Chapter 7
Lithodynamics of the Coastal Zone

Ruben D. Kosyan and Boris V. Divinskiy

Abstract The history of human civilization is directly linked to the social and technological state of the access to the sea, which ensured two very important aspects of the activity: trade and access to resources. On the other hand, the economic development of the shoreline depends on the protection from adverse natural processes such as storm waves or sediment motions. The development of coastal infrastructure is related not only to the current state of economy but also to its future state. The integration of accumulated knowledge led us to the creation of the lithodynamics science, which comprehensively studies the dynamics of the coastal zone. Despite the obvious successes, some problems of the coastal zone dynamics remain that require a deeper physical understanding. This Chapter describes the main problems remaining in the investigation of coastal zones and gives an analysis of poorly studied physical processes and mechanisms.

Keywords Lithodynamics • Coastal zone • Suspended sediment • Hydrogenic processes • Lithodynamic systems • Coastal zone hydrodynamics

7.1 The Role of Coastal Zones in Human Life

The coastal zone is a boundary region of the oceanic basin. It plays a special role in the dynamics of the World Ocean. The coastal zone is characterized by morphological peculiarities: shallow depths and steep slopes of the bottom topography, which determine its leading role in the dynamics of wind waves. The waves absorb enormous energy from wind and spend it generally in the coastal zone. The appearance of a number of specific hydrodynamic, lythodynamic, and morphodynamic processes follows from the wave energy dissipation. Strong and very variable currents develop here. Complex systems of intense water exchange are generated. Underwater ridges are formed and intensely move. A set of processes of coastal transformation appears. Specific peculiarity of the coastal zone is

R.D. Kosyan (✉) • B.V. Divinskiy
The Southern Branch of the P.P.Shirshov Institute of Oceanology, RAS, Prostornaya, 1g, 353467 Gelendzhik, Krasnodar, Russia
e-mail: rkosyan@hotmail.com; divin@ocean.ru

C.W. Finkl, C. Makowski (eds.), *Diversity in Coastal Marine Sciences*, Coastal Research Library 23, DOI 10.1007/978-3-319-57577-3_7

associated with the fact that dynamic processes are interrelated, and individual processes are included into this complex in various combinations.

From the point of view of a specialist involved in the problems of the deep ocean dynamics, the coastal zone is very interesting as a study region, in which many dynamic processes, characteristic of the oceanic basin, are presented in the concentrated form. The dynamic processes occur most intensely, and usually, their observation can be technically organized more easily.

It is likely that the peculiarities of the coastal zone are most clearly distinguished in the dynamics of the bottom deposits. Fragmentary material is continuously transported from land, which is later transformed; as a result, the particles are either transformed or buried here, or transported to the other regions of the ocean. Thus, the coastal zone is a filter for the material transported from land on its way to the oceanic depths.

The practical considerations, which focus the attention of scholars and engineers on this region of the oceanic basin, are not less important. For a long time already, the coastal zone has been a region of intense economical expansion whose development rate strongly increased in the last decades; it is clear that the process will become more intense in the nearest future. Of course, the economical development spreads now to the deeper layers of the sea, which are not related to the coastal zone. However, it is clear that this zone will remain the most important part of the oceanic basin for humanity.

Investigations of the coastal zone dynamics were initiated due to the interest to sea waves among the navigators. Indeed, sea waves and especially the waves in the coastal regions of the sea are hazards to seafarers. It was necessary to protect specific regions of the coastal zone, so that the ships could approach the shore for contacting the land in any weather and hide there from the storms. Ports with protection constructions at the open shores were built in the places that did not have natural harbors.

As the ship draughts increased, the ancient seafarers faced the problem of sediment accumulation in natural harbors (for example, in the mouths of rivers). This problem became especially important during the first attempts to build ports over open shallow water coastal zones. Hence, the knowledge of the natural regime of the coastal zones became necessary as well as foreseeing the processes, which would be caused by the constructions. It is likely that already in the middle ages the works were initiated to protect the shores from destruction by the sea, which followed the first constructions of ports. As the cities, especially the port cities, increased in size and lifetime, and cost of the constructions increased, a necessity appeared to protect the basements of the sea shores. In recent years, the tonnage of ships has increased significantly, which leads to the increase in the depth and other sizes of the channels allowing the ships to approach the ports.

Excavation of mineral resources from the sea bottom is a very important problem. It is related to the problems of differentiating the loose material and deposits of particles with specific properties. Large-scale excavation of sand, shells, pebbles, and gravel for construction and other purposes is a hazard to the coastal regime and can lead to undesirable consequences. However, a specific amount of the excavation of these materials from the sea is frequently quite admissible, which is important when other sources are not available on land. Therefore, a scientific approach to the solution of the problems of the possibility, locations, and admissible amounts of such material is important.

Using of the sea as the source for food resources led to the development of special aquaculture farms in the coastal locations, which is most productive for cultivation species of marine fauna.

Solution of the problems related to the ecology of the coastal zone is impossible without the data on the hydrodynamic transport of sedimentation. Solid particles transported by water flows may become absorbers of the chemical and radiation pollution.

