challenges due to wave energy
Proposed 2025 Master Plan

(Thompson 2002)
Wave Study for Breakwater Variations

Short Wave Amplification Factors

- **2025 Plan / Plan B:** Provide sufficient wind wave and swell protection for eastern piers, but may be a concern for new western pier.

- **Plan C:** Provides sufficient wind wave and swell protection.

(Thompson 2002)
Wave Study for Breakwater Variations

Resonant Long Wave Velocity Contours

- **2025 Plan / Plan B**: no impact on harbor oscillations
- **Plan C**: possible operational impact for long waves

(Thompson 2002)
2030 Master Plan

- Updated plan released in 2007 - included harbor dredging and deepening, a seaward extension of the harbor’s east breakwater, and a landward extension of the west breakwater.
Concerns with Proposed Development Plans

- Proposed breakwater solutions will not provide sufficient wave protection.

- Development plans (dredging) will require destruction of existing reefs.

- Development plans will result in loss of existing surf sites within the harbor.

**Mitigation through an MPASR:** Provide wave protection while creating a marine habitat and surf break outside of the harbor.
Numerical Modeling (Mild Slope Eqn.)

- MSE is preferred because of its generality in dealing with complex wave fields.
- Solved by generalized conjugate gradient method as it has a fast convergence rate.
- The combined refraction-diffraction equation that describes the propagation of periodic, small amplitude surface gravity waves over an arbitrarily varying mild sloped sea bed is (Berkhoff, 1972):

\[
\phi = \text{Complex velocity potential}
\]

\[
\omega = \text{wave frequency}
\]

\[
C = \text{phase velocity, and}
\]

\[
C_g = \text{group velocity}
\]

\[
\frac{\partial^2 \phi}{\partial t^2} - K^2 (x,y) \phi = 0
\]

where

- \( K^2 = \frac{k^2}{2 (CC_g)^{0.5}} \) and
- \( \frac{1}{C C_g^{0.5}} \)

Where, \( k = \text{wave number} \)

- \( K = \text{modified wave number} \)

\( \phi = \text{velocity potential} \)
• The Finite Difference scheme \( \rightarrow \) numerical discretisation of Helmholtz equation.
• The system of resulting algebraic equations can be written in matrix form as
  \[
  A\mathbf{\phi} = \mathbf{f}
  \]
  where \( A \) is the coefficient matrix,
  \( \mathbf{\phi} \) is the nodal values of velocity potential, and
  \( \mathbf{f} \) is a vector obtained from the boundary conditions.

• The numerical solution of the above system of equations is arrived using generalised conjugate gradient method.
• The method successively estimates new approximations to the solution, considering the direction of residual error vector, till the prescribed accuracy is achieved.
• The offshore boundary is modeled as an open boundary in which case only incident waves and reflected waves are allowed to propagate. The lateral boundary as well as the shore is considered to absorb the wave energy. The breakwater or any other obstruction is treated as partially reflecting boundaries by prescribing the reflecting coefficients.
• The model gives the wave characteristics inside the domain.
MPASR Solution

Conceptual Profile

(Foley and Singh, 2009)
Rose Diagrams
Dec 2011 to June 2012

Wave direction rose diagram

Wave height rose diagram
Rose Diagrams
Jan 1993 – Dec 1996
MPASR Solutions (Speculative)

**Concept Options**

1. End
2. Offset
3. Island

*Harbor Entrance – 660 feet wide*
Alternate MPASR Speculative Solution (Offset Option)
## Estimated Costs

### Kahului Harbor Multipurpose Artificial Surfing Reef

**Order of Magnitude Cost Estimate:**

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Construction Method</th>
<th>Unit Cost</th>
<th>Unit</th>
<th>Quantity</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Fill</td>
<td>Barge and crane</td>
<td>$303</td>
<td>cu.m.</td>
<td>100,000</td>
<td>$30,300,000</td>
</tr>
<tr>
<td>Geotextile sand filled containers</td>
<td>Split-hull barge</td>
<td>$50</td>
<td>cu.m.</td>
<td>100,000</td>
<td>$5,000,000</td>
</tr>
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<td></td>
<td>Barge and crane</td>
<td>$312</td>
<td>cu.m.</td>
<td>100,000</td>
<td>$31,200,000</td>
</tr>
<tr>
<td></td>
<td>Rapid Accurate Deployment</td>
<td>$160</td>
<td>cu.m.</td>
<td>100,000</td>
<td>$16,000,000</td>
</tr>
</tbody>
</table>

(Foley and Singh, 2009)

**Assuming that the reef will be:**

- Trapezoid 600 ft long X 200 ft wide X 30 ft tall
## Cost Analysis

### MPASR BENEFITS (SAVINGS)

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 Master Plan East Breakwater</td>
<td>$90,000,000</td>
</tr>
<tr>
<td>Dredge Material Disposal</td>
<td>$7,800,000</td>
</tr>
<tr>
<td><strong>Total Savings</strong></td>
<td><strong>$97,800,000</strong></td>
</tr>
</tbody>
</table>

### ESTIMATED COSTS OF MPASR

<table>
<thead>
<tr>
<th>Method</th>
<th>Amount</th>
</tr>
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<tbody>
<tr>
<td>RAD Method</td>
<td>$16,000,000</td>
</tr>
</tbody>
</table>

### BENEFIT/COST RATIO

| B/C (RAD Method) | 6.1 |

*(Foley and Singh, 2009)*
Summary

• Described coastal and harbor protection through use of artificial reefs and submerged breakwaters.

• Described artificial reef construction costs methods currently in practice using geotextile materials.
  ▫ $50/cu.m - $330/cu.m.

• Provided analysis of using an MPASR to provide wave protection at Kahului Harbor, Maui.

• Seems that MPASRs have a 6:1 possible cost advantage over emerged breakwaters.
References

References


• Harris, L.E., 2006. Artificial Reefs for Ecosystem Restoration and Coastal Erosion Protection with Aquaculture and Recreational Amenities. 5th International Surfing Reef Conference.


• Oceanit Laboratories, 2008. Honolulu, HI.

• Pilarczyk, K.W., 2003. Design of low-crested (submerged) structures – an overview. 6th International Conference on Coastal and Port Engineering in Developing Countries.

• Sundar, V. Breakwaters. Department of Ocean Engineering, IIT Maderas. (Personal communication August 2012).


THANK YOU!