COASTAL HYDRODYNAMICS FEATURES. WATER WAVES AND CURRENTS IN THE COASTAL ENVIRONMENT, IMPORTANCE OF HYDRODYNAMIC MODELS IN THE FRAMEWORK OF ENVIRONMENTAL IMPACT ASSESSMENT.

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1. Meteorological aspects

1.1 General remarks

The coast is the boundary between land and sea. The different properties concerning heat absorption by ground and water give rise to high gradients of temperature and humidity in the coastal regions. These features are typically unstable, and such instability processes produce eddies. Unstable flows may evolve radically, changing both their structure and dynamic balance from those that existed in the original situations. For example, our weather is dominated by high and low pressure systems which are manifestations of instabilities of the flow driven by the pole-equator temperature variation in the atmosphere. The coastal environment is therefore a very important and delicate system.

1. Meteorological aspects

1.2 The weather in the Mediterranean region

Being located at mid latitude, the Mediterranean Sea is characterized by strong seasonal variability and, typically, by synoptic weather variations (time scale of the order of 100 hours), modulated by the seasonal signal. High frequency synoptic variations are associated with passages of mid-latitude pressure lows related to the baroclinic instability of the planetary circulation. The passage of a mid-latitude low results in a change of the wind field, turning from southerly wind at the front side of the cyclone to northerly winds at the rear part of it. Such change typically takes place on a time scale of a week and mainly happens in winter, when the belt of the westerlies lies over the Mediterranean area.

1. Meteorological aspects

In summer, the westerly belt migrates northward and the meteorological conditions are determined primarily by the Azores anticyclone and the low pressure system over Asia. The weather is stable with weak northwesterly winds blowing between those two major structures and are prevalent over the open-sea areas. At the same time, the coastal regions are subject to the diurnal sea-breeze regime, in which the wind vector rotates daily predominantly in a clockwise direction.

1.3 Sea-wind interaction

Wind is one of the most important mechanical forcing source; wave generation is the most common, well known result of sea-wind interaction, but also currents can be enhanced by wind.

1. Meteorological aspects

For example, winds blowing from land typically give rise to coastal upwelling and to a corresponding offshore downwelling, by means of the so-called “driven cavity” mechanism (fig.1).

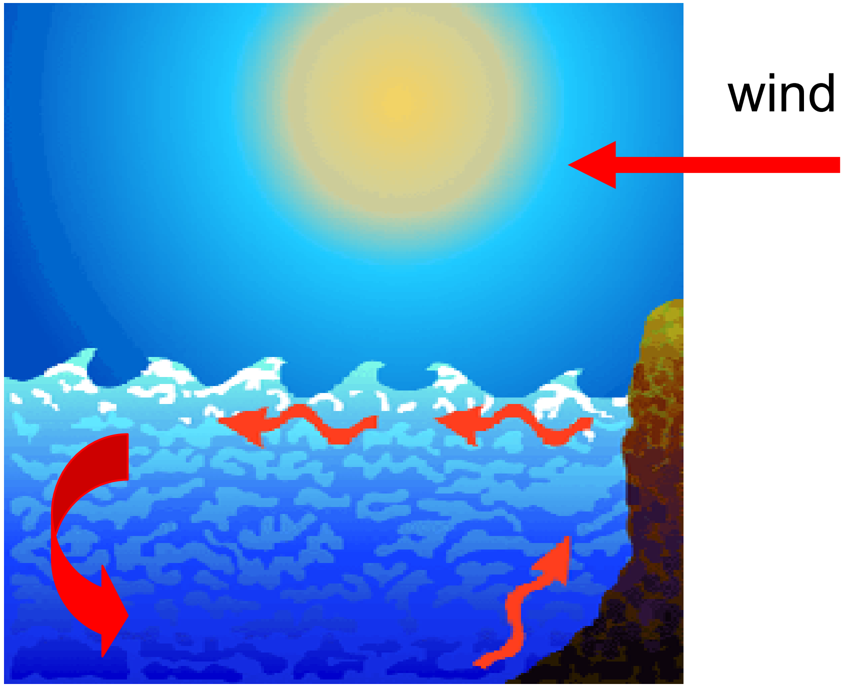

Figure 1: Wind-induced circulation.

1. Meteorological aspects

Furthermore, wind forcing gives rise to thermodynamic features, e. g. the air-sea heat flux generated by cooling and evaporation from the sea surface. Cold and dry continental air is particularly efficient from this point of view. Basically, water density increase at the sea surface is a very important consequence of sea-wind interaction, since it enhances vertical motions with significant effects on the distribution of nutrients and pollutants in the water column.