The role of the coastal zone in the human life and vital activity is not limited by these examples. They are given here only to illustrate the many-sided nature and importance of our interests in this part of the World Ocean. At the same time, the anthropogenic factor becomes one of the most important in the dynamics of the coastal zone. In addition, this part of the ocean is most vulnerable and sensitive to various forcing, and the problem of protecting and conservation of the environment is most pressing here. It becomes clear that the solution of the problem of the possibilities and methods of the technical expansion should be preceded by a forecast of its consequences. Such a forecast can be carried out on the basis of specific knowledge and thorough analysis of the dynamic processes in the coastal zone.

7.2 Lithodynamics of the Coastal Zone

In the last decades such terms as “lithodynamics”, “lithodynamic processes”, “lithodynamic research” have become more and more spread in the hydrotechnical, oceanographic, geo-morphological and geological publications. These terms define the phenomena and research of sediment transport along the Earth surface due to the exogenous factors and gravity. In the oceanographic science, these terms are the most accustomed owing to the growing interest to such researches in the ocean. Practical significance of these processes follows from the extensive human activity on the sea floor from the coastal zone to the continental slope. Special departments were organized in a number of scientific and design institutes to carry out lithodynamic research considered as one of the major problems in the study of the world ocean.

Nowadays, the Earth’s landscapes are involved into the lithodynamic research. These investigations are carried out by various specialists: geologists, hydrologists, hydrotechnicians, geomorphologists, and lithologists mostly with the aim of solving particular applied or scientific problems. A number of monographs appeared which are fully or partially devoted to the lithodynamics of some landscapes deserts, fluvial valleys, sea coastal zone, mountain slopes. Until very recently, research of fluvial processes has been most successful and intense.

Vladimir Longinov was the first to formulate the goals of the new geophysical field in 1954, which he called "lithodynamics" (Longinov 1954). He believed that this term was the most successful in relation to the sense of the new science. In his "Essays" (Longinov 1973), he formulated in detail the main aspects of this oceanographic field and gave a list of the existing concepts about the ocean lithodynamics and the main goals of its future development. He emphasized that according to its content and general goals, lithodynamics can be related to the geophysical disciplines, but owing to the variety of requirements to the lithodynamic investigations, they were conducted within various scientific fields: lithology, geomorphology, dynamical geology, oceanography, hydrology of land, and many other applied sciences (Longinov 1973; Longinov and Pykhov 1981; Longinov and Kosyan 1994).

Lithodynamic problems can be divided into the general geophysical and particular applied goals related to the interests of the other Earth sciences. Lithodynamics is related to a field of geophysics, but owing to the complexity of the processes and its multidisciplinary character, these researches are carried out at the boundary of different disciplines.

V.V. Longinov divided the lithodynamic problems into engineering, geological, geomorphlogical, biological, etc. The most important in the engineering aspect are:

- Distinguishing local differential time dependencies of matter transport on the factors that determine this transport;
- Transition from one or another expression for the sediment transport as functions of the determined parameters to the expressions for variations in topography;
- Establishing correlations between the engineering properties of the formed deposits, their mobility and character of their motion;
- Distinguishing the equilibrium conditions between different forms of material accumulation.

In the biological aspect, one can distinguish the problem of instantaneous and time average local mobility of deposits (its intensity) and establishing the degree of stability of variations in the composition and character of deposits as the most important ecological factors.

Investigation of the physical, and first of all of the dynamic processes in the contact zone between the lithosphere and hydrosphere or atmosphere is the basis of the lithodynamic research. As we investigate the local dynamic regularities in this contact zone it becomes possible to know how they spread in time and surface of the lithosphere based on the lithological and geophysical studies of the surface deposit column. Thus, the dynamics of the contact zone should be considered the physical basis of lithodynamics.

To evaluate borders of the contact zone, one should consider it as an area where interaction of sediment, water, and immobile floor produces dissipation of mechanical energy of the moving sediments and water.

Two main types of motion can be distinguished in the group of hydrogenic processes:

- the transport of bottom sediments by traction or rolling, and by saltation. In the gravitational transport, one can differentiate sediment collapse and talus on the one hand, and slide on the other. Movements of the first type are accompanied by the interaction between solid particles and underlying surface, processes of shifts of the whole mass of particles are typical of slides and similar phenomena-debris flows and mud flows;
- the transport of suspended particles, which can be regarded as a type of viscous liquid flow, strongly depends on the flow density. This relation is so strong that one can talk about qualitatively different processes of suspension flow motion with a high and low density.

There are lithodynamic processes in the world ocean, which are not involved in the dynamics of the bottom contact zone and occur beyond it. These processes are the horizontal and vertical sediment transports occurring in the entire water column and its top layers. These motions, as a rule, involve fine grained terrigenous particles and biogenic material into the water column. The inflow of sediment load brought by the rivers can occur outside the contact zone even on the continental shelf, while in the areas with greater water depths, accumulations of such particles with fine grain sediments brought by suspension flows can form nepheloid clouds, migrating several hundred meters along the isobaths and gradually descending towards the continental slope. Continuous deposition of the skeletons of sea microorganisms, being a lithodynamic process itself, is accompanied by their constant transport along the sea floor. Although this process is not related directly to the flow of the terrigenous material, it forms sediments, which together with the terrigenous component take part in the lithodynamic processes of the contact zone. The pathway of fine grained terrigenous material towards the contact zone is even more complicated, because this material is first absorbed by the living organisms and then excreted by them with changed mechanical and hydraulic properties. Coarse grained material driven by the ice is sometimes transported into the contact zone. Regularities of these migrations differ greatly from the regularities of the contact zone dynamics, but their participation in the general lithodynamic process of the ocean is evident and their existence should not be ignored when developing the regional and global models of ocean lithodynamics.

