INTRODUCTION

Coastal morphology is the result of physical processes operating along the margin of the sea. Of these processes, wave induced sediment transport has the greatest ability to reshape the coast. It should be possible to build numerical models that relate the wave energy distribution to the coastal features affected by the waves as ocean wave characteristics and the resulting sediment transport have been described by mathematical equations. Such a sediment transport model was created to help to explain the coastal features along the west coast of Central Italy between S. Felice Circeo and Terracina (Fig. 1).

This 15.9 km long section of popular recreational beach lies isolated from other beaches between the rocky headlands of Circeo and Terracina. The western portion has been experiencing more rapid beach erosion than the beach near Terracina on the east. In order to counter this beach erosion, two engineering projects were undertaken with mixed results. Construction of beach parallel breakwaters from 1960 to 1980 near Circeo attempted to arrest further erosion. In 1980-1983 about 110,000 cubic meters of gravel size limestone and 82,000 cubic meters of sand were added to the beach near Terracina to replace eroded sand. The breakwaters did not add new beach material and the gravel was buried by longshore sand transport. It seemed that further study and modelling was needed to preserve this section of coastline.

Beach sediment transport along this section of coast is largely the result of waves. Other transport mechanisms are too weak. Tidal currents are very weak as the tidal range is less than 40 cm. Although the easter Tyrrhenian Sea experiences a sustained current of 5.5 cm/sec., this study area is isolated from the adjacent flow. Furthermore, wind transport is minimal due to the extensive developed properties along this section of beach. Given these facts, it should be possible to explain the coastal morphology from Circeo to Terracina using mod-
eling techniques based on the near shore sediment transport resulting largely from wave action.

Delft Hydraulics Laboratory collected detailed wave data for this section of coast in 1991. This information consisted in the frequency of occurrence of wave heights and wave periods. The data were presented as the proportion of a year that each type of wave was observed. These data were critical for success in modeling the described coastline. It has been necessary to extrapolate some data to obviate the differences in location of the five profiles considered by the Delft Hydraulics Laboratory study.

METHODS

Simulation of beach morphology changes by waves not only requires detailed knowledge of wave characteristics, but also nearshore bathymetry, shoreline position, and a model that relates the wave energy spectra to sediment transport. Bathymetric maps generated by the Istituto Idrografico della Marina Italiana at a scale of 1:25,000 were digitized from the shore to depths of 100 m. The 100 m isobath is approximately 13 km offshore. Bathymetric digitizing was also extended beyond both the eastern and western ends of the beach to reduce possible edge effects in the computer model. The digitized data along with the profiles used in this study are depicted in Fig. 2. Note on this figure some details of the coastal morphology such as harbors at each end of the beach, shore parallel breakwaters, and two canals draining into the sea. These features were also digitized as part of the modeling process.

In the model, wave refraction and wave diffraction were calculated as single frequency first order waves with periods ranging from 3.2 to 11.0 seconds (about the minimum and maximum value of the Delft wave or swell data). The formula describing wave refraction and diffraction presented in the Shore Protection Manual (1984) were used in the program. Calculations were made at 125 m intervals across the study area on a square grid interpolated from the digitized bathymetry using a universal kriging algorithm. A finite difference scheme was used to migrate the waves from 12 offshore directions in 15-degree increments across the grid toward the shore. The wave refraction calculations took into account changes in direction of wave propagation and wave height as the waves began to interact with the sea floor. This portion of the model predicts incident wave direction and height at pre-selected points near the beach, but seaward of the breaker zone and of the depth of closure. These points are located at a depth of about 7 m to a better estimation of the initial conditions and are the starting positions for the detailed nearshore wave induced transport calculations. A total of five almost equally spaced beach profiles were located throughout the 15.9 km study area (Fig. 2). The beach profiles were generated from the bathymetric map by interpolating an average of 15 depth-distance coordinates along each profile line out to depths exceeding 15 m.

The Thornton & Guza (1983) model of breaking waves formed the basis for the littoral zone computer program. The wave shoaling and breaking model then applied various wave conditions to each profile location. The computer model calculated longshore sediment transport, longshore current velocity, bottom shear stress, maximum bottom velocity and percent breaking

Fig. 2 - Contoured bathymetry, shoreline features and beach profile locations.
waves in one-meter increments along each profile. A finite difference model was used to follow the waves from the starting point seaward of the breaker line through the breaker zone and onto the beach as swash.

