Stability of Armour Layer over Sand Bed in Waves/Currents: A Case Study

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ABSTRACT

Stability and suction removal of the sand bed under the rock-armoring layer were exposed under the wave and discharge generated steady flow and coexisting flow investigated at apron area of the open channel discharge system. Determination of the stability of the armoring layer was achieved by micro and macro scale tests focused just on the stones and all armoring area in 1/25 scale laboratory physical model. In micro scale tests, small underwater camera was recorded the motion of the stones and flow properties were measured by Acoustic Doppler (ADV) just over the stones at critical points. Shields parameter and Shields initiation of the motion criteria were applied of the measurements results. The variation range of the Shields parameter were determined (?) as: 0.003-0.007 for steady current case (only discharge condition), 0.008-0.04 for wave only (no discharge) and 0.01-0.03 in coexisting flow case. Photogrammetric method was applied at macro scale tests by 3D photographs of the armoring area before and at the end of the experiments. Instability was not determined for whole armoring layer by photogrammetric approach.

ADDITIONAL INDEX WORDS: Armour layer, current, wave, wave plus current, sand bed protection.

INTRODUCTION

One of the methods widely used for scour protection in coastal engineering is rock dumping on a sand bed. When such a rock layer (armoring layer) is exposed to steady current, waves or combined flow their stability are an important issue for engineering design. In the literature, most of the studies related to armoring layer stability were performed under the steady current. The interaction between an armoring layer and the bed sediment has been the subject of a great many investigations. Raudkivi and Ettema (1982) were focused on the stability of the armoring layer itself under the steady current. Worman (1989) was concerned with the initiation of erosion of the bed sediment layer underneath an armoring layer used as a protection measure around a bridge pier. Subsequently, Worman (1992) was investigated the incipient motion of the bed sediment covered by an armoring layer with different coverage ratios. Kampsuhs (1975), Jensen et al. (1989), Jonsson and Carlsten (1976) and Stealth (1987) works were supplied great experimental and analytic contributions about determination of wave friction factor, wave boundary layer over coarse bed. Fredsoe and Deigaard (1992) were collected that works and reflected their experience on that subject at understandable manner. However, such a coarse bed like armoring blocks generated and coexisting flow effect were not focused detailed in the previous works.

In this study, stability armoring layer against erosion over the sand bed of open channel thermal discharge system of the power plant in an industrial area in Sohar, Emirate of Oman, was performed. Sohar is located nearly 200 km. North-West of Muscat, capital of Oman. The Omani Government decided to establish an industrial complex at Sohar including a fertilizer plant, a refinery, a methanol plant and several other industries. It is calculated that these industries may required a peak cooling seawater of 334,000 m3/hr. Cooling water will be given in the water by stone pitched conical outlet structure thru the sea. Stone pitching used at the sea bottom varies between -0.5 and 2 m chart datum, CD, elevations.

EXPERIMENTAL SET-UP

Hydraulic model of outlet structure was built at -1/25 geometric scale (Figure 1). Model was covered nearly 500 m beach and bathymetry in the model was taken between +4.5 and -4 m. Regular wave makers were replaced nearly 300 m (in prototype) far from the ending of the stone-protected area. The wave basin in the laboratory has dimensions of 25x28x1 m. Stone pitching was used at the sea bottom between -0.5 m and -2 m elevations. Discharge channel was constructed of concrete and brick walls (Figure 1). The chute at the end part of the channel was also constructed of concrete. Stone covered outlet part has concrete bottom, with an overlying fine sand layer (d50=0.4 mm), was placed over concrete bottom and armoring layer applied over this by using crushed stones. The sand layer has a thickness of 6 cm and placed to simulate the bottom conditions of the units. The d50 stated above is of the sand used in the laboratory (It is not possible to model sand and to use 25 times smaller diameter material, as it will not be sand but silt). D50 of the units was determined by measuring 30 different stone heights after placing at the discharge structure, which was found to be 1.25 cm.

