SEDIMENT TRANSPORT IN THE COASTAL ZONE

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INTRODUCTION

Nearshore zone, i.e. the ocean area bordering on the land, plays a special role in ocean dynamics. Its morphology is characterized by shallow depths and considerable sloping of bottom surface, which determine its leading part in the wind wave dynamics.

The enormous wind energy, absorbed by the waves is mostly spent in shallow areas. Here, the dissipation of wave energy generates quite a few specific hydro-, litho- and morphodynamical processes, which lead to the development of strong and highly variable currents and complex patterns of intensive water exchange, the formation and active displacement of underwater bars and migration of the shoreline. A specific peculiarity of nearshore zone is that the dynamic al processes are complex here, and individual processes are involved in this complex in the very different combinations.

Equally serious are the practical considerations which make researchers and engineers concentrate their attention on this part of the ocean area. nearshore zone had long become the field of intensive economic expansion, which has considerably accelerated during the past decades and it will grow up even further in the near future. Of course, the economic development today is being extended to depths, which can no longer be regarded as nearshore zone. It is obvious, nevertheless, that coastal zone will retain its special economic importance to mankind for a long time.

Nearshore water motion results from external forces and takes forms of tidal currents, swell and wind waves, various wave currents generated in the surf zone, storm surge and tsunami. In natural environments these phenomena have various repeatability and differ in their effect on bottom slope. In most cases nearshore dynamic processes control wind waves and swell, velocity field of which directly affects on the bottom sediment. Energy dissipation, interaction and breaking of the surface waves generate secondary motions such as long-period waves, longshore currents, horizontal and vertical circulation. Spatial and temporal scales of these motions evidently depend on the scales of morphodynamic elements of bottom slope and shore.

The main energy source of wave formation is wind, constantly blowing above water surface. Parameters of waves depend on wind velocity and duration and on fetch value. Wind waves are usually irregular. When wind dies out, or when waves leave the windy zone they propagate as swell characterized by nearly constant period and form.

When waves propagate shoreward, they reach a certain point where their length becomes less than the local depth. From that moment, waves induce oscillatory motion of the near-bottom water, amplitude of which increases with propagation on shallower depths. Under certain conditions movement and transport of bottom sediment begin. Waves are refracted which results in landfall normal to isobaths. Simultaneously to refraction, wave deformation occurs - their forms and heights are changed. With further deformation there comes a moment when wave breaks and in the process of energy dissipation water movements of various scales are induced, such as small-scale turbulence, large-scale vortices in a breaking wave, long-period waves and nearshore currents, determining the intensity and direction of sediment transport in surf zone.

Seaward of wave breaking zone, sediment motion is induced both by surface waves and by various currents (tidal, drift, etc.). In areas with tidal current velocities up to tens of centimeters per second and such currents generally control the resulting bottom sediment transport in the offshore zone. The superposition of surface waves and current intensifies near-bottom water motion and as a result, discharge of transported sediments is also increased. Outside the wave breaking zone, sediment motion occurs close to bottom, and for sediment transport modeling one should know the dynamics of bottom boundary layer both for pure wave movement and for combined wave and current action.

The ultimate purpose of sediment transport studies is the prediction of bottom relief in the zone of active wave effect accompanied by transport of significant sand volumes. The energetic longshore currents induced by the oblique wave approach, transport large amounts of sand lifted by waves from the sea bottom. This mass sediment transport and its longshore variations finally determine the shore-line configuration and the location of accumulative and erosion areas on the underwater slope. Because of great practical significance, the problem of longshore sediment transport has attracted much attention.

BASIC DESCRIPTION OF THE SEDIMENT MOVEMENTS BY WAVES IN NEARSHORE ZONE

The following continuity equation is a physical basis, which connects changes of the bottom level and sediment flux (Kachel, Smith, 1989).

$$\frac{\partial H}{\partial t} + \frac{1}{1-n}\left(\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y}\right) = 0 \qquad (1)$$

where

$$Q_x(x,y,t) = \int_{-H}^{h} \frac{1}{T_M} \int_{0}^{T_M} S(x,y,z,t) \bullet U(x,y,z,t)\,dtdz$$

$$Q_y(x,y,t) = \int_{-H}^{h} \frac{1}{T_M} \int_{0}^{T_M} S(x,y,z,t) \bullet V(x,y,z,t)\,dtdz$$

The axis x is directed to the cross shore, the axis y is directed to longshore, the axis z is directed from the bottom to the sea surface; n is concentration of sediments at the bottom level; Q_x and Q_y - are depth integral sediment fluxes in the cross-shore and longshore directions; T is a time period of averaging (in field conditions it is usually 10-60 minutes); a horizontal line marks the time averaging.

Instantaneous values of concentration and velocity components for irregular waves can be presented as a sum of the main time scales

$$C(x,y,z) = C + C_w + C_l + C', \qquad (2)$$

$$U(x,y,z) = U + U_w + U_l + U', \qquad (3)$$

$$V(x,y,z) = V + V_w + V_l + V', \qquad (4)$$

where U and V are mean for time period T values of sediment concentration and water velocity components in the cross-shore and longshore directions; C_w, U_w, V_w are fluctuations of those characteristics in gravity band of the spectrum of irregular waves; C_l, U_l, V_l - fluctuations of sediment concentration and water velocity components in the infragravity band; C', U', V' are turbulent components of these characteristics. The boundary frequency between infragravity and gravity bands of spectrum of irregular waves is 0.05Hz and 1Hz between gravity and turbulence bands (Bowen, Huntley, 1984). The frequency of 0.05 Hz is a relative one, and from a physical point of view it is not a constant one. Its value can be determined by a certain power spectrum of wind waves and swell waves in the course of field measuring. Substituting (2)-(4) and taking into account that average in time values of fluctuation components of concentration and water velocity, and that their products for different frequencies are equal to zero, we get the following expressions for local sediment fluxes

$$qx = C\ U + CwUw + ClUl + C'U' \qquad (5)$$

$$qy = C\ V + CwVw + ClVl + C'V' \qquad (6)$$

It is seen from (5) and (6), that for the strict and grounded form a physical aspect assessment of local sediment fluxes in the cross-shore and longshore directions, it is necessary to know dependencies of mean and fluctuation concentration components on the parameters of irregular waves and their cross-correlations with water velocity components at the different distance from the bottom. The possibility to obtain such dependencies occurred in the last years due to creation of optic and acoustic devices for field measuring of instantaneous values of suspended sediment concentration with the discreteness in a tenth fraction of a second. That allows to analyze fluctuations of concentration in a full band of the spectrum of irregular waves. This task was one of the most important in field study of sediment transport during last years (Kos'yan, Pykhov, 1991; Onishchenko, Pykhov, 1990; Kos'yan, Kuznetsov, Pykhov, 1994; Hanes, 1991; Wright et al., 1991; Davidson et al., 1992), but it is still a long way off for its solution.