The sediment transport on the surface of the lithosphere causes a number of phenomena, which follow the laws dictated by the water transport. The most essential of these phenomena is sediment differentiation according to its hydraulic properties and topography variations related to the changing volume of the clastic material moving towards the contact zone. On the other hand, migration of sediment is accompanied by numerous phenomena, which are not directly related to the mechanics and energies of the lithodynamic processes but influence them greatly. These processes include coagulation of fine grained particles, chemical and thermal weathering of rocks, which contribute to their subsequent destruction and mobilization by water flows, as well as the motion of organisms on the ocean floor and in the water, causing transport and transformation of fine grained sediments. These phenomena are not caused by lithodynamic processes and do not follow their regularities but should be also considered in the lithodynamic research. Investigation of such sediment transport consequences as its differentiation according to the mineral composition or formation of definite sediment textures and structures should not be regarded as an object of lithodynamics, though their understanding requires the knowledge of the regularities of the contact zone dynamics. Thus, the major object of lithodynamics is to study the process of transport itself rather than the analysis of migrating sediments or resulting sediment forms. Morphodynamic phenomena and differentiation of sediments according to the hydraulic coarseness are the consequences immediately governed by the regularities of the sediment transport; hence they are related to the secondary lithologic, geomorphologic, and other consequences of the lithodynamic processes.

The regularities of the ocean contact zone dynamics can be used to solve many applied and scientific problems. They include all kinds of engineering problems connected with the dynamics of sediment and topography of shallow depths, protection and reinforcement of coasts, construction of hydrotechnical stations in the near-shore and shelf zones, provision of navigation security, prospecting and exploitation of deposits on the ocean shelf and coastal zones. Understanding the surface sediment accumulation and transport forming the sequence of the ocean floor deposits is most essential at greater depths. It is difficult to have a clear picture of the depositional history and development of the ocean floor without full understanding of the dynamics of these sediments.

Finally, the construction of an overall picture of the sediment transport from the continents to the ocean floor and the creation of a reliable model of all links of global lithodynamic processes are the major tasks of the ocean lithodynamics as a whole.

The whole variety of lithodynamic phenomena and processes in the ocean can be divided into two methodically distinct groups and consequently into two types of models of the systems under study. These models can be conventionally called physico-mathematical and physico-geographical. Investigations of the first group are included into the contents of the dynamics of the oceanic contact zone, while the research complex of the second group represents the subject of the physical geography, which can be called regional lithodynamics of the ocean.

The concept of sediment transport in the ocean as a phenomenon representing the subject of our investigation, should be considered as a starting point for both types of research. The sediment transport is a general concept: it includes overall, unidirectional sediment transport averaged over any given period of time. In accordance with the models of the lithodynamic system, the sediment transport may be also divided into the local and regional. We understand the local transport as the simplest implementation of the processes of unidirectional sediment transport with the shortest averaging time interval (seconds and minutes). The local transport models usually imply a possibility of raising a two-dimensional problem, while transport sections to be modeled are rather short (up to several tens of meters) in accordance with the averaging time intervals. Thus, the regional transport means sediment transport across the regions from 100 m to 100 km long with the averaging time intervals from several hours to several years. Natural regional transports may be measured only very roughly over short sections. When studying the regional transports, researchers rarely undertake direct investigation of the transport processes. Instead, they study its integral consequences and later try to relate them to the energetic, hydrologic, and other integral parameters. The most important parameter of any flow is its discharge, expressed in the units of sediment mass transported in a unit of time through a unit cross-section normal to the general flow direction. The value of the total discharge transport of sediments through a cross-section during the averaging time interval is sometimes used for the regional flows. In geomorphology this total discharge, as applied to the alongshore currents, is called the “power” of the transport. Discharge distribution, normal to the direction of the transport, results in the “cross structure” of the transport, which is of the major importance in many practical cases. We call the combination of sediment transport and the contact zone, in which it moves, a “lithodynamic system”. This system can be hierarchically organized in an order of complication. The initial link of this hierarchy is an elemental system. Only one elemental mechanism of the transport acts in these systems. Uniform systems including only one type of transport: hydrogenic, gravitational, or turbidity current, are the next in the hierarchy. These systems exist in the nature and can be classified according to the parameters of the contact zone topography, sediment nature, water mass regime, etc. Investigation of uniform systems is possible both in the laboratory and field conditions on the specially chosen typical uniform systems. They can be considered as the final stage of research within the dynamics of the contact zone, or dynamics of the local systems. The study of uniform systems in certain natural conditions, which can be referred to as “regional”, begins at this stage. In this aspect one can find non-uniform systems, comprising transports of various types, where various transport mechanisms exist either successively or simultaneously on the given floor area. Regional systems include the individual ocean landscapes and the ocean major regions: shelf, slope, continental rise and abyss, global systems of separate seas and oceans or of their major parts and, finally, general lithodynamic systems of the World Ocean. Real nature conditions, i.e. the environment, in which regional systems are active, should be called a lithodynamic region rather than a contact zone. This definition includes all the factors, causing initiation and development of the regional flows hydrodynamic, geomorphological and lithological, sometimes, anthropogenic.