Main issue at the model study was the determination of the stability of stone armour layer on the sand dredging channel in the sea. Various flow measurements and observation techniques were used in the model tests. For this purpose a 3D NORTEK 10 MHz Acoustic Doppler Anemometer, a mini under-water recording camera and 3 digital photography cameras and wave height measurement probes were used in the tests. Micro-scale tests on stones forming armouring layer were observed by under-water camera in close-up. Velocity profiles, Reynolds shear stresses and wave velocities near the bottom were determined with 3D ADV by determining flow properties and shear stresses. Place of the wave probes and velocity measurements with camera recording locations are given also in the Figure 1. Macro-scale observations were achieved by recording the tests and capturing 3D images with digital cameras fot photogrammetric approach. Wave properties were determined by measuring the water surface fluctuations using resistance type wave probes.
TEST CONDITIONS

Water table fluctuations at the area were given as follows; Highest Astronomical Tide (HAT) is +3.4, mean high water level (MHHW) is +2.9, mean sea level (MSL) is +2.0, mean low water level (MLLW) is +0.90 and lowest astronomical tide (LAT) is 0.0. 1/75 years turn period wave height (Hₜ) was performed in the regular wave tests. This wave height was determined by 3.20 m at -2 m water depth in prototype and wave heights controlled by probe 2 as given in the Figure 2.

Stability of the armoring layer was tested under the various hydrographical and flow conditions. Test conditions in the experiments were summarized in the Table 1.

In the experiments, velocity measurements were performed by Nortek 3D Acoustic Doppler. Critical points (possible instability locations for the armoring layer) were determined during the initial tests with some velocity and wave measurements over all armoring zone. Locations of the measurement points were marked on the Figure 1 by 1 and 2. After that, velocity probe was fixed on this points and velocity values recorded for 2 minutes period. An underwater camera was placed also on the bottom with 8 cm focus far from objective at the same section with velocity probe and stones were recorded by the camera during the test. Critical measurement points (1 and 2) were taken at shallow water zone (depending on the water level condition) and symmetry axis of the discharge channel for all wave alone, current alone and coexisting flow case conditions. During the wave alone test series, wave breaking was observed just on the offshore beginning point of the stone protection because bottom roughness changing dramatically there, for some wave conditions. So, during the wave alone tests, velocities were measured at that point and stone protection layer was filmed by underwater camera at the same time, too.

RESULTS AND DISCUSSIONS

For stability of the riprap protection effect of the flow condition following parameters that bottom friction factor (f) and shear stress (τₑ or τₑ) and shear velocity (Uₑ or Uₑ) were determined to base on those velocity measurements. For wave alone case, shear velocity, Uₑ was found by following calculation procedure for determining stability of stone protection;

Velocity time series were measured at the possible closest point to the bottom on the specified location for 2 minutes with 25 Hz time period and amplitude of the movement, a, at that point was determined by;

\[
a = \frac{U m T}{2\pi}
\]

where; a, Uₑ and T are free stream particle amplitude, amplitude of near bed wave orbital velocity (maximum horizontal velocity value at one period) and wave period respectively. kₑ equivalent sand roughness coefficient were chosen as 31.25 cm in prototype scale (1.25 cm in model scale) which corresponds to Dₑ, because applied stone protection has a uniform size distribution. Then a/kₑ were determined for each test series. For all test series this ratio is less than 50, because kₑ has a relatively large value with respect to the amplitude of motion. Bottom friction factor, fₑ was given for namely a/kₑ values as (KAMPHIUS,1975) (FREDSON and DEIGAARD, 1992);

\[
fₑ = 0.4 \left( \frac{a}{kₑ} \right)^{-0.75}, \quad \frac{a}{kₑ} < 50
\]