FIELD INVESTIGATIONS OF LONGSHORE SEDIMENT TRANSPORT

The experiment "Shkorpilowtsy-85" held on the Bulgarian section of the Black Sea coast was devoted to the field study of the structure of the longshore sedimentary flux (Leont'ev, Pykhov, 1989). Simultaneous measuring of the concentration profiles and the water velocity was done. The point measuring position on the submerged slope changed depending on the position of the boundary of the wave breaking start. A local sedimentary flux on a given horizon z was determined as a product of an average for an hour values of the longshore velocity and concentration:

$$q(z) = v(z)\ c(z) \qquad (7)$$

The verification of the Leont'ev model (1988) has been made on the basis of the data obtained in these experiments. In this model an integral sediment discharge is described by:

$$Q_y = \left(0.186 \frac{c_B}{tg\Phi} + 0.038 c_s \frac{(gh_B)^{1/2}}{\varpi_s} \right) F_{yB}, \qquad (8)$$

where tgΦ is an angle of internal friction of the bottom sediments; h_B is the depth of the wave plunging of 1% probability; ϖ_s is a mean value of the settling velocity; F_{yB} is longitudinal flow of the wave energy defined according to a linear theory on the line of the wave breaking; c_B and c_s are coefficients of the intensity of the bottom and suspended sediment transport consequently. The first term in brackets defines the bottom sediment transport and the second one - suspended sediment transport. According to field measuring the values of Sc for all eight series varies from 0.05 to 0.017. A mean value is 0.01 that agrees with the assess for the river streams. During these experiments we failed to find the meaningful values for local fluxes in cross-shore direction since an average value of the cross-shore velocity was 1.3 cm/s that could be compared with the errors of its measuring.

The impossibility of strict assessment of sediment flux on the one hand, and the necessity of the solution of practical tasks on the other hand, resulted in the elaboration and use of energetic models for calculations of sediment flux in cross-shore direction (Bowen, 1980; Bailard, 1981; Guza, Thornton, 1985a, b; Roelvink, Stive, 1989; Leont'ev, 1994). A Bagnold hypothesis (Bagnold, 1966) about proportionality of sediment flux and dissipation of the wave energy near the bottom has been taken as a principle of those models. Value and direction of the sediment flux are determined through 3-rd and 5th moments of near-bottom water velocity, which usually is given as a sum of two first harmonics and a constant in time velocity of water drift near the bottom. Those models are conformed qualitatively to laboratory measuring, when monochromatic waves influence upon the bottom. But the use of them for quantitative assessment of sediment flux and bottom deformation in marine conditions is nowadays a problematical task according to the following consideration, which is based on not numerous measurements of the instantaneous values of suspended sediment concentration.

1. The peaks are observed at the infragravity frequency <0.05Hz in energy spectra of free surface elevations, near bottom water velocity and suspended sediment concentration (Kos'yan, Kuznetsov, Pykhov, 1993; Russel et al., 1991; Beach, Sternberg, 1992). Then, in the breaking zone near the shore wave energy at the infragravity frequencies is sometimes one order more, than wave energy at the frequencies of approaching waves and the harmonics divisible to it (Beach, Sternberg, 1992). Cospectra of concentration and velocity show that sand transport in band of infragravity

frequencies makes a considerable contribution and sometimes determines the net sediment transport (Russel et al., 1991: Osborn, Greenwood, 1992 a,b; O'Hare, Huntley, 1994). But in existing models this factor is not practically taken into account.

2. The presence of a set of wave fluctuations at the infragravity frequencies in field conditions results in the necessity of the choosing of necessary average time for obtaining of reliable assess of sediments. This problem may be solved only by estimation of moments of water velocity taken in models with field measuring for different scale of time averaging.

3. In the energetic models it is supposed that the temporal changes of concentration occur in the phase with near bottom velocity of water. But field measurements shows that this term is not kept. Different nature of energy spectra of concentration and water velocity, especially in the band of infragravity frequencies, testifies to this fact (Osborn, Greenwood, 1992 a, b; 1994). Sediment suspending does not happen continuously but as sharp peaks, usually when groups of large waves are passing. Then a phase displacement of velocity and concentration is observed, the value of it increases, when the distance from the bottom grows, and this value influences considerably upon the net sediment transport (Osborn, Greenwood, 1993; Greenwood, 1994).

4. The character of bottom surface is not practically taken into account in these models. Some observations show that even in the case of monochromatic waves above the ripple bottom the net sediment transport is directed from the shore (Inman, Bowen, 1963; Tanana, Shuto, 1987), while according to models sediment transport would be directed to the shore due to wave asymmetry. Such a contradiction may be explained by peculiarities of sand suspending by vortexes, which are formed behind the ripple crests, and by their advection into the water column in the moment of sign changing of orbital velocity, when a great amount of sand, captured by vortexes, is transported seawards by orbital velocity. When wave regime and ripple forms are changing, the intensity of vortexes and the conditions, under which they lift off and move, will change too. Regularities of this process have been cleared up rather weakly yet and they may be obtained by experiment only.

5. Large scale vortexes with horizontal or vertical axes, which are able to transport actively bottom sediments to the water column, are formed in the surf zone, where waves are broken by plunging or by spilling (Zang et al., 1994). Their transport under infragravity and time mean water movement in this zone can give a considerable continuation to the net sediment transport. Models do not take this into consideration, as well. The hypothesis about predominant sand transport by infragravity waves in the breaking zone or about formation of underwater bars wins more and more supporters (O'Hare, Huntley, 1994). But till now there are no reliable field data for its check up.

ABOUT PROGNOSIS OF LONGSHORE SEDIMENT TRANSPORT

The energetic longshore currents induced by the oblique wave approach, transport large amounts of sand suspended by waves from the sea bottom. This mass sediment transport and its longshore variations finally determine the shore-line configuration and the location of accumulative and erosion areas on the underwater slope. Because of great practical significance, the problem of longshore sediment transport has attracted much attention.