All investigations of the regional lithodynamic systems can be attributed to the physical geography of the ocean while the dynamics of the contact zone, i.e. the study of elemental and typical uniform systems, should be attributed to the physical research and considered as a branch of physics of the contact zone. Based on this physical aspect we use the theoretical approach and experimental field measurements to study the main regularities of the formation and motion of sediment transport and learn how their dynamics is governed by the factors of contact zone relief, hydrodynamic regime, and floor character. Investigation of the typical uniform systems occupies an intermediate position between the study of the elemental systems and regional lithodynamics. These investigations can be carried out, as mentioned above, both within the dynamics of the contact zone and within the regional lithodynamics of the ocean. Naturally, it is both difficult and unreasonable to draw a sharp distinction between these three methods of investigation. Placing lithodynamics completely into the field of the physical geography, geology or physics would also be unreasonable and not natural. Each of these branches of science considers the same phenomena in the ocean from their viewpoints; they have their own subjects and own tasks of research. Clastic material, undoubtedly, should be studied by marine geology, while its transport is a subject of lithodynamics. At the same time, regional lithodynamic systems are, undoubtedly, the constituent parts of the complexes called ocean or ocean-floor landscapes, and from this point of view these systems should be studied by the physical geography of the ocean. Elucidation of the main regularities of origin, development and movement of sediment transport in the lithodynamic systems is a task of the ocean dynamics of the contact zone, which is a branch of marine physics or geophysics in a broad sense.

Let us return to the description of the main tasks and concepts of the ocean contact zone dynamics or lithodynamics of the local lithodynamic systems. The construction of models of local systems should result in the expression of sediment transport discharge. This expression should be given in a form, suitable for the discharge under given conditions of the contact zone. These conditions include such factors as the nature of the underlying surface, energy parameters and structure of hydrodynamic field for hydrogenic processes, floor gradient and composition of the bottom and moving sediment for suspension flows and gravitational displacements.

The next stage of the investigation of the contact zone lithodynamics is the determination of the influence of unstable environment of the contact zone on transport discharge. At this stage, the main concept of the lithodynamics of any system arises, which is the discharge gradient. The value and sign of the gradient determine the morphologic effect or system performance on the given area and processes of sediment differentiation on the flow route according to the hydraulic coarseness.

If a constant speed is maintained by exogenous forces in a flow, moving above the washed-out floor, this flow becomes saturated with solid load over a part of its route, and during subsequent motion, the interchange between the sediment and the floor occurs, while the load, applied in the saturation area, remains constant. However, even after the saturation the flow still consumes energy to overcome resistance to its motion at a given speed to maintain the entire motion of the solid load. When the energy supply to the flow decreases, the speed becomes slower, negative discharge gradient develops, and a part of sediment is deposited simultaneously with its differentiation in accordance with the hydraulic coarseness. If the energy decrease is smooth, deposition will proceed over some portion of the route until the balance is gained between the consumed and received energies. If the energy supply stops completely or decreases sharply, a local accumulation form will result.

It should be noted that a quantitative solution, which requires the knowledge of the flow discharge parameters, is possible only in rare cases, related to the dynamics of the local systems. In the lithodynamics of the regional systems, it is possible to solve only part of the applied problems with qualitative evaluations or approximate generalized quantitative characteristics.

Referring to the contact zone dynamics, special attention should be paid, besides lithodynamics, to its second part, the hydrodynamics. This part does not play a great role in the analysis of hydrogenic processes but it has its own applied significance, particularly in the coastal dynamics. Elementary and complex hydrodynamic systems can be also distinguished in the hydrodynamics of the contact zone. Finally, hydrodynamics of the contact zone must result in a complete picture of the whole spectrum of speeds in the given dynamic setting in the bottom layers. This picture is necessary for specific reliable computing expressions of the solid load discharge in hydrogenic lithodynamic systems and for the solution of many other problems, related to the physics of the ocean bottom contact zone.

As our knowledge of the contact zone lithodynamics increases, the construction of physical models of increasingly more complex systems becomes possible, though the transition from the models of the local systems to those of the regional systems are yet far from being clear. It is quite possible that the solution of many applied problems of the regional lithodynamics even in the future would require the use of approximate qualitative evaluations and ideas.

Let us discuss some general features of the ocean lithodynamic systems. Comparison of the ocean hydrogenic systems and similar Earth systems shows that they have basic differences. In the fluvial flows on the Earth surface, the water, being an active agent, flows in a restricted channel due to the composite gravity determined by the flow gradient. Thus, a surface water flow eroding its channel is at the same time governed by this channel, and the flow speed depends directly on the properties of this channel. In the hydrogenic ocean flows, the underlying surface "governs" the flow to the extent, to which it (together with the transported sediment) dissipates the energy of the flow. The source of this energy is outside the contact zone and does not depend on the character of the surface underlying the flow. When describing the evolution of the fluvial flows, Velikanov (1948) tried to use a principle of the system's striving for the minimum dissipation of the flow energy, but in the ocean this suggestion is not true, and striving for complete dissipation of the flow energy with the minimum power of dissipation process is most likely the general principle of the development of ocean lithodynamic system. Morphologically this tendency manifests itself in striving for the increase in the energy dissipation and decrease of the gradient, which can be observed when the equilibrium profile is worked out in the coastal zone.