The aim of these short notes is to point out the importance of wind forcing in the coastal environment. Indeed, correct coastal zone management cannot be performed without sufficient information related to wind.

2. Shallow water hydrodynamics: currents

2.1 General remarks

The conventional division of flows into currents and waves is adopted, though currents in the sea are related to surface gradients and, on the other hand, waves are related to flows, characterized by their typical velocity fields. Moreover, waves and currents interact and, in shallow waters, waves break generating currents.

In both cases, water is typically considered incompressible, and the main problem in performing accurate simulations of costal flows is turbulence modeling. Indeed, flows are typically classified into two broad categories, laminar and turbulent flows. Turbulence in fluids gives rise to mixing action throughout the flow field due to eddies of various scales.

2. Shallow water hydrodynamics: currents

The parameter relating the flow conditions to the flow category is the Reynolds number, defined as:

$$\mathrm{Re} = \frac{Uh}{\nu}$$

with U characteristic velocity, h water depth and ν kinematic viscosity. In free surface flows, the laminar condition can be observed only for very low Reynolds numbers ($Re<500$ can be adopted), whereas in coastal engineering problems the Reynolds number is typically $>10^5$. Coastal flows are indeed always turbulent, and need in principle a very fine computational grid to be accurately simulated, in order to describe all the generated eddies. In fact, in 3D flows the dissipation mechanism implies, via the energy cascade, the generation of small eddies (non-dimensional length scale of the order $\mathrm{Re}^{-3/4}$) which cannot be, in practice, simulated. Turbulence modeling is in fact adopted, in order to avoid the simulation of very small scale phenomena.

2. Shallow water hydrodynamics: currents

2.2 Shallow flows

The flows that occur most commonly in coastal areas are nearly horizontal, since the vertical scale is much smaller than the horizontal one, and are subject to negligible accelerations in the vertical direction. Pressure distribution is therefore nearly hydrostatic. These kinds of fluid motions, called shallow flows, behave like two-dimensional ones, from the turbulence dynamics point of view. In two-dimensional flows the energy cascade is inverse: the energy passes from the small scales to the large ones. This phenomenon is called back scatter, and gives rise to the generation of stable, large scale vortices. Turbulence modeling in shallows flows takes into account this property.

2. Shallow water hydrodynamics: currents

2.3 Barotropic flows

The definition of barotropic flow is:

$$\nabla p \times \nabla \rho = 0$$

in which p is the pressure and ρ is the fluid density: this means that in barotropic flows, the pressure and density gradients are parallel. In other words, density variations are related to compressibility only. In the present hydrodynamics framework, water can be considered incompressible, and this definition implies density to be constant in time and space. In the coastal environment, barotropic flows result from tide, wind and wave forcing. In fig.2 a snapshot of barotropic jet evolution is shown: in this case, the mixing process of the jet is only concerned to vorticity, related to Kelvin-Helmoltz instability.