In-situ measurements of sediment discharge are rather limited at present due to significant technical and methodical difficulties.

Result of practically insuperable difficulties of direct measurements and estimates of near-bottom discharge is that the rigour prediction is evidently impossible. On the other hand, the immense practical significance of this problem stimulated the development of some tens of equations of longshore sediment transport evaluation during the last 20 years. Various aspects of this problem have been reviewed in Longinov (1966); Voitsekhovich (1986); Beloshapkov (1988); Hallermeier (1982), and joint monograph "Nearshore Dynamics and Coastal Processes" (NDCP, 1988).

The great number of models is the direct indication on the poor knowledge of the physical sense of these phenomena. Universal predictive models for the long-shore sediment discharge are still lacking. The models are rather simple structurally being based on the general physical concepts; calculations based on them depend mainly on the correct specification of the constants involved. The models based on calculations by the known sediment concentration profiles and transport velocities, have similar demerits. And still the latter approach seems more promising as, in contrast to the energy approach, with improvement of our knowledge, it will become possible to calculate three-dimensional structure of sediment discharge with varying settling velocities, observed in field conditions.

It is convenient to present the calculation sequence as a modular scheme consisting of several interrelated algorithmic operations (Kos'yan, Phylippov, 1990; Kos'yan, 1993). Step-by-step calculations can be made from one block to another by the chosen physical models and methods (Fig.1). This scheme provides for operative alterations and additions to separate modules in compliance with the environment of the studied coast. Besides, the content of calculation modules can be changed without alteration of calculation sequence within the scheme, as soon as the better knowledge of elementary process physics is attained.

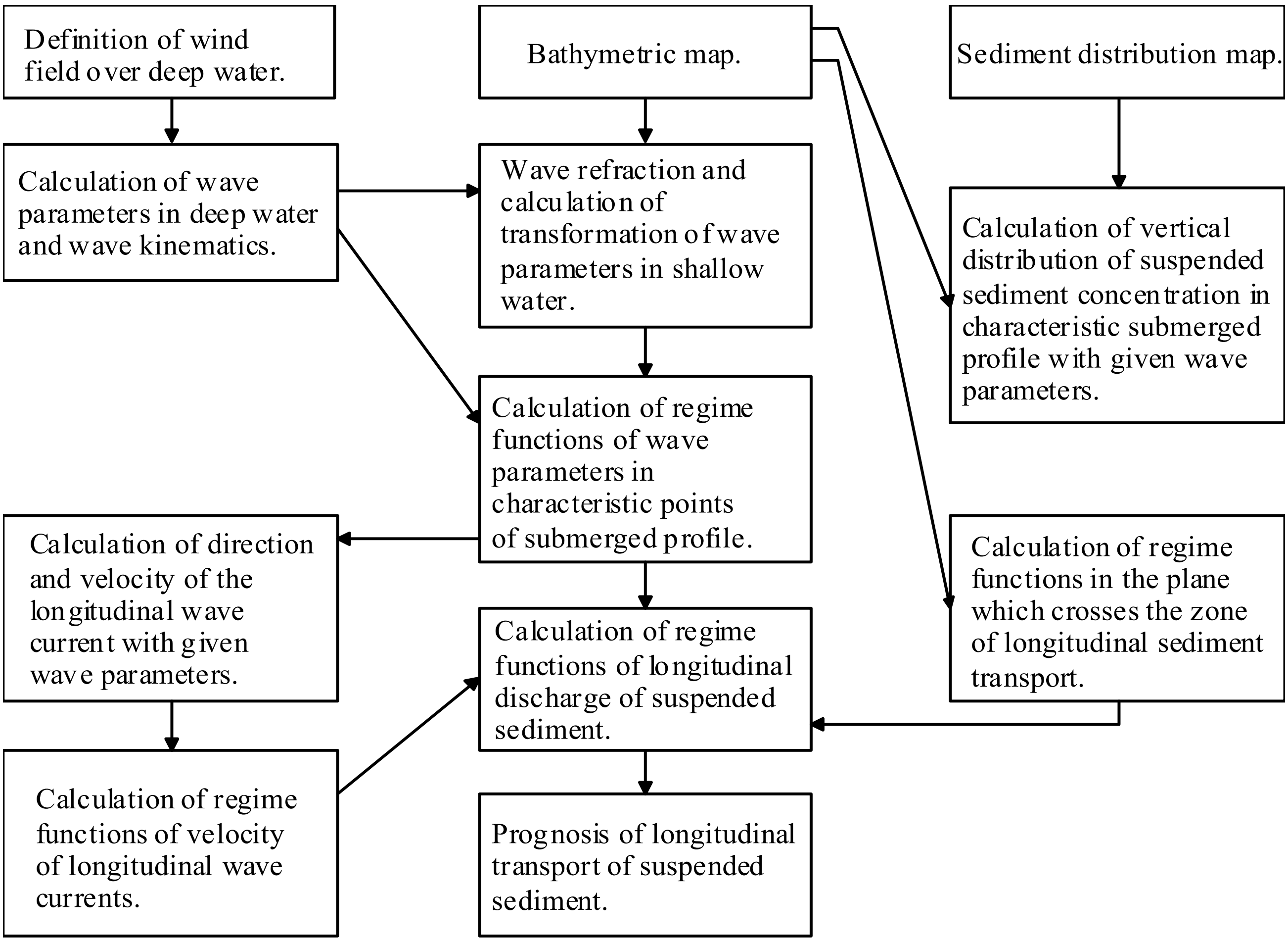

Fig.1 - The modular scheme for calculation of longshore transport of suspended sediment.

All calculations begin from the wind parameters determination in the deep part of a basin. The observation data on wind direction and velocity for many years, bottom relief and geology on the studied nearshore zone are transmitted from the coastal stations to the calculation scheme input. The nearshore zone is divided into roughly uniform sections, and the deep-water wave parameters, their transformation and refraction in shallow water, direction and velocity of longshore current, suspended sediment concentration, cross-section of the suspended flow, and, finally, the sought-for value of the suspended sediment discharge are calculated sequentially for each of them.

Intermediate and final results are both presented in the probabilistic form as regime functions or recurrence curves. The calculation procedure can be automated completely.