7.3 The Basic Properties of the Coastal Zone Hydrodynamics

Water motion in the coastal zone is determined by external forcing. It is manifested as tidal currents, swell, and wind waves, various kinds of wave currents generated in the wind waves breaking zone as storm surges, and tsunami. Recurrence of these phenomena in the nature and their influence on the underwater slope are different. Tsunami waves and strong storm surges are possible only in the specific coastal regions of the World Ocean, but even here, their recurrence is very low. In the most cases, dynamic processes in the coastal zone of the sea are determined by the surface waves and swell whose velocity fields have a direct impact on the bottom sediments. In addition, during dissipation of the wind waves energy and interaction between these waves and breaking, secondary motions appear in the water: long-period waves, alongshore currents, water circulation in the vertical and horizontal planes whose spatial and temporal scales most likely determine the scales of the morphodynamic elements of underwater slopes and coasts (Kosyan and Pykhov 1991).

Wind is the main energy source of waves, which always blows over the water basins. Parameters of stationary waves are determined by the wind speed, duration of its forcing, and fetch. Wind waves are usually three-dimensional and irregular. After the wind calms or beyond the zone of wind forcing, the waves propagate in the sea in the form of swell; they are characterized by approximately constant period and form.

When waves propagate from the open sea to the coast they reach a point, in which their length becomes shorter than the local depth. From this moment, the waves induce oscillating motions of water near the bottom whose amplitude increases as the waves propagate to shallower depths. Under specific conditions the motion and transport of the bottom sediments particles starts. If the waves propagate not normally to the coast, refraction starts. As a result, they tend to approach the isobaths normally. Deformation of waves occurs simultaneously with refraction: their form and height change. After further deformation the wave breaks, and water motions of various scales are generated as the wave energy dissipates: small-scale turbulence, large-scale eddy motions in the breaking wave, long-period waves, and coastal currents, which determine the intensity and direction of the hydrogenic sediment transport in the surf zone.

Sediment motion in the region offshore the wave breaking zone occurs not only under the wave forcing, but also under the influence of currents of different origin (flood-ebb tides, wind drift, etc.). In the regions, where the velocities of the flood-ebb tidal currents may reach tens of centimeters per second, they can strongly determine the total transport of bottom sediments in the upper region of the shelf (Soulsby 1983). Superposition of surface waves and currents increases intense water motions at the bottom; hence it leads to the increase in the transport of fragmentary material. Beyond the zone of wave breaking, the motion of sediments after its initiation occurs near the bottom; hence, the needs of modeling the hydrogenic transport requires the knowledge of the dynamics of the bottom boundary layer both for the pure wave motion and in the case of joint wave and current forcing.

When surface waves reach shallow depths, oscillatory motions of water at the bottom and bottom friction form the boundary layer. Transformation of sediments motion occurs immediately in the oscillating boundary layer, which is accompanied by the bottom erosion, formation of microforms of bottom topography that actually determine the boundary conditions for modeling of the mass transport of sediments under forcing of sea waves.

7.4 Elementary Hydrogenic Processes

One can distinguish several main elements in the group of hydrogenic displacements of the sedimentary material: initial motion of particles, bottom transport, suspension transport to the ripple and smooth phases of the sediment motion. It was suggested to call the mechanisms characterizing the sediment transport as elementary processes in the analysis of lithodynamic oceanic systems (Longinov and Pykhov 1981). Elementary processes, being the first stage and the basis of the lithological studies, can be investigated theoretically and experimentally as a physical process of the interaction between the suspension flow and bottom.

As a rule, all types of the sediment transport can be observed simultaneously in the natural conditions; although one can distinguish the regions on underwater slopes, in which one or another elementary process dominates. In the outer part of the coastal zone, the extreme offshore point of hydrogenic displacement of sediments is the point on the underwater slope, in which the first displacements of bottom particles occur. This point may move along the slope depending of the size of the sediment particles and parameters of the surface waves. As the velocities of the orbital motion near the bottom increase, more and more particles are involved into motion. In this phase of the interaction between the flow and current, the particles in the bottom layer are involved into the rolling motion, sliding, or saltation (the height of the jumps usually does not exceed a few diameters of the particles), which determine the bottom transport of sediments over a smooth bottom. This regime is called the smooth phase of sediment motion up to the beginning of formation of bottom microforms. The further increase in the velocities upslope leads to the increase in the transport of displaced particles. Formation of ripples starts under specific conditions. Ripples are observed on the bottom up to the zone of wave breaking. Bottom transport of sand over windward slopes of microforms and in the suspension layer whose approximate thickness is of the order of the ripple length occurs simultaneously in this phase of the interaction between the flow and the bottom, which is called the ripple phase.

Ripples are washed out in the region of the wave breaking point where the wave forcing on the bottom is maximal. Here, sand transport occurs in the suspension layer over smooth bottom. We shall call this regime the upper smooth phase of sediment motion. Suspension motion of sediments dominates immediately in the zone of wave breaking owing to the development of eddy motions, while all elementary processes may exist simultaneously closer to the shore in the surf zone where the bottom sediment particles are larger and bottom forms can appear again. The motion in the form of sand layer over smooth bottom dominates when the wave energy finally dissipates in the runup zone; this is the upper smooth phase of sand transport.