2. Shallow water hydrodynamics: currents

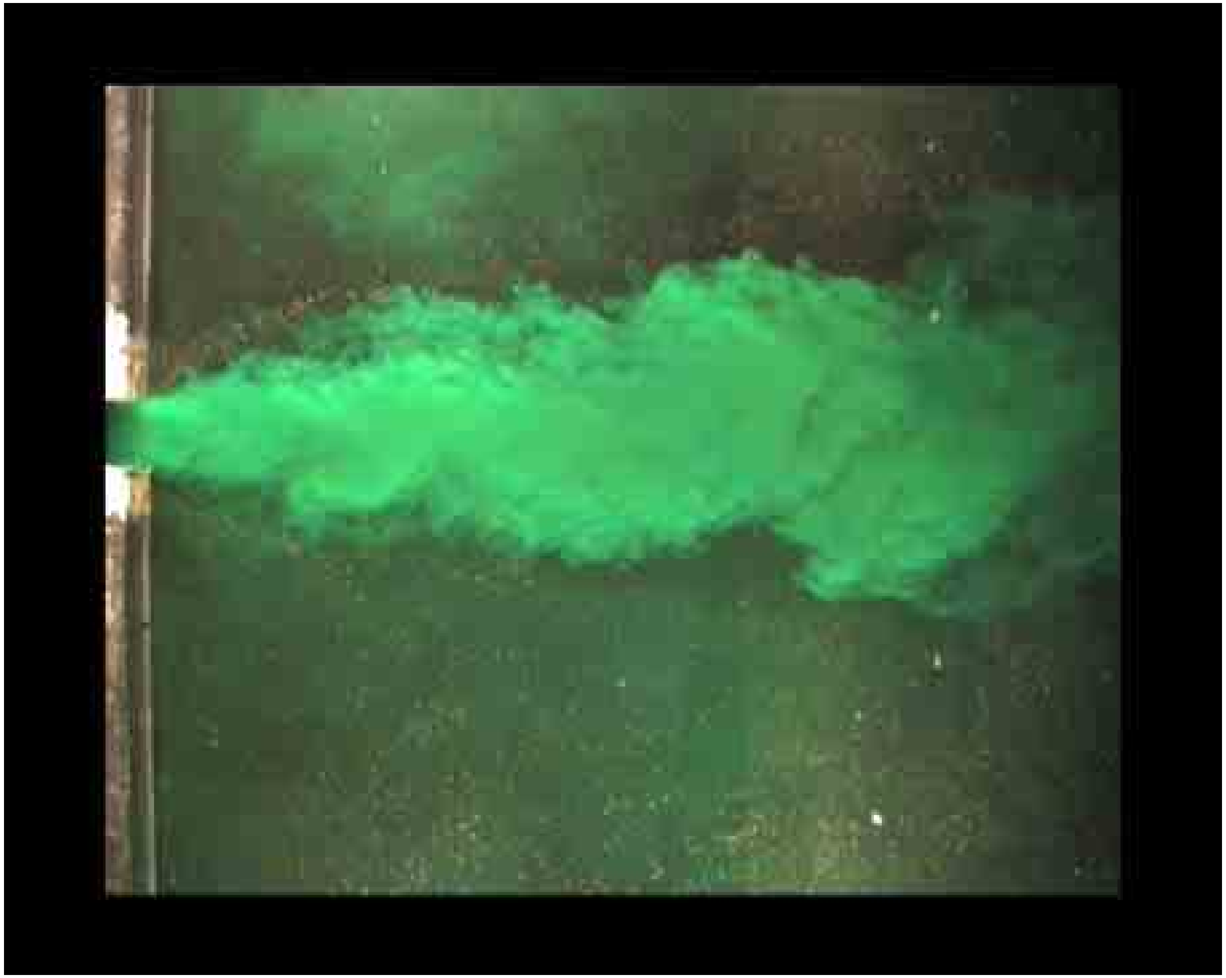

Figure 2: Barotropic jet

2. Shallow water hydrodynamics: currents

2.4 Baroclinic flows

The definition of baroclinic flow is:

$$\nabla p \times \nabla \rho \neq 0$$

In baroclinic flows, pressure and density gradients are not parallel and density variations within the fluid are not only related to compressibility. In the incompressible case, a baroclinic flow is generated by the mixing process between fluids of different densities. Therefore, this kind of flow is strongly characterized by buoyancy. In the coastal environment, the most significant forcing for baroclinic flows is river runoff. At a river mouth, the fresh water comes in contact with salt water at a different temperature, and and the resulting difference in density gives rise to buoyancy effects (see fig.3).

2. Shallow water hydrodynamics: currents

Figure 3: Baroclinic jet.

2. Shallow water hydrodynamics: currents

River flows generate storage of fresh waters in coastal regions; in winter, the coldness of these waters enhances vertical mixing and river plumes remain confined to shore, while in summer their buoyancy allows them to spread much further offshore. The presence of stratification in coastal regions is very important from water quality point of view. According to European guidelines, along the Italian coast the Brunt-Vajsala parameter (see fig.4) has been obtained, by measured field data:

$$N = \sqrt{\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}}$$

It represents the frequency of oscillation of a fluid particle, removed from its equilibrium position, under the effect of the buoyancy restoring force. High values of the parameter indicate stability of the water column (mixing processes inhibited).

