Coastal Hydrodynamics along the Eroded Beach of Akyaka in Gökova Bay, Turkey

ASU INAN\(^1\), NIHAL YILMAZ\(^2\), ASLI NUMANOĞLU GENÇ\(^3\) and LALE BALAS\(^4\)

\(^1\)Department of Construction Education, Technical Education Faculty
Gazi University
06550 Ankara TURKEY

\(^2\)Department of Civil Engineering, Engineering Faculty
Mugla Sitki Koçman University
48000 Muğla TURKEY

\(^3\)Department of Civil Engineering, Engineering Faculty
Gazi University
06550 Ankara TURKEY

\(^4\)Department of Civil Engineering, Engineering Faculty
Gazi University
06550 Ankara TURKEY

asuinan@gazi.edu.tr    http://www.fbe.gazi.edu.tr/kazalar/English/asuinani.htm
nyilmaz@mu.edu.tr    http://www.ce.mu.edu.tr
aslingenc@yahoo.com
lalebal@gazi.edu.tr    http://www.mmf.gazi.edu.tr/insaat/english/academicstaff/cv/lalebalasi.htm

Abstract: - The town of Akyaka, located in the northeast of Gökova Bay at the Southern Egean Sea coastline of Turkey, has a sandy beach lying in the north-south direction that has been significantly eroded. Two coastal structures, a breakwater and a groin, both constructed just at the mouths of two fresh water creeks are the main causes of shoreline change in the region, affecting the coastal sediment dynamics. About 60 meters of erosion has been observed between these structures when the present coastline is compared with the coastline in 1945. Being an important recreational destination in the Gökova Specially Protected Area, it is quite essential to stop the coastal erosion problem and to regain the eroded beach for Akyaka. Therefore, in order to understand and identify the coastal dynamic processes and sediment transport characteristics of the region, and thus, the reasons for the beach erosion, a research project, entitled as “Determination of Sediment Transport Rate and Shoreline Changes on Akyaka Coast” and financially supported by The Scientific and Technical Research Council of Turkey, TÜBİTAK, was carried out. For an accurate prediction of sediment transport in a region, as the first step, the wave and current hydrodynamics of the coastal area should be well understood. Therefore, in the mentioned research project, first of all, long-term wind and wave climate and wind induced currents and circulation patterns were studied in the region. Wind and wave statistics were obtained from the wind measurements of Turkish State Meteorological Service at Bodrum meteorological station between the years 1970 and 2011, and the wave characteristics predicted by CEM method for the same period. The current patterns were numerically modelled by three-dimensional baroclinic model, HYDROTAM-3D, which consists of hydrodynamic, transport and turbulence model components. Results of this study have been an important input to understand the coastal sediment dynamics of the region.

Key-Words: - Gökova Bay, hydrodynamics, wind climate, wave climate, modelling, coastal erosion, shoreline change.

1 Introduction
The morphology of the beaches change under the effects of winds, currents and waves, and especially coastal structures. Coastal structures significantly affect the natural balance of sediment transport and cause erosion and shoreline change problems in the coastal areas. Coastal erosion has always been an important issue for engineers. Any long-term deficit in the longshore and/or cross-shore sediment transport budget leads to shoreline changes. Many researchers work on the development of models for the prediction of coastal sediment transport rates and changes in the beach morphology. These models can be analytical, numerical or physical. Whatever the model type is, together with the sediment characteristics and bathymetry, the main data required in sediment transport computations are...
the wind, wave and the corresponding current characteristics of the region, since the causes of the sediment transport are, primarily, the wave-induced currents and the tide/wind induced currents. Therefore, an accurate prediction of sediment transport is possible only if the coastal hydrodynamics of the area is well understood [1].

The knowledge of wind and wave characteristics is essential for almost any engineering activity in coastal waters. In many applications, it is necessary to use long-term wind and wave data. In case of sediment transport computations for instance, analyses of long-term wind and wave statistics are necessary to obtain the parameters required to determine the annual amount of sediment transport. However, in many areas, long-term measurements are not available and it is necessary to use wave prediction models for wave hindcasting [2].