The calculations of wind parameters in the deep-water areas are incorporated in one of the first stages. Observations on the nearest coastal hydrometeostations, or typization of synoptic maps over a multi-year period (usually 20 to 25 years) generally serve as a source data, providing for calculation of regime functions of wind strength and direction distribution above the deep-water areas.

Later on the "significant" wave parameters in the deep-water areas are calculated, together with the functions of wave element regime formation under the given computed wind velocities and "simple" conditions of wave formation. A stage of wave elements calculations on given wind characteristics is very important for all further constructions. Regime functions of wind characteristics are used as input data in this case. Any model describing the process satisfactorily can be used for calculations in each stage of the suggested scheme.

On the basis of the data on the regime functions of deep-sea wave elements and of bathymetric map of the chosen coast section, refractions plans and shallow-water wave parameters are calculated next.

Regime functions of shallow-water wave elements in the typical points of the underwater slope are found from those of the deep-sea waves. Characteristic points are chosen on the bathymetric map of the coast subject to the purpose of investigations. Then, together with the angles between wave approach and isobaths they are used to calculate the longshore current velocities.

The velocities of longshore energetic current and the regime functions of shallow water wave parameters serve as a source data for the next stage, in which the regime functions of longshore current velocities are formed for all wave-dangerous directions of the studied coast section.

The velocity, recurrence and direction of resulting longshore current formed by storm-induced currents approaching the shore at different angles relative to normal to the water edge, are needed for the further calculations. This current is formed due to streams induced by storm waves which come to shore from the directions on different sides of normal to water edge. If necessary on the base of velocity regime functions of resultant longitudinal current we can plot a scheme of velocity distribution of this current on a coast segment under study with any security and to determine the volume of water mass transported alongshore during any time period. The recurrence of the resulting current velocities is a sum of velocity recurrences of unidirectional currents. On this basis the velocity regime functions of the back and forth currents are formed, from which the recurrences of summary resulting longshore water transport are found. If necessary, the distribution of the resulting longshore current velocity along the studied shore section can be plotted with the needed recurrence.

Afterwards, the vertical distribution of the suspended sediment concentration is calculated. To calculate the profile of the suspended sediment concentration in the zones of broken, unbroken and slightly deformed waves, the models suggested by Kos'yan, Pykhov (1991) were used. To calculate sediment concentration on the standard level Nielsen's (1979) or Kos'yan's (1986) formula can be used. Since we use the elements of surface waves for the calculation of suspended sediment concentration on the coastal zone and the regime functions of these parameters are known. On this basis we plot regime functions of suspended sediment concentration (average in the water column and maximum at the bottom). With the help of these regime functions we can determine the distribution of clastic material all over the investigated aquatory under any hydrological conditions.

The major longshore transport of the suspended sediment occurs in the narrow nearshore zone between the depth of significant wave breaking and water edge. Thus, as a first approximation, the longshore discharge of suspended sediment on a unit of coast length can be expressed in terms of concentration and longshore current velocity values averaged over the cross-section of this zone (W):

$$Q=VSW, \qquad (9),$$

where V and S are the averaged values of alongshore velocity and suspended sediment concentration.

The value of W will be defined by the depth of significant wave breaking, which can be found in each particular case. Thus, from the wave parameter regime functions those of mean concentration, longshore current velocity and W can be found. At the final stage of the calculation we construct regime functions of the volume of suspended material transported along the shore can be obtained.

The calculation scheme has been practically realized on the 120-km long section of Bulgarian Black Sea coast from Caliacra Cape to Emine Cape, which totals to one third of the overall sea border of Bulgaria (Kos'yan, 1993). The calculation results gave good similarity with the test data.

CROSS-SHORE SEDIMENT TRANSPORT AND VARIABILITY OF THE UNDERWATER SLOPE PROFILE

When the underwater slope is acted upon by the frontal storm waves approaching the shore with uniform conditions along it, the only sediment transport is normal to isobaths. As a result of this transport, the underwater slope profile is changed in the zone of active wave effect. Cross-shore movement of bottom sediment is also possible at oblique wave approach to the shore with heterogeneous bottom relief. The direct estimates of cross-shore discharge and simulation of the variations of the underwater slope profile in real conditions are still impossible correctly. But along with predictions of the water slope profile deformation, the indirect evaluative methods of transversal sediment transport have been developed.

The ultimate purpose of sediment transport studies is the prediction of bottom relief in the zone of active wave effect accompanied by transport of significant sand volumes. The modeling of bottom relief variations is based on the equation obtained by bottom to surface integration of mass preservation equation:

$$\frac{\partial H}{\partial t} = \frac{1}{1-n}\left(\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y}\right) \qquad (10)$$

In contrast to the longshore sediment transport characterized by unidirectional movement at all levels above sea bottom, cross-shore movement of sand occurs both shoreward and seaward, the sign of movement direction reversing with depth at various points of the underwater slope. In order to evaluate the amount of transported sediment in this case, the profiles of concentration and of velocities in the zone of unbroken waves, breaking point, bore and swash zone should be known.

Measurements of sediment discharge above the sloping bottom deformed by wave action present significant difficulties, and in this case the resulting discharge can be estimated by the method based on repetitive measurements of bottom profile. The main idea of this method is as follows. If the longshore conditions are constant (parallel isobaths, constant wave heights, absence of any longshore currents) then $\frac{\partial Q_y}{\partial y} = 0$, and profile variations, according to (10), will be defined by

$$\frac{\partial H}{\partial t} = \frac{1}{1-n}\frac{\partial Q_x}{\partial x} \qquad (11)$$

where n is bed sediment porosity. Integration of (11) with respect to x gives:

$$Q_x = Q_{x_0} + \int_{x_0}^{x} (1-n)\frac{\partial H}{\partial t}dx \qquad (12)$$

Axis x is directed seaward with zero being at the water edge. It is convenient to choose the point x as a boundary point of the offshore profile, as the initial conditions for sand particle displacement are satisfied here and Qx_o=0 can be assumed. In this case takes the form:

$$Q_x = \int_{x_0}^{x} (1-n)\frac{\partial H}{\partial t}dx \qquad (13)$$

Thus, if the deformations $\frac{\partial H}{\partial t}$ are known, being determined by the successive measurements, the resulting sediment discharge normal to shore can be found for any point of the underwater slope. It follows from (13) that when the equilibrium profile is being built (usually defined as the ultimate stable profile constructed by infinite wave action), $\frac{\partial H}{\partial t} \rightarrow 0$ and $Q_x \rightarrow 0$.