2. Shallow water hydrodynamics: currents

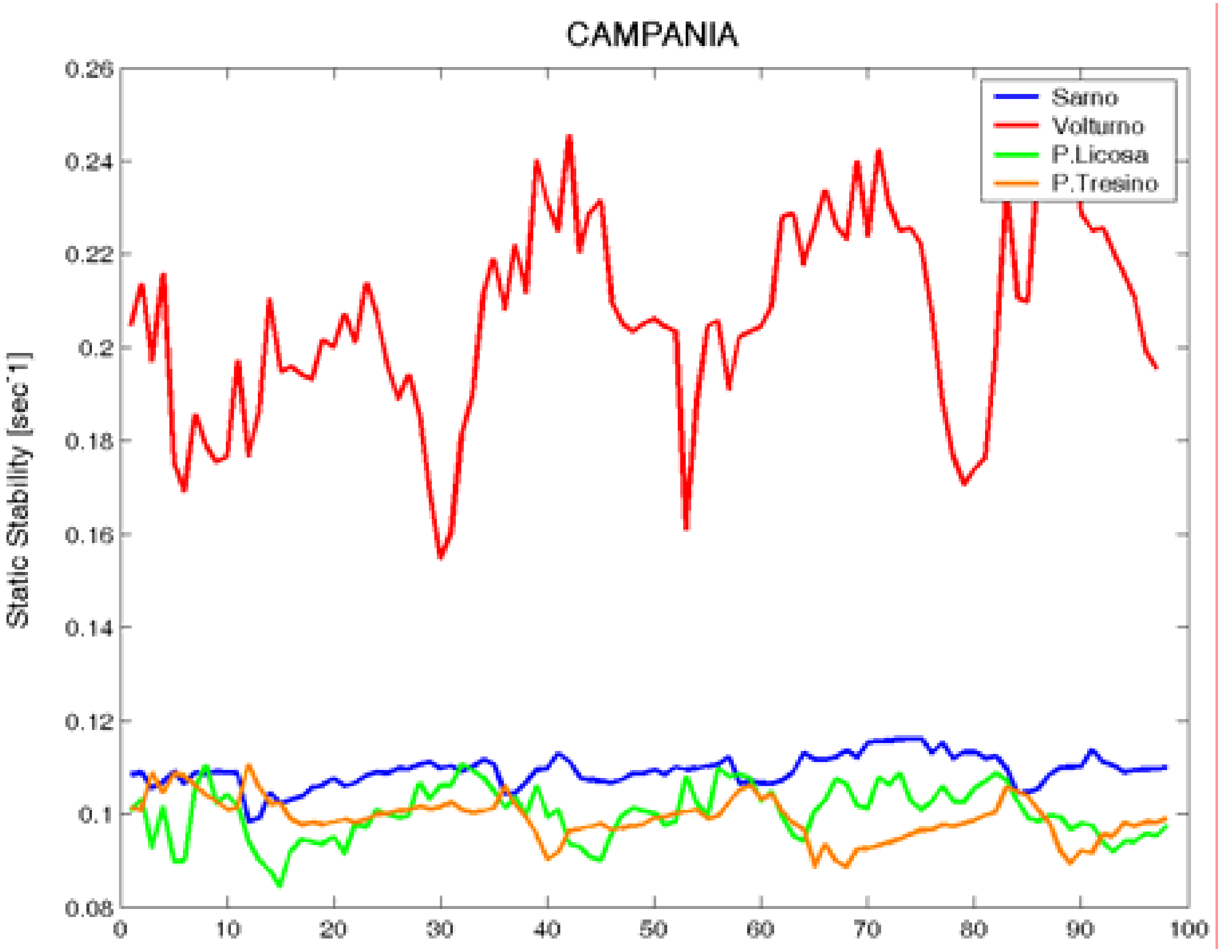

Figure 4: Time history of Brunt-Vajsala parameter in Campania region (Tyrrhenian Sea, Italy)

3. Shallow water hydrodynamics: waves

3.1 General remarks

Water waves represent a very efficient mechanical energy storage, charged by wind. These free surface perturbations, when interacting with the coast, break and give rise to violent motion, characterized by strong mixing (see fig.5) and generation of longshore currents, producing coast erosion/accretion.