During the past decades, some empirical and numerical models have been developed for wave prediction. Numerical models, which solve the energy balance equation, require abundant bathymetric, meteorological and oceanographic data. In some regions, these data are not available and numerical modeling is both difficult and expensive [2]. Besides, many numerical models have problems in producing accurate results in some coastal areas, such as the Aegean Sea and the Sea of Marmara coasts of Turkey, where the coastal land boundary may not be represented well due to the limitations in computational mesh size. Therefore, in many coastal engineering projects, engineers tend to use simplified empirical wave prediction methods that base on interrelationships between dimensionless parameters. There are several empirical wave prediction methods that have been developed and verified with the measurements in the past decades; Wilson [3], SMB [4], JONSWAP [5], Donelan [6] SPM [7], CEM [8].

In this study, beach of Akyaka in Gökova Bay (city of Mugla) located at the Southern Aegean Sea coastline of Turkey was chosen as the study area. The long-term wind and wave statistics, wind induced currents and current patterns were determined for the area as a part of a project aiming to study the shoreline changes on Akyaka coast [1].

To investigate the long-term wave climate, the wave characteristics of the Bay were estimated by the well known CEM [8] method utilizing the hourly averaged wind data of Bodrum meteorological station.

To investigate the circulations and current pattern in Gökova Bay, three-dimensional hydrodynamic and transport model HYDROTAM-3D has been applied to the coastal area [9]. HYDROTAM-3D is a three dimensional baroclinic numerical model, which consists of hydrodynamic, transport and turbulence model components. It includes wind, tide or density induced currents, water levels, salinity and temperature variations, transport of pollutants, forced flushing like sink or source induced currents. In the hydrodynamic model component, the Navier-Stokes equations are solved with the Boussinesq approximation. A composite finite difference-finite element method is applied to the governing equations. Finite difference method and finite element method are commonly used in various types of problems of computational fluid dynamics Equations are solved numerically by approximating the horizontal gradient terms using a staggered finite difference scheme. In the vertical plane however, the Galerkin method of finite elements is utilized. Water depths are divided into the same number of layers following the bottom topography. At all nodal points, the ratio of the length (thickness) of each element (layer) to the total depth is constant. To increase the vertical resolution, wherever necessary, grid clustering can be applied in the vertical plane. Grids can be concentrated near the bottom, surface, or intermediate layers. The mesh size may be varied in the horizontal plane [10],[11]. The main agent of the circulation is the wind shear in Gökova Bay where the tidal range is only in the order of 25cm. The circulation pattern in the eastern part of Gökova Bay was modeled under the effect of wind shear.

2 Project Area

Gökova Bay is located along the West-East direction, at the Southern Aegean Sea coastline of Turkey. Gökova is one of the first Specially Protected Areas (SPA) of Turkey. Its mathematical coordinates are 28-29 degrees East Longitude and 37-38 degrees North Latitude. Akyaka Beach is located at the East end of the Gökova Bay along the North-South direction and shown in Fig.1. The coastline in year 1945 and the present coastline in year 2010 are given in Fig.2. Today, there exist a groin (G) that is nearly 150 m in length at the south and a breakwater (BW) that is almost 200 m in length at the north of the beach. There are two rivers (A1, A2) with low discharge rates and no sediment loads, discharging into the coastal area. Firstly the breakwater was constructed at the North of the beach to protect the fisherman boats and sand accretion started in the west side of the breakwater. Then groin was constructed at the South of the beach and erosion was started along the North-
South direction of the beach, between the structures. Erosion caused almost 60 m inland movement of the coastline since 1945 (Fig.2 and Fig.3). At the south of the groin there occurs accretion, but since there is a river and boats are entering into this river, there occurs a regular dredging work of sand to prevent the sand deposition. This can be defined as a regular human work performed against the nature.

At the west of the breakwater located at the North of the beach there occurs sand deposition as well, and that sandy beach is used as a municipality public beach. However, Akyaka municipality beach is not able to satisfy the increasing requests especially in the holiday season. Therefore, being an important recreational destination in the Gökova SPA, it is quite essential to stop the coastal erosion problem and to regain the eroded beach for Akyaka.