This method is widely used in laboratory conditions as its basic requirements can be satisfied easily. But direct extension of these results to natural conditions seems objectionable.

The evaluation of cross-shore sediment discharge by the measurement technique has one uncertainty which should be accounted of when the data obtained by various authors are being compared or when the empirical relationships are being constructed. The fact is that as the bottom profile approximates equilibrium state in course of time, the cross-shore sediment discharge under constant wave parameters in the seaward part of the profile tends to zero. Thus, in laboratory conditions, with initial sloping flat bottom, most intensive profile modifications and sediment transport occur in the very beginning of the experiment. As the profile approximates the equilibrium state, these processes decay. Thus, along-profile Q_x values appear to be time-variant under the same wave parameters in deep water and it is not clear which of them are most representative for the given waves. In real conditions, one never knows how far from equilibrium the given profile is.

Among the known concepts of quantitative evaluation of cross-shore sediment transport, those used for longshore transport prediction predominate. Available formulae, generally empirical ones, are reviewed in detail in NDCP (1988). Dimensional theory is most frequently used, according to which the dimensionless sediment discharge is a function of Shields parameter.

The difference between the equations suggested by various authors results mainly from various estimates of gravity role and wave height distribution in surf zone chosen for calculation of velocities.

The problem of cross-shore sediment transport has been developed intensively only in the last decade and is still far from solution. There exists a significant shortage of experimental data concerning the cross-shore sediment transport. This problem is an essential task of future investigations. When constructing numerical models, it is also advisable to allow for variations of sediment composition along the profile and during storm, which will be shown to be typical for field conditions.

SOME REGULARITIES OF CROSS-SHORE SEDIMENT TRANSPORT

In order to consider the bottom relief variations during storm, the underwater slope profile was divided into three zones, differing in intensity of bottom deformation: trough zone of the slope close to water edge; bar zone and seaward bar slope zone.

At relatively slight sea, surface waves are breaking only on the slope close to water edge. Surf and compensating outflow thus formed, induce circulation which transports finer fractions (if present in this zone) toward the trough, in which they precipitate or remain suspended. The slope being composed of coarse sand, water depth does not change significantly at this stage.

As storm develops and wave height increases, their deformation and breaking on the seaward bar slope generates more complex motion of water masses. In these conditions finer particles can be transported seaward, beyond the bar top. The equilibrium profile is developed near the water edge. For a short period sand particles are dragged shoreward by surf. Compensating outflow acts for a longer period, during which finer particles cover a longer distance seaward and are accumulated there. The sediment is differentiated in a particular pattern along the slope. Sea calming causes precipitation of suspended particles on near-edge slope, reducing the mean diameter of bed sediment.

The underwater bar zone is characterized by high grading and uniformity of bed sediment. Insignificant growth of d value was caused by erosion of shoreward bar slope due to transport of finer fractions on its seaward side. Alteration of bar height and its migration along the profile depend on preferential action of compensating outflow upon the sediment of shoreward bar side, on turbulence within the breaking wave suspending large amounts of sediment, and on asymmetry of wave velocities. Predominance of the latter at the initial stage of storm development causes shoreward migration of the bar due to transport of bed sediment from its seaward side onto a shoreward one. Storm intensification results in wave breaking at the seaward bar slope, which is accompanied with seaward migration of its top, so that sand particles are transported to its seaward side by stronger compensating outflow. When the storm attenuates and wave breaking zone migrates shoreward, this tendency is reversed. Absence of finer fractions around the bar can be explained by their removal by compensating outflow.

The sediment particles behave similarly on the seaward bar slope and within the bar zone. The boundary between these zones can be traced by abrupt drop of finer fraction percentage. Being the function of bottom slope and wave length, the third zone width is dynamic. Under higher waves this zone expands seaward. Bed sediment particles are preferentially transported up the slope and become coarser when reaching the bar. Under certain hydrodynamic conditions the particles of similar coarseness are being transported along the slope until they reach the equilibrium state.

It should be noted as a conclusion that the seaward part of the bar retains the slope profile when the storm abates abruptly, while the sediment coarseness everywhere tends to pre-storm values.

In many cases suspended sediment shift makes the principal contribution into sediment flow formation in the coastal zone. An intensive suspension of sand particles occurs only in the nearshore zone. Under the effect of storm waves bottom sediments start to move, are suspended intensively from the bottom and transported in the cross-shore and longshore directions, and it results in changing of the bottom and beach relief. The basic factors, which influence on the net sediment transport in nearshore zone, are the following ones: asymmetry of wave orbital velocities, Stokes drift of water: water undertow in offshore direction in the surf zone; tide-ebb currents; longshore and rip currents; infragravity waves of different genesis.

During storms, the main part of the sandy and silty sediment migrates in a suspended state, and this mode of motion has attracted special attention of the scientists. We have not time to consider all kinds of sediment movement, so we'll concentrate ourselves on this one.

A quantitative assessment and prognosis of suspended sediment distribution and sediment flux are the most prior problems in nearshore zone study.

TIME MEAN CONCENTRATION OF THE SUSPENDED SEDIMENTS

Data on the time-mean suspended sediments concentration and composition for storm period are primarily needed for solution of the applied tasks. Thus, the results of observations on a vast aquatory during a few storms enable one to choose the best place to locate a raceway, a cooling system of atomic and thermal power plants, a waste water discharge, etc. Such observations allow one to estimate aquatory dynamic activity, and can be used for analysis of longshore sediment transport rate, sorting and sediment composition of surface layer.

Figs. 2-4 show a typical distribution of a mean suspended sediment concentration on the test-grounds in the Black Sea (Kos'yan, Pykhov, 1991). These results show that even during moderate storms when a mean wave height at the depth of 10-15 m does not exceed 1.1-1.6 m, and period is 5.5-6.5 sec., appreciable sand suspending near the bottom takes place at the depth of 15-20 m. In wave deformation zone the suspended sand concentration increases monotonously and reaches the highest values near the breaking point (points 3 and 4, Fig.2), and then it becomes less one again in the bore zone. Vertical profiles of the concentration (Fig.3, 4) are characterized by considerable gradients near the bottom in the wave shoaling zone and they become almost of an exponential type in the surf zone. A mean diameter of the suspended sand changes also in the near bottom water layer, and immediately near the bottom (about 10 cm) it can be more than a mean diameter of the bottom sediments in the moments of a calm water due to the washing out of fine fractions in the water column during the phase of the storm stabilization, when the wave height is the largest one (Fig. 4).