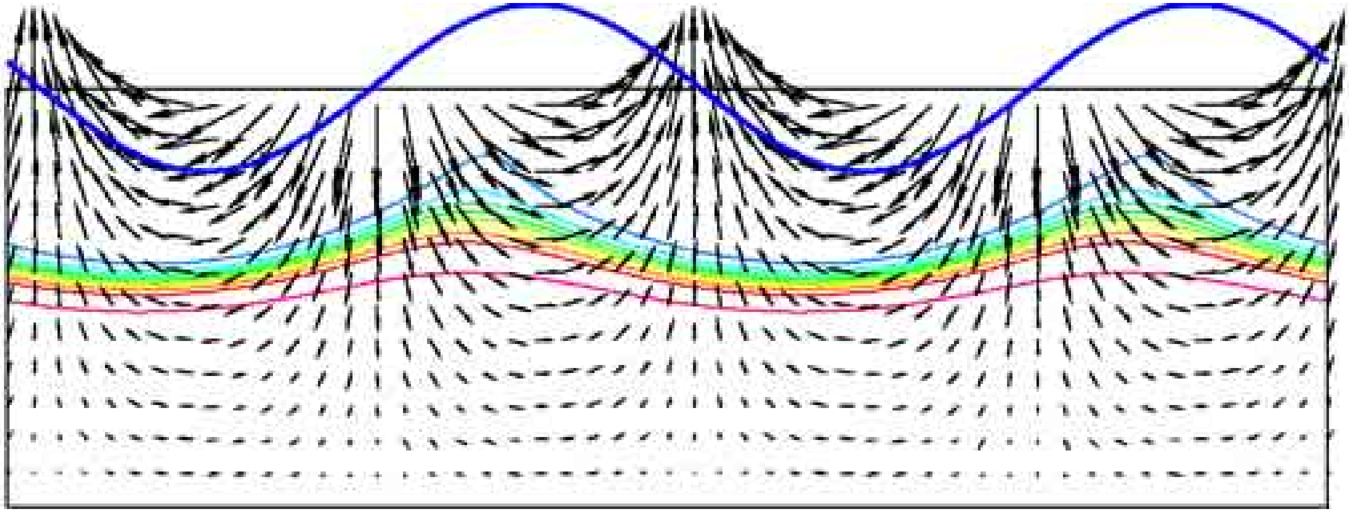

Figure 5: Wave-induced mixing in the water column.

3. Shallow water hydrodynamics: waves

Waves can be used for power generation, are cause of hindrance and danger for navigation. When their amplitude is large (see fig.6), waves can also create damage to coastal structures.

Figure 6: Overtopping of Pescara breakwater by a 4.5 m amplitude wave.

3. Shallow water hydrodynamics: waves

3.2 Water waves

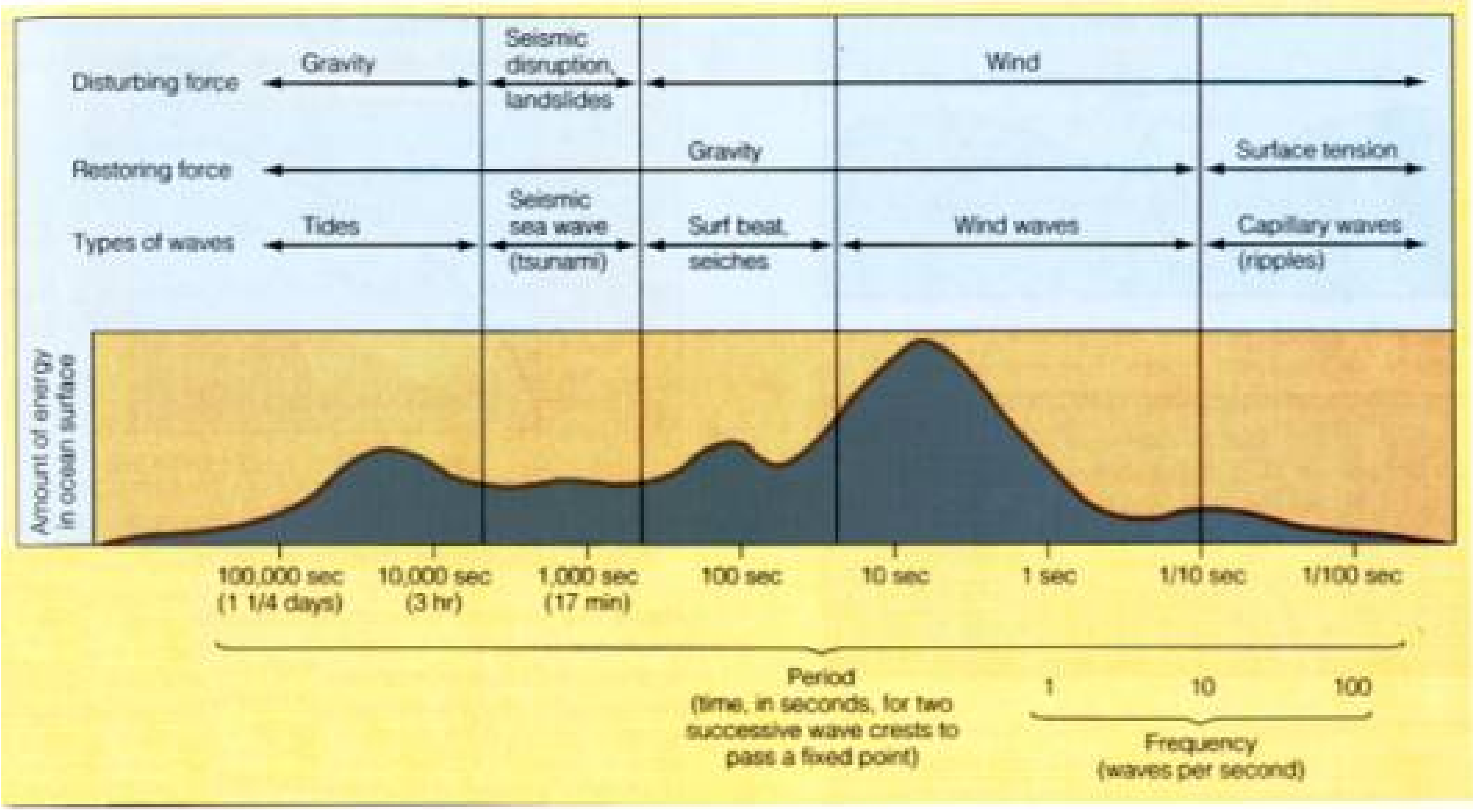

Figure 7: Classification of water waves.