3 Wind and Wave Climate

In order to understand and identify the coastal dynamic processes and sediment transport characteristics of the region, and thus, the reasons for the beach erosion, a research project, entitled as “Determination of Sediment Transport Rate and Shoreline Changes on Akyaka Coast” and financially supported by The Scientific and Technical Research Council of Turkey, TÜBİTAK, was carried out.

To investigate the sediment transport and shoreline changes in a coastal area, it is necessary to understand the coastal hydrodynamics, wave and current system in the area. Therefore, for the mentioned research project, first of all, long-term wind and wave climate and wind induced currents and circulation patterns were studied in the region.

Firstly, wind characteristics of the area were analyzed. The wind rose, which provides the directional distribution of wind speeds, was obtained using the measured wind data between the years 1970 and 2011 of the State Meteorological Station in Bodrum. Wind rose is given in Fig. 4.

The recorded maximum northerly wind speed is 20.6 m/s. Secondly recorded maximum wind speed is 19.5 m/s blowing from South-south-west (SSW) direction. Effects of westerly winds show an increase in the summer season. Gökova Bay lies in the west-east direction. Due to the location of the study area, the directions for the wind wave growth are in between NNW and S.
Then, the wave parameters, significant wave height ($H_s$) and corresponding wave period ($T_s$), were estimated by CEM method. For this purpose, wind speed measurements were converted to wind speeds at 10 m height and the fetch lengths were determined for the point at 37.04°N and 28.32°E in front of the eroded beach (Table 1). Fetch lengths were determined by cosine average method. For a certain direction, the average of fetch distances in the ±22.5° interval at 7.5° increments was computed and assigned as the fetch length of that direction. For the study area, the directions for wind wave growth which contribute to sediment transport processes are in between NNW and S. Fetch lengths for these directions are given in Table 1.

### Table 1. Fetch lengths for 37.04°N-28.32°E.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Fetch length (km)</th>
<th>Direction</th>
<th>Fetch length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNW</td>
<td>1.5</td>
<td>WSW</td>
<td>76</td>
</tr>
<tr>
<td>NW</td>
<td>2</td>
<td>SW</td>
<td>3.8</td>
</tr>
<tr>
<td>WNW</td>
<td>3.3</td>
<td>SSW</td>
<td>2.5</td>
</tr>
<tr>
<td>W</td>
<td>25</td>
<td>S</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Thus, the long-term wave climate of the area were studied utilizing the wave heights, wave periods and wave directions, estimated from the hourly wind data and fetch lengths by CEM method. Yearly and seasonal wave roses were prepared. The monthly mean significant wave heights were computed as the average of all significant wave heights occurred in a given month during the 40-year period of 1970-2011. The monthly peak wave heights during the same period were collected and the lowest, highest and mean values of those peaks were determined. The relation between the significant wave heights and the wave periods is observed to estimate the range of wave periods associated with a given wave height.

There are various probability distributions used for the long-term wave climate studies. Among them, the log-normal probability distribution which is given by Equation (1) is widely used to represent the durations of exceedences for the significant wave heights from each direction.

$$H_s = A + B \ln(P(>H_s))$$

The graph of significant wave heights, $H_s$ and their exceeding probabilities, $P(>H_s)$ for WSW direction, that is the dominant one for the project area, is given in Fig.6. Together with the WSW direction, for other directions, the log-normal distribution parameters, A and B, and the significant wave height values exceeded for 1 hour, 5 hours and 10 hours in a year are given in Table 2. It is observed in Table 2 that the significant wave heights to be exceeded for 1, 5 and 10 hours in a year for WSW, the dominant wave direction with a fetch length of 76 km, have been estimated as 2.48 m, 2.02 m and 1.83 m, respectively. As a more general conclusion, however, it is seen that, for the directions between W and SW, the waves exceeded for 1 to 10 hours in a year have significant wave height values changing from 2.5 m to 1.5 m. In the other directions, there is a wave height range of about 1.5 m to 1.0 m.