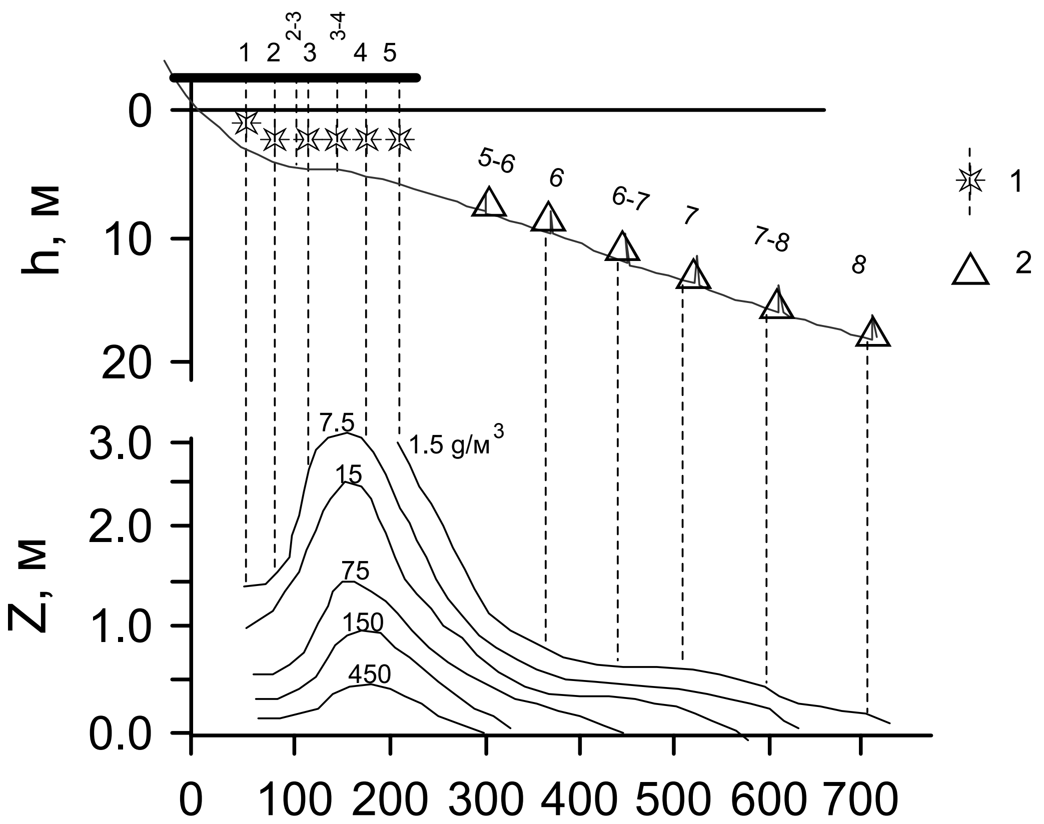

Fig.2. Distribution of suspended sediment concentration during storm at the nearshore zone of the «Kamchia» site. 1-8 - points of measurements.

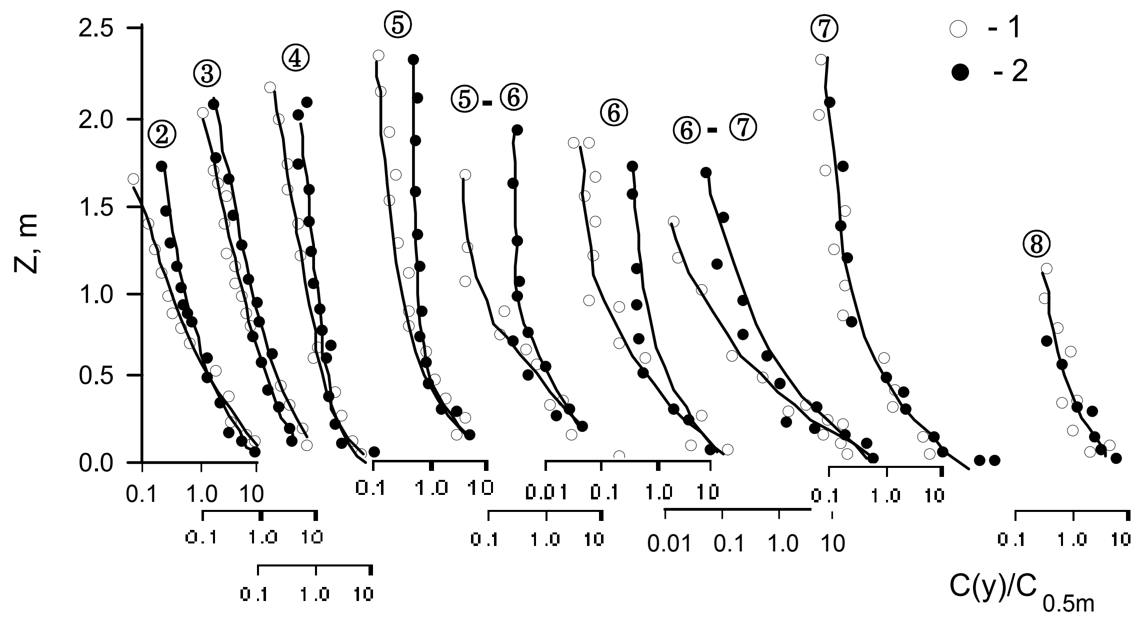

Fig.3. Distribution of suspended sediment concentration during storm at the « Kamchia» site. Numbers of the measuring points as in Fig.1.