3. Shallow water hydrodynamics: waves

Figure 7 shows the most common types of water waves. All of them are characterized by dispersion, unlike, for example, sound waves. In the linear case the dispersion law can be written as (c wave speed, g gravity acceleration, k wave number, h water depth) :

deep waters (short waves) $c = \sqrt{\frac{g}{k}}$

intermediate waters $c = \sqrt{\frac{g}{k}\tanh(kh)}$

shallow waters (long waves) $c = \sqrt{gh}$

It is worth noticing that: (i) in deep waters the wave speed is independent on h and (ii) in shallow waters it is independent on k. That is, long waves propagate in shallow waters (<u>if h=const.</u>) with constant speed, like sound waves.

3. Shallow water hydrodynamics: waves

3.2.1 Capillary waves

Capillary waves are very short free surface ripples and behave as short waves in deep waters. Driven by surface tension, are relevant at very small scales only (of the order of a few cm). However, in the wind wave generation mechanism they play a significant role: at the 1st stage, very short waves are generated by Kelvin Helmoltz instability; then, wave energy transfers to large scales (downshifting) and, eventually, long waves grow up.

3.2.2 Wind waves

These waves are the most common in the sea. Their characteristics (period, amplitude) are strongly related to the length scale of the stretch of water in which are generated by wind. According to wave length and water depth, they can behave both as short waves in deep waters and long waves in shallow waters.

3. Shallow water hydrodynamics: waves

3.2.3 Seiches and surf beat

These long period (about 100 sec) waves are related, respectively, to standing wave oscillations (generated e.g. by atmospheric pressure differences or by abrupt in or out flow of large quantities of water) and to periodic modulations in the swell envelope, due to nonlinear effects.

3.2.4 Tsunami

These waves are generated by landslides or seismic disruption, and can be characterized by a very high energy content.

3.2.5 Tides

Finally, the longest water waves which can be found in the sea are generated by the attraction of celestial bodies.

4. Wave breaking, wave-current interaction

Figure 8: Wave breaking on a beach.

When wave steepness becomes too high and/or water depth becomes too low, waves become unstable and break (fig.8).