In the natural conditions, intensity of elementary processes and their relation to specific zones in the underwater slope are determined not only by the composition of sediments, but also by external forces: variations in the sea level due to the tides or onshore winds, wave currents, infragravity waves, and local bottom slopes.

7.5 Problems of Investigation of Hydrodynamic Processes in the Coastal Zone

All dynamical processes in the coastal zone can be separated into three categories: small-, intermediate- and large-scale processes, based on the spatial and time scales of near-shore fluid motions (Fig. 7.1) (State of Nearshore Processes Research 2000; Akivis 2008).

During the last decade, field experiments and numerical modeling have shown that near-shore wave transformations, circulation, and bathymetric change involve coupled processes at many spatial and temporal scales (Fig. 7.2).

Inconsistency currently exists between the level of our knowledge about the hydrodynamic processes in the coastal shelf zone and the necessity of the effective forecasting of possible ecological variations caused by the intense economical

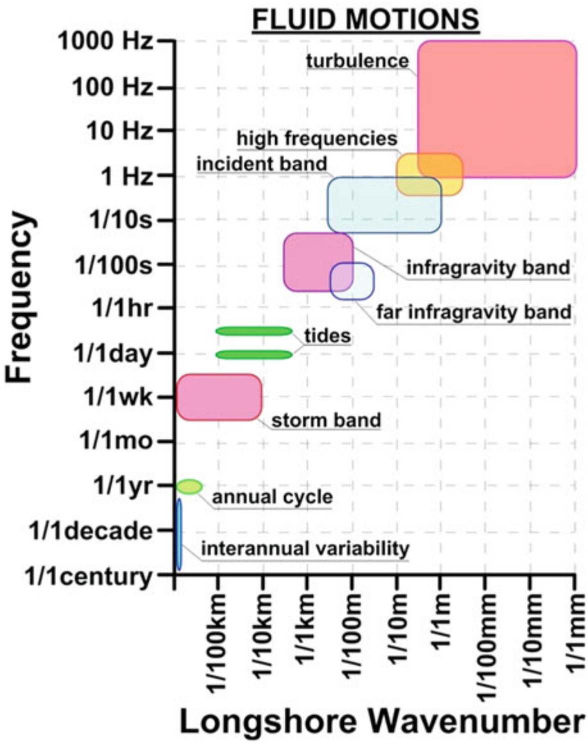

Fig. 7.1 Space-time scales of the near-shore processes

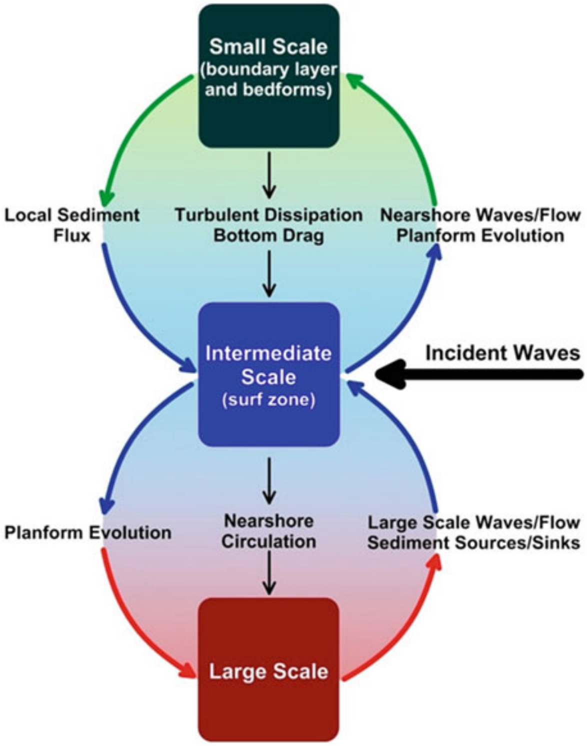

Fig. 7.2 Coupling of the small-, intermediate-, and large-scale processes

development of this zone, which has been increasing in the last years. A possibility to decrease this inconsistency is determined by the results of the recent field investigations, according to which the group structure of waves and infragravity waves strongly influence the sediment transport and currents generated by waves in the zone of wave transformation and breaking. In the existing models, water circulation and sediment transport are considered only as the time averaged characteristics without taking into account the group structure of waves, their transformation in the coastal zone of the sea, and the contribution of the fluctuation component of sediment transport and admixtures at different frequencies of the spectrum of irregular waves.

Since the mid-1980s, a notable progress appeared in the understanding of physical regularities and methods of the calculation of wave parameters, coastal currents, and sediment transport during storms in the coastal zone of the sea. The field studies showed that in the first approximation, the variations in the higher moments (asymmetry, excess, etc.) of the wave motions when the waves approach the shore determine the character of wave breaking, generation of infragravity waves and wave currents, suspension processes, and sediment transport, which is the entire dynamics of the coastal zone. The theoretical studies are mainly focused on the analysis of quantitative characteristics of hydrodynamic processes by means of numerical solution of the Boussinesq equations with additional terms, which parametrically describe the energy losses during wave breaking. This method of the solution of the hydrodynamic problems of the coastal zone is undoubtedly promising after eliminating some disadvantages in the existing models related to our poor knowledge of the group structure of waves and infragravity waves and their influence on the circulation in the coastal zone.