1) normally incident waves. $\boldsymbol{H}$ = 1.1m, $\boldsymbol{T}$ = 6.5s

2) oblique incident waves. $\boldsymbol{H}$ = 1. 1 m, $\boldsymbol{T}$ = 6.0 s

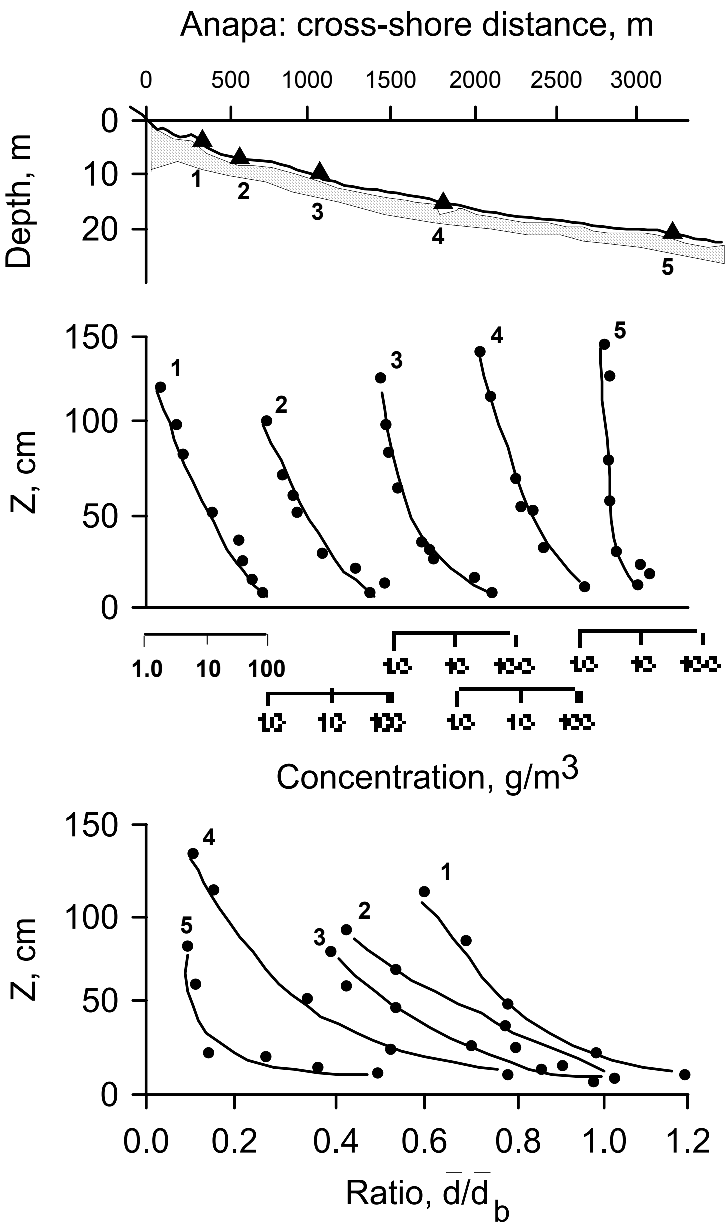

Fig.4. The vertical distribution of the suspended sand concentration and median diameter for the Anapa site. ***H*** =1.6 m, ***T*** =5.6

VARIABILITY OF THE SEDIMENT CONCENTRATION DURING STORM

Above given examples demonstrate a general picture of the concentration field along the whole coastal zone, averaged during the storm period. But the changes of the wave height and period, the angle of their approaching and the migration of the boundary of the wave breaking in the course of the storm will considerably influence upon the distribution of the suspended sediment concentration during different storm phases.

Figs. 5-7 present the examples of the changes of suspended sediment concentration and a mean diameter during the storm that has lasted for 52 hours.

They were obtained with the time averaging of 5 hours on the Kamchia test-ground in the Black Sea (Pykhov et al, 1980). In Fig. 5 the distance from the bottom is shown on the Y-axis, on the abscissa axis there is given the time from the beginning of the storm (in hours) and isolines show the values of suspended sand concentration and a mean diameter. In the upper part of the figure there are given the values of the time-mean wave height and period in points 2,3,5 the position of which on the bottom profile is given in Fig.2. During the phase of development (the storm beginning) and during the phase of damping (the storm end) the wave breaking has happened in the area of point 3 where local maxima of the concentration near the bottom are seen vividly. Analogous local maxima are present near the bottom in point 2 as well, which is situated in the bore zone. At the same time interval the increasing of the suspended sand mean diameter is observed there. When the wave height and period are increasing during the phase of the storm stabilization, the wave breaking point is shifting to the point 5 area, that results in a sharp growth of the suspended sand concentration and a mean diameter at all horizons above the bottom.

The vertical distributions of the suspended sand concentration and a mean diameter in points 1-5 during the storm is illustrated in Figs. 6 and 7. Digits 1-9 above the profiles are the numbers of exposures successively from the storm starting with the averaging time about 5 hours. In all the measuring points, the vertical gradient of concentration decreases at all levels above the bottom with growth of the wave height. In the storm starting and end periods the suspended sand concentration changes in 2-3 orders within 2-m layer, its largest gradients are near the bottom in a layer of 0.5m thickness. During the phase of the storm stabilization (exposures 3-7) the concentration gradient becomes less one at all levels above the bottom, due to the turbulization of the water column by breaking waves.

The vertical distributions of the suspended sediment mean diameter are similar in all the measuring points despite the various absolute values of *d*. Near-bottom *d* gradient is somewhat higher in the beginning and in the end of storm only in points 1 and 2. In all the measuring points and at all the exposures d values generally decrease with height: 2 times in points 1 and 2, near the shore, where the coarse sand fractions prevail in the bottom sediments and 10-20% in other points within a 2-m near-bottom layer.