### 4 Wind Induced Circulations

Wind induced water exchange patterns in Gökova Bay were modeled by the three dimensional hydrodynamic transport model HYDROTAM-3D [9]. It is a Geographic Information System (GIS) integrated model. The average steady state circulation patterns in the Bay under the shear forcing of wind blowing from North, West and from South-West, with a speed of 15 m/s are shown in Fig.7, Fig.8 and Fig.9, respectively. It is seen that,
under the effect of southerly winds, in the study area there occur currents from south to north direction whereas under the effect of westerly winds, along the beach, currents from the north meet with currents from the south and they turn towards the deep waters (to the west direction) almost in the middle of the beach. Northerly winds cause a closed clockwise circulation in the Bay and currents along the beach are from north to south. Due to closed circulation pattern under the effect of notherly winds, flushing rate is expected to be low. Current speeds are about 20-35 cm/s.

Table 2. Log-normal distribution parameters, A and B, and $H_s$ values exceeded for 1, 5 and 10 hrs/year for wave propagation directions.

<table>
<thead>
<tr>
<th>Direction</th>
<th>$H_s$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
</tr>
<tr>
<td>NNW</td>
<td>0.128</td>
</tr>
<tr>
<td>NW</td>
<td>0.111</td>
</tr>
<tr>
<td>WNW</td>
<td>-0.050</td>
</tr>
<tr>
<td>W</td>
<td>0.222</td>
</tr>
<tr>
<td>WSW</td>
<td>-0.106</td>
</tr>
<tr>
<td>SW</td>
<td>-0.482</td>
</tr>
<tr>
<td>SSW</td>
<td>-0.214</td>
</tr>
<tr>
<td>S</td>
<td>-0.084</td>
</tr>
</tbody>
</table>

Fig. 7. Average steady state circulation pattern (wind speed 15 m/s, N)

Fig. 8. Average steady state circulation pattern (wind speed 15 m/s, W)

Fig. 6. $H_s$-$P(>H_s)$ graph for WSW direction
Current patterns were also observed seasonally in the study area. Buoys were used to track the sea currents. Some of the monitored path lines of currents during the measurements in the summer (S) (23-29 August 2010) and winter (W) (8-14 March 2010) have been shown in Fig. 10.

During the summer measurements, the prevailing wind direction was in between North-north-west and South-west, with a speed of 3-6 m/s. Surface current speeds were in the order of 10 cm/s and directed from south to north and similar to winter time, they turned towards the west nearly in the middle of the beach.

Numerical model predictions are comparable with the observed current patterns. Therefore, model simulated quite successfully the current system and circulations along the Akyaka Beach.

5 Longshore Sediment Transport Rate

Total and net longshore sediment transport rate and its distribution are crucial for coastal engineering studies. Prediction of longterm coastal line changes, beach response in the vicinity of coastal structures, and sedimentation rates in navigation channels all require accurate estimations of longshore sediment transport rates. The most widely used model for estimating total longshore sediment transport rate is the “CERC” Formula [7] that is based on field measurements and is often applied to calculate the total longshore sediment rate. Accuracy of the CERC formula is believed to be ±30–50 percent under favorable conditions, and several parameters that logically might influence sediment rate are excluded from the formula, such as breaker type and grain size[12]. The model, based on the assumption that the total longshore sediment transport rate is proportional to longshore energy flux, is given as:

\[
I_y = \frac{K}{16\gamma_b^2} \rho g \frac{3}{8} \frac{H_{sb}^2}{\gamma_b} \sin(2\gamma_b)
\]  

where \(I_y\) is the total immersed weight longshore sediment transport rate, \(K\) is an empirical coefficient, \(\rho\) is density of water, \(g\) is acceleration due to gravity, \(H_{sb}\) is significant wave height at breaking, \(\gamma_b\) is the breaker index, and \(\theta_b\) is wave angle at breaking. In
this work the Bailard (1984) equation is applied for K empirical coefficient as:

$$K_{rms} = 0.55 + 2.6\sin^2(2\theta_b) + 0.007\frac{u_{mb}}{w_f}$$  \hspace{1cm} (3)$$