Lack of a clear qualitative picture of nonlinear deformation of irregular waves frequently leads to incorrect interpretation of the experimental data. For example, paradoxes appear like anomalous dispersion of waves (Kuznetsov and Speranskii 1994), which contradicts the generally accepted concepts about non-dispersive wave motion in limiting shallow water. Despite the fact that the Boussinesq equations quite well describe the propagation of irregular waves, the group velocity in the existing models is ignored and the comparison of numerical simulations with the experiment is performed only using the time averaged wave parameters. The existence of the group wave structure and infragravity waves in the natural conditions with a broad spectrum of their scales leads to indefiniteness and frequently to the arbitrary selection of the time needed for averaging and obtaining reliable estimates.

The energetic concept is generally used to calculate the sediment transport normal to the shore and along the shore. According to this concept, sediment transport is determined through the dissipation of the wave energy. The Baillard model developed in 1981 is most frequently used for these calculations (Bailard 1981). Detailed verification of the basic principles of this model on the basis of the field data and spectral and cross-spectral analyses showed that at its best it makes possible to estimate only the order of magnitude of the transport (Kosyan et al. 1999). In the most cases, the model wrongly predicts the direction of the sediment transport normal to the coast at the frequencies of wind and infragravity waves. The contribution of sediment transport at these frequencies to the total sediment transport normal to the shore is especially sensible in the zone of wave breaking. The main mass of sediments is transported in this zone during storms and leads to the morphodynamic changes in the underwater slope and the coastline. The main cause of the divergence is in the fact, that the energetic models are based only on the general physical approach that the sediment transport is proportional to the wave energy dissipation without the account for the actually observed mechanisms of the suspension deposits from the bottom existing in the nature. In addition, they do not take into account the intermittency of the sediment transport and their dependence on the group structure of waves; they skip variations in the spectral composition of individual waves and phase shifts between the velocity of water, parameters of turbulence, and concentration of suspended sediments (Kosyan et al. 1997).

A number of morphodynamic models have been published by present, which use various approaches to the description of the actual mechanisms applied to different regions of the coastal slope. The majority of them are related to the conditions of regular wave forcing applied to the uniform alongshore slope formed of sand sediments uniform by size. Under these conditions, compensation countercurrent is considered one of the main mechanisms of sediment transport along the slope profile (Okayasu and Katayama 1992). However, the other important factors: runup flow, which determines the dynamics of periodically drained part of the beach and fluctuating transport by infragravity and wind waves are poorly studied, but their contribution is significant. This hampers quantitative description of the sediment dynamics in this region. As a result, investigators use various interpolations in modeling the evolution of the submarine slope profile without considering realistic mechanisms of sediment transport.

While considering the morphodynamic problems in the conditions of non-uniform bottom topography there is a need to calculate horizontal circulation of water in the zone of transformation of breaking waves. At present, modern numerical models of the coastal circulation have been developed based on the concept of the radiation stress (Van Dongeren et al. 1994; Pechon and Teisson 1994), and Boussinesq equations (Sorensen et al. 1994). Unfortunately, these models do not take into account the group structure of the waves approaching the shore. In addition, these models are quite expensive in the sense of the consumption of computer time. Their application for specific practical problems related to a large number of time iterations is frequently inconvenient and not efficient. Therefore, the problem remains pressing of selecting an economical hydrodynamic model, which takes into account the influence of the group structure of waves adjusted to the conditions of morphodynamic simulations and provides the acceptable accuracy at minimum expenses.

In recent years, a number of investigations, related to the analysis of the influence of frequency distribution of surface wave energy on the dynamics of the bottom material, have been carried out (Kosyan et al. 2009; Divinsky et al. 2014). In particular, it was found that under equal characteristics of irregular surface waves the specific features of the wave forcing applied to the sandy bottom are determined precisely by the peculiarities of the frequency distribution of wave energy. Concentration of the wave energy in the region of the frequency of the spectral maximum facilitates a transition from irregular to regular waves and to the general regulation of the dynamic impact on the solid bottom. In the physical sense, this mechanism leads to the realization of more stable external conditions for the development of microforms of bottom topography. These data are, of course, not final, but nevertheless they allow us to formulate the general vector of future research.

7.6 Conclusions

The coastal zone is the most dynamic part of seas and oceans. The enormous wave power obtained from wind is damped precisely here. Formation of strong currents and complex water exchange systems, formation and displacement of underwater ridges, suspension and transport of large masses of sediments, etc. are the results of energy dissipation. All these processes are interrelated in various combinations. The state of shores and especially the state of beaches and coastal bottom topography are to a great extent determined by the character of sediment transport in the coastal zone under the influence of waves and currents; therefore, in the conditions of extended economical activity at the coast, the scientific knowledge of the hydro-lithodynamic processes here is extremely important. Calculations of the sediment transport and deformations of underwater slopes are needed for the operation of hydro-engineering constructions, developing of the projects of coast protection, and providing the ecological safety. Constructions of channels for the ships to enter the ports, trestles for oil pipes, mining of construction materials, providing safe communications, and recreation regime on the beaches is impossible without taking the account for the regularities of sediment transport in the coastal zone.