Wave boundary layer thickness, was calculated by;

\[
\frac{\delta}{kₑ} = 0.09 \left( \frac{a}{kₑ} \right)^{0.82}
\]
The maximum bottom shear stress ($\tau_{\text{max}}$) was calculated by using $f_w$ values in the following equation:

$$\tau_{\text{max}} = \frac{1}{2} \rho f_w U_m^2$$

and here $\rho$ is specific mass of the fluid (in this case specific weight of sea water). Maximum shear stress velocity ($U_w$) could be calculated from:

$$U_w = \sqrt{\frac{\tau_{\text{w}}}{\rho}}$$

For stability check of the armour layer under the flow effect, Shields criterion was used for mobility of the armouring layer under the wave conditions and, Shields parameter ($\theta$) was calculated by:

$$\theta = \frac{U_w^2}{g(s-1)d_{50}}$$

Calculated Shield values from test result were compared by Shields critical value for mobility of the stones. Sediment initiation of motion and suction out under the armouring layer also tested by calculated Shields parameters, too by following literature knowledge. WORMAN (1992) results and criteria for initiation of motion under the riprap layer over sand bed and work of SUMER et al. (2001) suggested curve for suction out fine sediment from armouring layer were used.

In coexisting flow case (discharge current and wave in the basin); the same calculation procedure were applied. But in coexisting current case velocities near the bottom was not symmetrical like wave alone case and wave and current velocities were superimposed. In this condition maximum reference velocity near the bottom;

$$U_m = U_w + U_c$$

Where, $U_m$ is maximum orbital velocity and $U_w$ and $U_c$ are current and maximum wave velocity components of it. Friction factor, shear stress and, shear velocity were calculated to base on this velocity. Same criteria were applied for stability of

### Table 1: Test conditions.

<table>
<thead>
<tr>
<th>Flow Conditions</th>
<th>Current alone</th>
<th>Wave alone (Regular)</th>
<th>Waves and Currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Level</td>
<td>Lowest Astronomical Tide (10.0 m)</td>
<td>Mean Low Water Level (+0.9 m)</td>
<td>Highest Astronomical Tide (+3.4 m)</td>
</tr>
<tr>
<td></td>
<td>Lowest Astronomical Tide (40.0 m)</td>
<td>Mean Low Water Level (+0.9 m)</td>
<td>Highest Astronomical Tide (+3.4 m)</td>
</tr>
</tbody>
</table>

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### Table 2: Measurement Results (values were presented in model scale).