4. Wave breaking, wave-current interaction

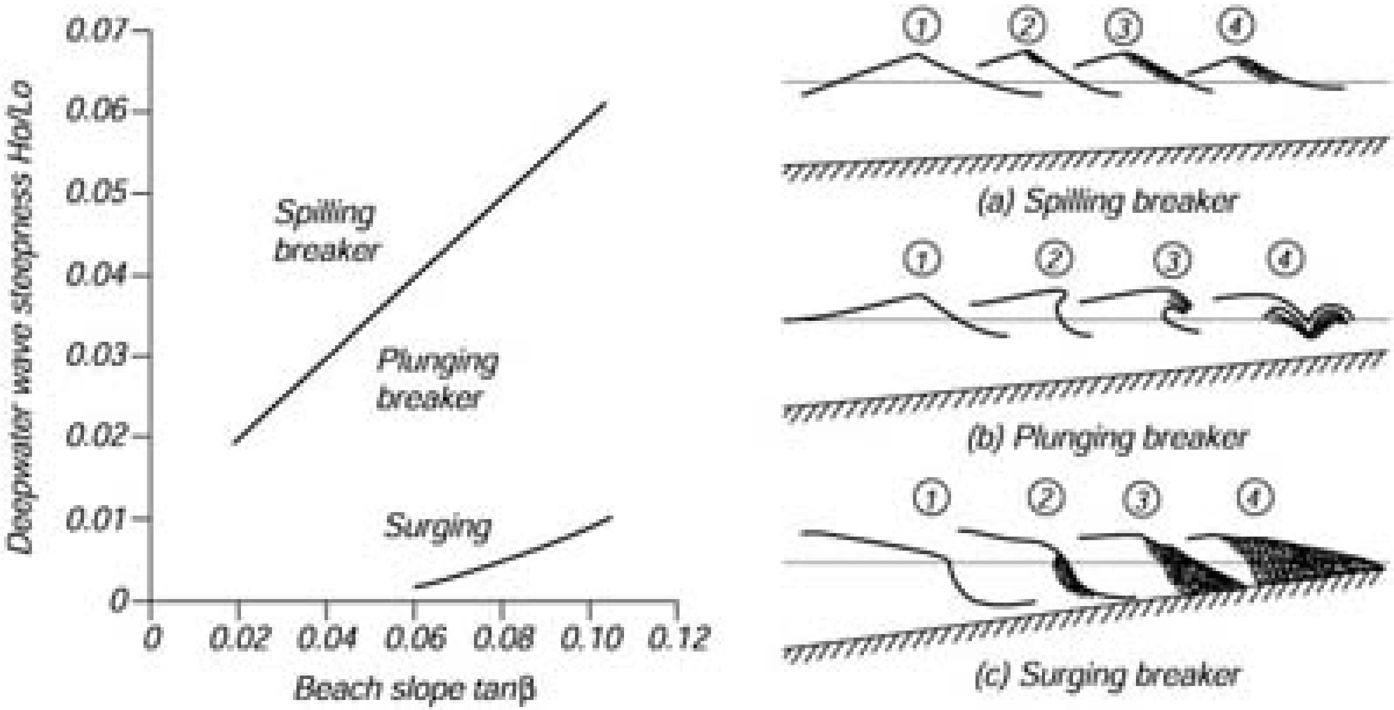

Figure 9: Breakers.

Breaking can occur in a gentle fashion (spilling, that can also happen in deep waters) or in a violent way (plunging, typical of shallow waters). When the slope is very steep the wave does not actually break. Instead, it rolls onto the steep beach (surging).

4. Wave breaking, wave-current interaction

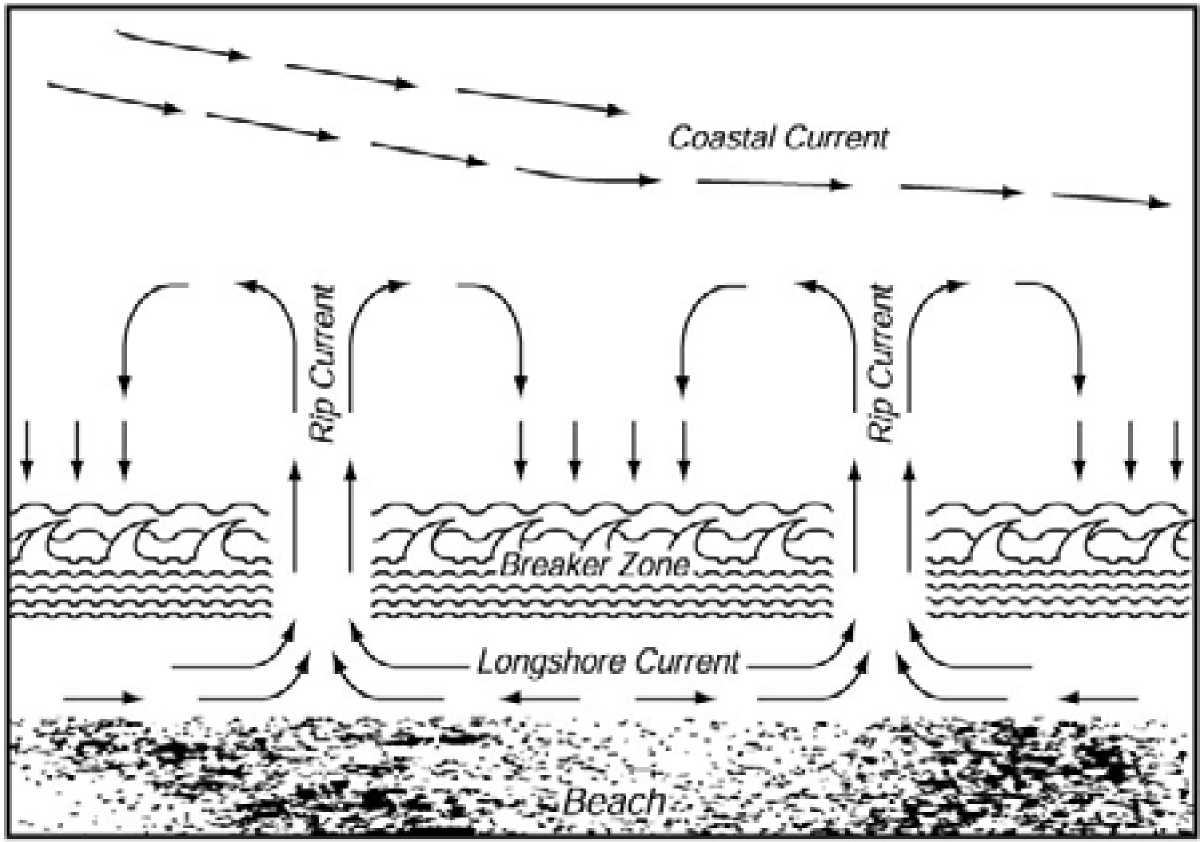

Figure 10: Wave breaking effects along the coast.