Let us emphasize the poorly studied aspects in the researches of the coastal zone dynamics:

- sediment transport in the zone of wave runup in the conditions of permeable bottom;
- spatial distribution of wave energy due to wave breaking; generation of infragravity waves and their contribution to the dynamics of sediments;
- interaction of surface waves, sea currents, variations in the morphometric peculiarities of the bottom and sediment transport in the coastal zone; this interaction implies a feedback between these processes;
- the influence of frequency-angular distributions of spectral energy of the approaching waves on the transport of bottom sediments;
- transformation of bottom material and interannual changes in its granulometric composition;
- transport of sediments in the conditions of pebble and mixed (sandy-pebble) beaches.

Solution of the abovementioned problems is possible only within a multidisciplinary monitoring of the state of environment with inclusion of the improving instrumental means for measuring parameters of wind waves, currents, bathymetry, and character of the bottom sediments. In this relation we emphasize the importance of laboratory experiments. Despite some specific limits, laboratory experiments allow us to specify, control, and repeatedly reproduce the parameters of the hydrodynamic environment. In this sense, they are more preferable than the field experiments. Laboratory experiments are actually the elements of environmental modeling, whose final results are improved (or developed) physical mechanisms of the coastal zone dynamics.

Acknowledgement The presented paper was prepared with support of the Russian Science Foundation (project no. 14-17-00547).

References

Akivis TM (2008) Defintions and main dynamical processes in the coastal zone. In: Dynamics of coastal zone of non-tidal seas. Terra Baltica, Kaliningrad, pp 20–24

Bailard JA (1981) An energetics total load sediment transport model for a plane sloping beach. J Geophys Res 86(C 11). William Byrd Press for John Hopkins Press, United States, pp 10938–10954

Divinsky BV, Kosyan RD, Grüne J (2014) Influence of the wave spectrum form on the bottom sediment dynamics. Oceanology 54(2):132–143. Publishing House "Nauka", Moscow

Kosyan RD, Pykhov NV (1991) Hydrogenous movement of sediments in the coastal zone. Publishing House Nauka, Moscow. 280p. (in Russian)

Kosyan RD, Kunz H, Kuznetsov SY, Pykhov NV, Krylenko MV (1997) Sand suspension and intermittence of turbulence in the Surface Zone. In: Proceedings of the 25th international conference on coastal engineering, "COASTAL ENGINEERING' 96". American Society of Civil Engineering, New York, pp 4111–4119

Kosyan R, Kunz H, Kuznetsov S, Pykhov N, Podymov I, Vorobyev P (1999) Physical regularities of suspended sand concentration and transport under irregular waves based on field data. Die Kuste. Vol. 64. Verlagsanstalt Boyens, Heide, pp 161–200

Kosyan R, Divinskiy B, Grüne J, Podymov I, Vincent C, Ahmari A, Oumeraci H (2009) Laboratory research of the dependence of suspended sand concentration on the spectra form of irregular waves. In: The ninth international conference on the Mediterranean coastal environment, MEDCOAST 09, Sochi, Russia, 10–14 Nov 2009

Kuznetsov SY, Speranskii NS (1994) Anomalous dispersion paradox in shallow water gravity waves shoaling over slopping bottom. In: Magoon OT, Hemsley JM (eds) Proceedings of 2nd international symposium "ocean wave measurements and analysis" (waves-93). Published by ASCE, New York, pp 364–373

Longinov VV (1954) Patterns of development of the pebble beaches. In: Proceedings of the Institute of Oceanology, USSR Academy of Sciences. v.10 (in Russian)

Longinov VV (1973) Assays of ocean lithodynamics. Publishing House Nauka, Moscow. 244 p. (in Russian)

Longinov V, Kosyan R (1994) About ocean lithodynamics. Acta Oceanol Sin 13(4), ISSN: 0253-505X Springer International Publishing, pp 527–534

Longinov VV, Pykhov NV (1981) Lithodynamics systems in ocean. In:. Lithodynamics and hydrodynamics of ocean contact zone. Publishing House Nauka, Moscow, pp 3–64 (in Russian)

Okayasu A, Katayama H (1992) Distribution of undertow and long-wave component velocity due to random waves. In: Proceedings of 23rd conference on coastal engineering. Published by ASCE, Venice, pp 883–893

Pechon P, Teisson C (1994) Numerical modelling of three-dimensional wave-driven currents in the surf-zone. In: Proceedings of 24rd conference on coastal engineering. Published by ASCE, Kobe, Japan, pp 2503–2512

Sorensen OR, Schaffer HA, Madsen PA, Deigaard R (1994) Wave breaking and induced nearshore circulations. In: Proceedings of 24rd conference on coastal engineering. Published by ASCE, Kobe, Japan, pp 2583–2593

Soulsby RL (1983) The bottom boundary layer of the shelf seas. In: Physical oceanography of coastal and shelf seas. Elsevier, Amsterdam, pp 189–266

State of Nearshore Processes Research II (2000) Technical Report NPS-OC-00-001, St. Petersburg, Florida

Van Dongeren AR, Sancho FE, Svendsen IA, Putrevu U (1994) SHORECIRC: a quasi-3D nearshore model. In: Proceedings of 24rd conference on coastal engineering. Published by ASCE, Kobe, Japan, pp 2741–2754

Velikanov MA (ed) (1948) Movement of sediment Office Ministry of River Fleet USSR, Moscow. 415 p. (in Russian)