<table>
<thead>
<tr>
<th>Run No</th>
<th>Run Conditions</th>
<th>Point</th>
<th>Distance from the Bottom (cm)</th>
<th>$T$ (S)</th>
<th>$U_{\text{max}}$ (Cm/sec)</th>
<th>$k_s$ (Cm)</th>
<th>$a$ (cm)</th>
<th>$f_w$</th>
<th>$\tau_{\text{w}}/\rho$ (Cm²/sec²)</th>
<th>$U_w$ (Uf) (Cm/sec)</th>
<th>$\theta$ (Cm)</th>
<th>$\delta$ (Cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum Water Level, Wave Only</td>
<td>1</td>
<td>1.02</td>
<td>1.11</td>
<td>18.00</td>
<td>1.2500</td>
<td>3.180</td>
<td>0.199</td>
<td>32.1696</td>
<td>5.6718</td>
<td>0.0159</td>
<td>0.2419</td>
</tr>
<tr>
<td>2</td>
<td>Maximum Water Level, Wave Only</td>
<td>1</td>
<td>0.82</td>
<td>1.11</td>
<td>19.64</td>
<td>1.2500</td>
<td>3.470</td>
<td>0.186</td>
<td>35.8742</td>
<td>5.9895</td>
<td>0.0177</td>
<td>0.2598</td>
</tr>
<tr>
<td>3</td>
<td>Maximum Water Level, Wave Only</td>
<td>1</td>
<td>0.79</td>
<td>1.14</td>
<td>19.45</td>
<td>1.2500</td>
<td>3.529</td>
<td>0.184</td>
<td>34.7391</td>
<td>5.8940</td>
<td>0.0172</td>
<td>0.2635</td>
</tr>
<tr>
<td>4</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.96</td>
<td>0.93</td>
<td>10.09</td>
<td>1.2500</td>
<td>1.493</td>
<td>0.350</td>
<td>17.8176</td>
<td>4.2211</td>
<td>0.0088</td>
<td>0.1302</td>
</tr>
<tr>
<td>5</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>1.46</td>
<td>0.93</td>
<td>13.70</td>
<td>1.2500</td>
<td>2.028</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>1.96</td>
<td>0.85</td>
<td>10.41</td>
<td>1.2500</td>
<td>1.408</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.72</td>
<td>1.10</td>
<td>11.04</td>
<td>1.2500</td>
<td>1.926</td>
<td>0.289</td>
<td>17.6279</td>
<td>4.1986</td>
<td>0.0087</td>
<td>0.1603</td>
</tr>
<tr>
<td>8</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.72</td>
<td>1.11</td>
<td>10.70</td>
<td>1.2500</td>
<td>1.882</td>
<td>0.294</td>
<td>16.8483</td>
<td>4.1047</td>
<td>0.0083</td>
<td>0.1573</td>
</tr>
<tr>
<td>9</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.72</td>
<td>1.11</td>
<td>12.61</td>
<td>1.2500</td>
<td>2.228</td>
<td>0.259</td>
<td>20.6181</td>
<td>4.5407</td>
<td>0.0102</td>
<td>0.1807</td>
</tr>
<tr>
<td>10</td>
<td>Minimum Water Level, Current Only</td>
<td>1</td>
<td>0.72</td>
<td>N/A</td>
<td>18.48</td>
<td>1.2500</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>3.76</td>
<td>0.0070</td>
<td>N/A</td>
</tr>
<tr>
<td>11</td>
<td>Minimum Water Level, Current Only</td>
<td>1</td>
<td>0.72</td>
<td>N/A</td>
<td>12.62</td>
<td>1.2500</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2.81</td>
<td>0.0039</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.62</td>
<td>1.10</td>
<td>29.35</td>
<td>1.2500</td>
<td>5.120</td>
<td>0.139</td>
<td>59.8411</td>
<td>7.7357</td>
<td>0.0296</td>
<td>0.3575</td>
</tr>
<tr>
<td>13</td>
<td>Minimum Water Level, Wave Only</td>
<td>1</td>
<td>0.62</td>
<td>1.11</td>
<td>25.45</td>
<td>1.2500</td>
<td>4.496</td>
<td>0.153</td>
<td>49.5981</td>
<td>7.0426</td>
<td>0.0245</td>
<td>0.3214</td>
</tr>
<tr>
<td>14</td>
<td>Minimum Water Level, Wave+Current</td>
<td>1</td>
<td>0.62</td>
<td>1.10</td>
<td>30.00</td>
<td>1.2500</td>
<td>5.247</td>
<td>0.136</td>
<td>61.3763</td>
<td>7.8343</td>
<td>0.0303</td>
<td>0.3648</td>
</tr>
<tr>
<td>15</td>
<td>Minimum Water Level, Wave+Current</td>
<td>1</td>
<td>0.62</td>
<td>1.13</td>
<td>30.00</td>
<td>1.2500</td>
<td>2.385</td>
<td>0.246</td>
<td>22.4529</td>
<td>4.7384</td>
<td>0.0111</td>
<td>0.1911</td>
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<tr>
<td>16</td>
<td>Minimum Water Level, Wave Only</td>
<td>2</td>
<td>0.56</td>
<td>1.30</td>
<td>28.17</td>
<td>1.2500</td>
<td>5.824</td>
<td>0.126</td>
<td>50.0465</td>
<td>7.0744</td>
<td>0.0247</td>
<td>0.3973</td>
</tr>
<tr>
<td>17</td>
<td>Minimum Water Level, Wave Only</td>
<td>2</td>
<td>0.56</td>
<td>1.16</td>
<td>38.44</td>
<td>1.2500</td>
<td>7.115</td>
<td>0.109</td>
<td>80.1940</td>
<td>8.9551</td>
<td>0.0396</td>
<td>0.4682</td>
</tr>
<tr>
<td>18</td>
<td>Minimum Water Level, Wave Only</td>
<td>2</td>
<td>0.56</td>
<td>1.11</td>
<td>32.19</td>
<td>1.2500</td>
<td>5.687</td>
<td>0.128</td>
<td>66.5283</td>
<td>8.1565</td>
<td>0.0329</td>
<td>0.3897</td>
</tr>
<tr>
<td>19</td>
<td>Minimum Water Level, Wave Only</td>
<td>2</td>
<td>0.56</td>
<td>0.86</td>
<td>30.94</td>
<td>1.2500</td>
<td>4.257</td>
<td>0.160</td>
<td>76.3702</td>
<td>8.7390</td>
<td>0.0377</td>
<td>0.3073</td>
</tr>
<tr>
<td>20</td>
<td>Minimum Water Level, Current Only</td>
<td>1</td>
<td>0.48-0.68-0.95-1.26-1.82-2.02-2.76-3.40-4.34</td>
<td>7.00 (depth average)</td>
<td>1.2500</td>
<td>2.38</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.003</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Journal of Coastal Research, Special Issue 39, 2006
armouring layer and mobility of the sediment bed by wave alone case.