where $K_{rms}$ is the CERC formula coefficient applied to root mean square breaking wave height $H_{rms}$, and has a recommended value of 0.77 [7], $w_f$ is the fall speed of the sediment, and $u_{mb}$ is the maximum oscillatory velocity magnitude at breaking obtained from shallow-water wave theory as:

$$u_{mb} = \frac{\gamma_b}{2} \sqrt{g h_b}$$  \hspace{1cm} (4)$$

The relationship was developed based on fall speeds between 0.025 m/s and 0.205 m/s (corresponding to a median grain size, $d_{50}$, between 0.2 mm and 1.35 mm), breaker angles between 0.2 degrees and 15 degrees, and $u_{mb}$ between 0.33 m/s and 2.83 m/s[12].

Annual longshore sediment transport rates of Akyaka Coastline have been calculated based on longterm wave analysis presented and given in Table 4.

Table 4. Annual longshore sediment transport rates $Q$ (m³/yr)

<table>
<thead>
<tr>
<th>Direction</th>
<th>North to South</th>
<th>South to North</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>-</td>
<td>127544</td>
</tr>
<tr>
<td>SSW</td>
<td>-</td>
<td>248408</td>
</tr>
<tr>
<td>SW</td>
<td>-</td>
<td>231353</td>
</tr>
<tr>
<td>WSW</td>
<td>89924</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>135104</td>
<td></td>
</tr>
<tr>
<td>WNW</td>
<td>745739</td>
<td></td>
</tr>
<tr>
<td>NW</td>
<td>1296511</td>
<td></td>
</tr>
<tr>
<td>NWW</td>
<td>539165</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2716520</td>
<td>697229</td>
</tr>
<tr>
<td>Net</td>
<td>2019291</td>
<td></td>
</tr>
<tr>
<td>Gross</td>
<td>3413749</td>
<td></td>
</tr>
</tbody>
</table>

6 Conclusion
The morphology of the beaches changes under the effects of coastal structures, wind, current and waves. Coastal structures significantly affect the natural balance of sediment transport in the coastal areas. To investigate the sediment transport and shoreline changes, it is necessary to well understand the coastal hydrodynamics, wave and current system in the area.

Therefore, the long-term wind and wave climate and wind induced currents and circulation patterns were studied along Akyaka coast in Gökova Bay. Wind statistics were obtained from the wind measurements of Turkish State Meteorological Service at Bodrum meteorological station between the years 1979 and 2011. For the wave statistics, the wave parameters predicted by CEM method for the same period, were utilized. The wind-induced current patterns were numerically modeled by the three-dimensional baroclinic model, HYDROTAM-3D. It is a Geographic Information Systems (GIS) integrated three-dimensional baroclinic numerical model that has been developed to simulate the waves, hydrodynamic and transport processes in coastal waters.

Prevailing wind direction for the area is north. For the flushing of the Bay, however, westerly winds that cause strong currents towards the open sea, are significant. Dominant wave direction is WSW with a fetch length of 76 km. The significant wave height values to be exceeded for 1, 5 and 10 hours in a year have been estimated as 2.48 m, 2.02 m and 1.83 m, respectively. Wind-induced currents simulated by the numerical model HYDROTAM-3D in the study area have shown that, under the effect of south-west winds (15m/s), there occur currents from south to north direction whereas under the effect of westerly winds (15m/s), along the beach, currents from the north meet with currents from the south and turn together towards west direction to deeper waters almost in the middle of the beach. For these 15 m/s wind speeds, current speed is estimated as about 20-35 cm/s.

Results of this study have been an important input to understand the coastal sediment dynamics of the region. The breakwater (BW) prevents sediment to move from west to east, and from north to south, so causes erosion along the beach lying in the north-south direction and also the groin (G) prevents sediments to move from south to north, and therefore causes a further increase in the erosion.

Acknowledgement
Authors would like to thank The Scientific and Technical Research Council of Turkey, TÜBİTAK, for financial support to the research project entitled as “Determination of Sediment Transport Rate and Shoreline Changes on Akyaka Coast.”
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