4. Wave breaking, wave-current interaction

In any case, breaking is a mechanism in which water particles collapse from wave crest to wave through, and this flow occurs in the same direction of wave propagation. In other words, part of the wave energy is used to generate a turbulent current. As a result of this process, the wave length increases (downshifting).

On the other hand, when waves interact with currents flowing in the same direction as the waves, the currents cause the waves to lengthen and decrease in height, while currents opposing the waves cause them to become shorter and higher. Fig.11 shows the effects of the described phenomena: sailing boats experience wave steepness in Pescara channel harbor (Adriatic Sea, Italy).

4. Wave breaking, wave-current interaction

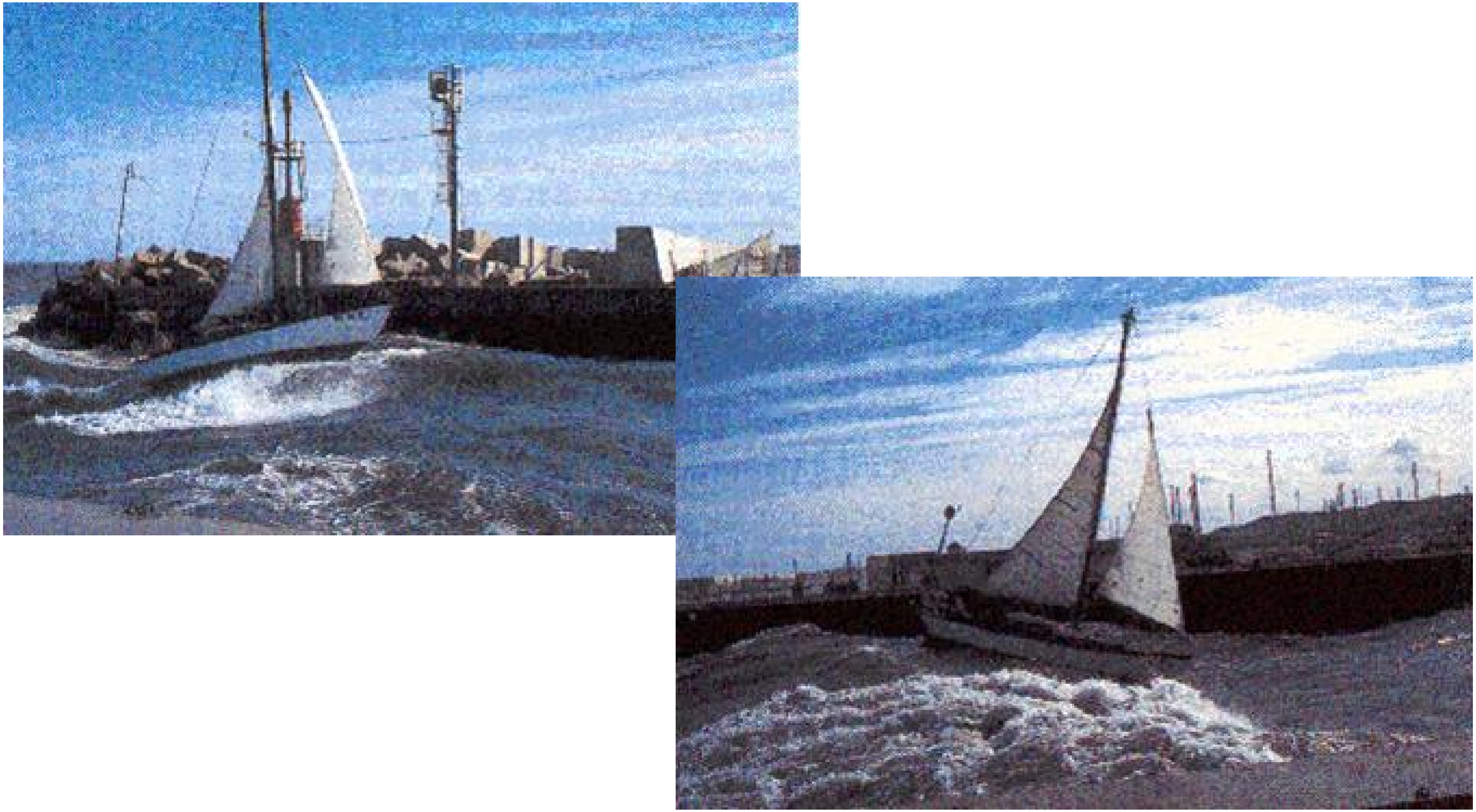

Figure 11: Wave-current interaction in a channel harbour.