During the current alone case (no wave and just water discharge from channel) shear velocity $U_i$ was determined from velocity profile by depth. $U_i$ was determined by using following relation of velocity distribution $U(y)$;

$$\frac{U(y)}{U_f} = \frac{1}{\kappa} \ln \left( \frac{30z}{k_N} \right)$$

(8)

here; $U$ is time average value of velocity at reference point, $U_f$ is friction factor of Karman constant (0.4) and $z$ is theoretical bed $k$ is bed roughness. Shear stress velocity was calculated in this approach by using semi logarithmic velocity profiles slope. After determination of the shear velocity, Shields parameter was calculated and stability of the armouring layer also sediment sand bed mobility was checked by same literature values for wave alone case. Results of the experiments were presented in the Table 2.

As a seen form the table all the values are smaller than the critical values for initiation of motion criteria. This critical value should be greater than the Shields criteria because of send layer as given in the Worman (1992) work. During the experiments no significant damage was determined at any test series. But, as mentioned before, during the wave and current combine flow condition (Test no 14 in Table 2) only one stone at armouring layer was rocked and snap shots from recorded film were taken from the digital camera and movement of the stones were investigated frame by frame. Snap shoots were given in Figure 2. From the snapshots rocking of the one rock could be seen around the pivot point with the same period with wave. A point was marked on the stone for clearly visible to stone. In the figures distance of motion then the previous image was marked.

In the photogrammetric methods 3D photographs were taken before filling water to basin and some strips marked on the

![Figure 2. Subsequent snapshots of underwater camera records (due to physical obscures the view is upside down).](image)
armoring layer with paint. Some photographs were taken also after the experiments and marked places evaluated. Photogrammetric tests were signed no possible instability occurred on the armoring layer.

CONCLUSIONS

Stability of stone covered armoring layer under the waves and currents also both were investigated during this study by experimentally. Given stones sizes for armoring layer are satisfied the design criteria and there is no possible damage occurred under the mentioned flow conditions. In the steady current case, effect of flow over the rough boundary (armoring layer) was not significant. Shields parameters were also taken the smallest values in that case. In the wave alone case, relatively larger shear velocity values were determined. In that case Shields parameter takes larger values too but that values still less than critical the initiation of motion values. Video capturing also were supported that results no motion observed during the tests. During the coexisting flow case, shear velocity values was almost the same as wave alone case. The suction of fine sediment under the armoring layer was not determined because of small shear stresses over the rough boundary. The results were indicated the importance of the laboratory tests and measurements for certain design of that type of constructions.

LITERATURE CITED