The wave model that was used along the beach profiles fitted spectra of wave frequencies, wave heights and wave directions to the given wave input parameters. The spectral spreading was greater for sea than for swell. The model integrated the effects of these multispectral waves as they shoaled, refracted, broke, generated longshore currents and moved sand along the beach.

Total annual sediment transport was calculated using the empirical formula by Komar & Inman (Komar, 1976). Their formula relates the incident waves to instantaneous sediment transport rate. This value was multiplied by the percent of the year that each type of wave struck the coast to estimate the annual sediment transport. Observed wave heights from the Delft Hydraulics wave climate study were squared to give a value proportional to wave energy. In order to estimate the potential work this value was then multiplied by the proportion of occurrence in one year (probabilistic approach; Tab. 1). The model used six combinations of wave height, wave period and four wave directions that had the potential for doing work on the beach during one year.

RESULTS

To gain general information on the area of study, the longshore transport rate has been calculated for four dominant directions. Considering that waves generate net sand transport because of their direction of approach (more or less perpendicular to the coast), because they are frequently occurring waves, or because of their wave height (energy), four combinations of wave height and wave period corresponding to condition of “Sea” and two combinations for “Swell” have been analyzed (Tab. 1).

Results of the analysis (Fig. 3) indicate a maximum sand transport for a sea generally lower than that of the swell. The wave conditions referred to as sea show that the amount of sediment transport toward the east is almost balanced by the amount of sediment transport toward the west.

The seas from 120 and 150 move sediments toward the western part of the coastal area, while the seas from 180 and 202.5 move sediments toward east. The seas from 180 have slightly higher transport in the central western portion of the beach, while those from 202.5 seem to be a constant low transport along the coast.

The wave conditions referring to swell produce a higher amount of sediment transport across the whole study area. Along the western half the transport due to the swell from 180 increases gently from west to east while in the eastern one decreases abruptly at the end of the beach. The swell from 202.5 produced the highest longshore transport rate in the region increasing until location 4 followed by a decreasing of sand movement at the eastern part.

Additional output from the model is also shown. The bottom profile 1 and the variation of the shear stress at the bottom for sea from 180 degrees along the profile

<table>
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<tr>
<th>Direction</th>
<th>Wave</th>
<th>Period</th>
<th>Height</th>
<th>Probability of Occurrence</th>
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</thead>
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<td>(type)</td>
<td>(seconds)</td>
<td>(meters)</td>
<td>(year)</td>
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<td>0.0079</td>
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<td>0.0075</td>
</tr>
<tr>
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<td>0.0061</td>
</tr>
<tr>
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<td>Sea</td>
<td>4.5</td>
<td>0.99</td>
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</tr>
<tr>
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<td>0.0067</td>
</tr>
<tr>
<td>202.5</td>
<td>Swell</td>
<td>5.5</td>
<td>0.95</td>
<td>0.0115</td>
</tr>
</tbody>
</table>

Tab. 1 - Values of wave parameters analyzed in this study.
itself are sketched (Figure 4). As evidenced in the figure, for southern seas the shear stress is higher at some tens of meters offshore and at a depth of 4-5 meters. Moreover, in this location the dominant breaker type is in general plunging, which generally results in spilling waves.

CONCLUSION

The modeling of wave induced longshore beach sediment transport produced results that are in agreement with observed changes in beach morphology over time. The predicted imbalance of longshore transport generates a net easterly migration of sand resulting in more severe beach erosion in the western one third of the beach. However, the model is incomplete because it does not directly predict onshore/offshore sediment transport, an important factor for predicting the annual sediment budget for this particular coastline. Inferences based on bottom shear stress which the model does predict coupled with a knowledge of wave dynamics suggest a shoreward migration of sand at the western part of the beach and thereby reducing the rate of beach erosion near Circeo.

The waves that are actually responsible for the net longshore transport of sand were not easily predictable a priori. Of the six wave combinations analyzed in this study, two accounted for most of the net long shore transport.

This model, in spite the uncertainty of the Komar equations (Komar, 1976) to predict actual transport, seems to offer some potential to increase the understanding of the relationship between the incident waves and sand movement. The algorithms are flexible and can be run on most modern personal computers. Additionally, only four types of input data are needed: the continental shelf depth bathymetry, the geographic location of the beach, a series of depth profiles at locations where sediment transport calculations are desired, and, perhaps the most important for annual budget calculations, a known wave climate. With the availability of these data, this model can be used to predict longshore sediment transport along most clastic coastlines.

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