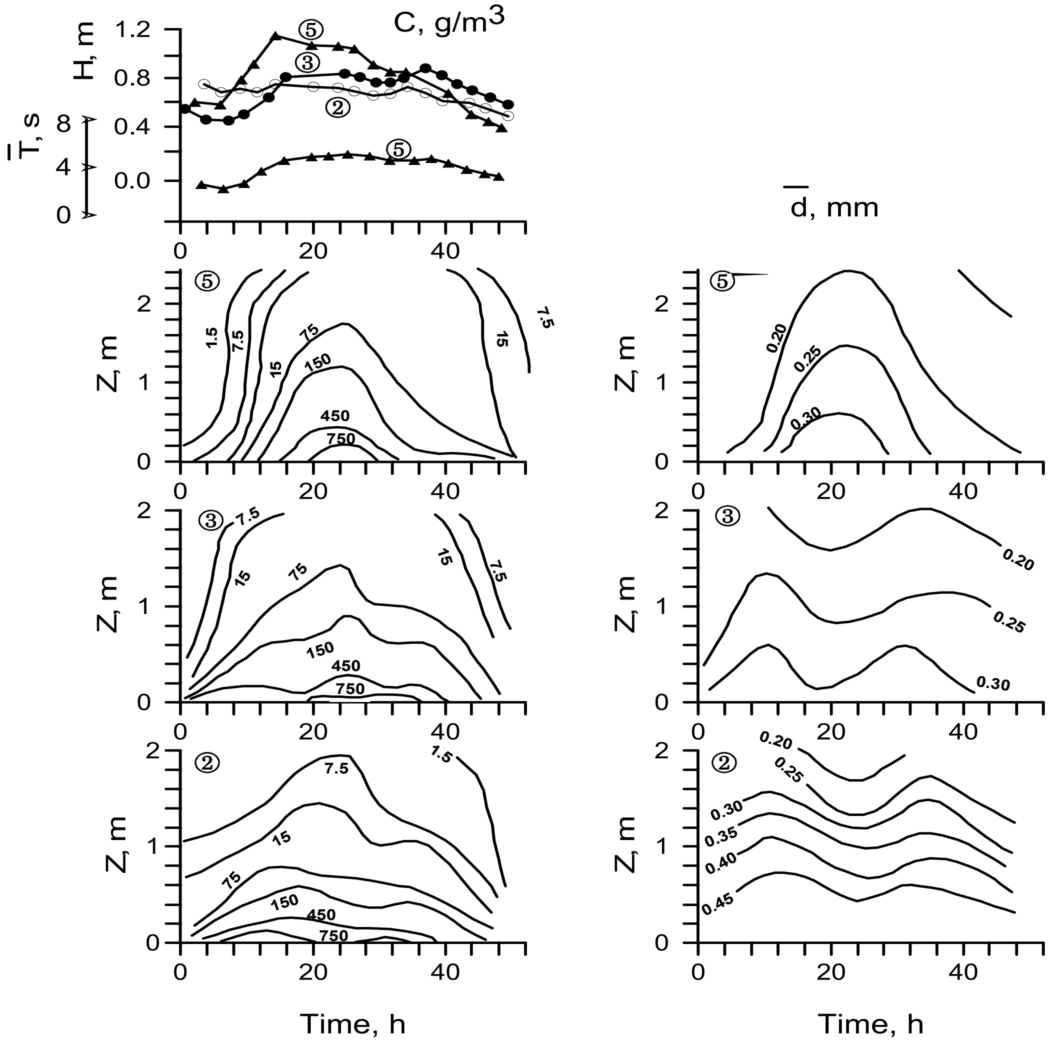

Fig.5. Variation of suspended sand concentration (left) and median diameter (right) in the course of storm at the «Kamchia» site. Figures in circles show the location of measuring points

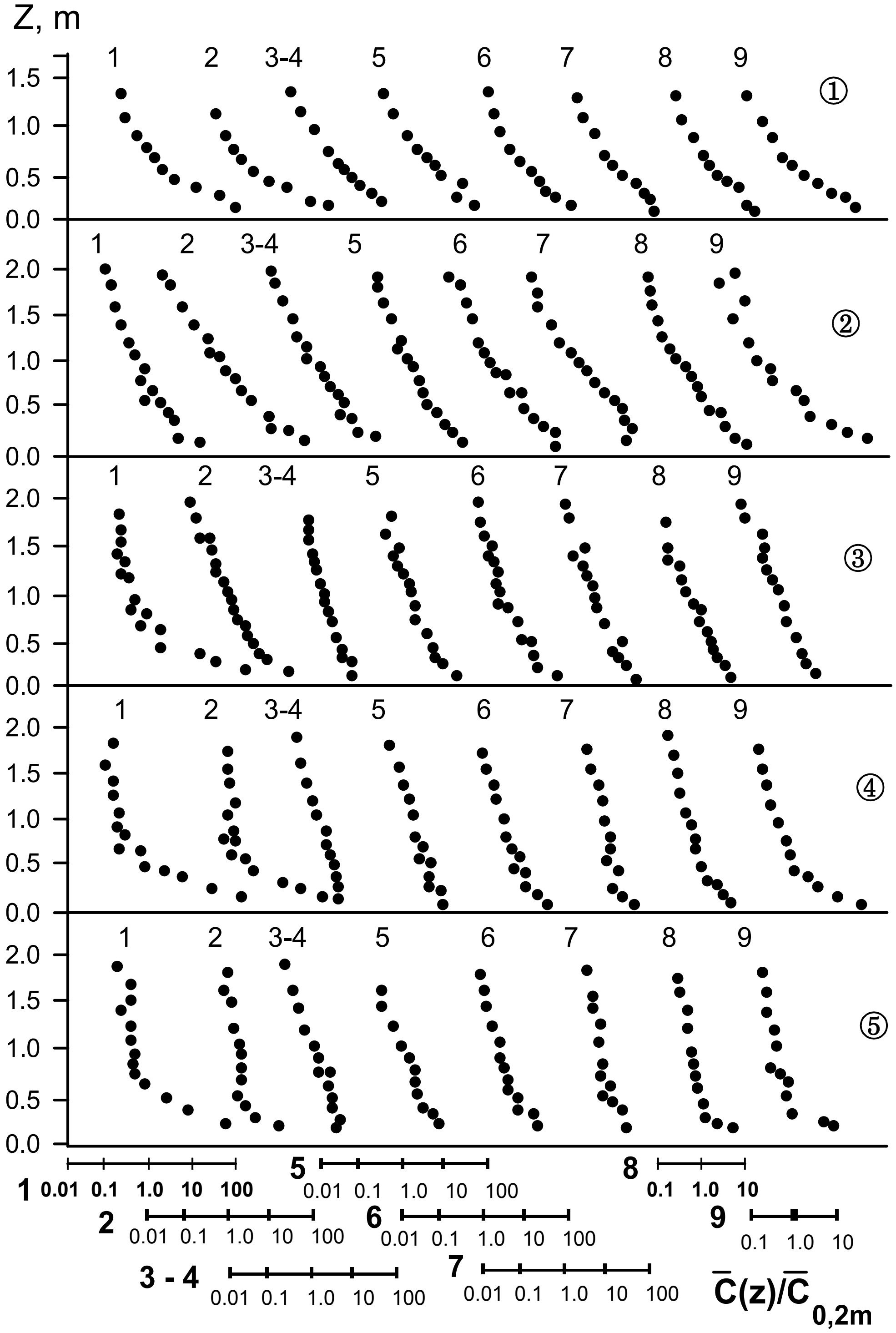

Fig.6. The vertical profiles of suspended sediment concentration during storm («Kamchia» site).

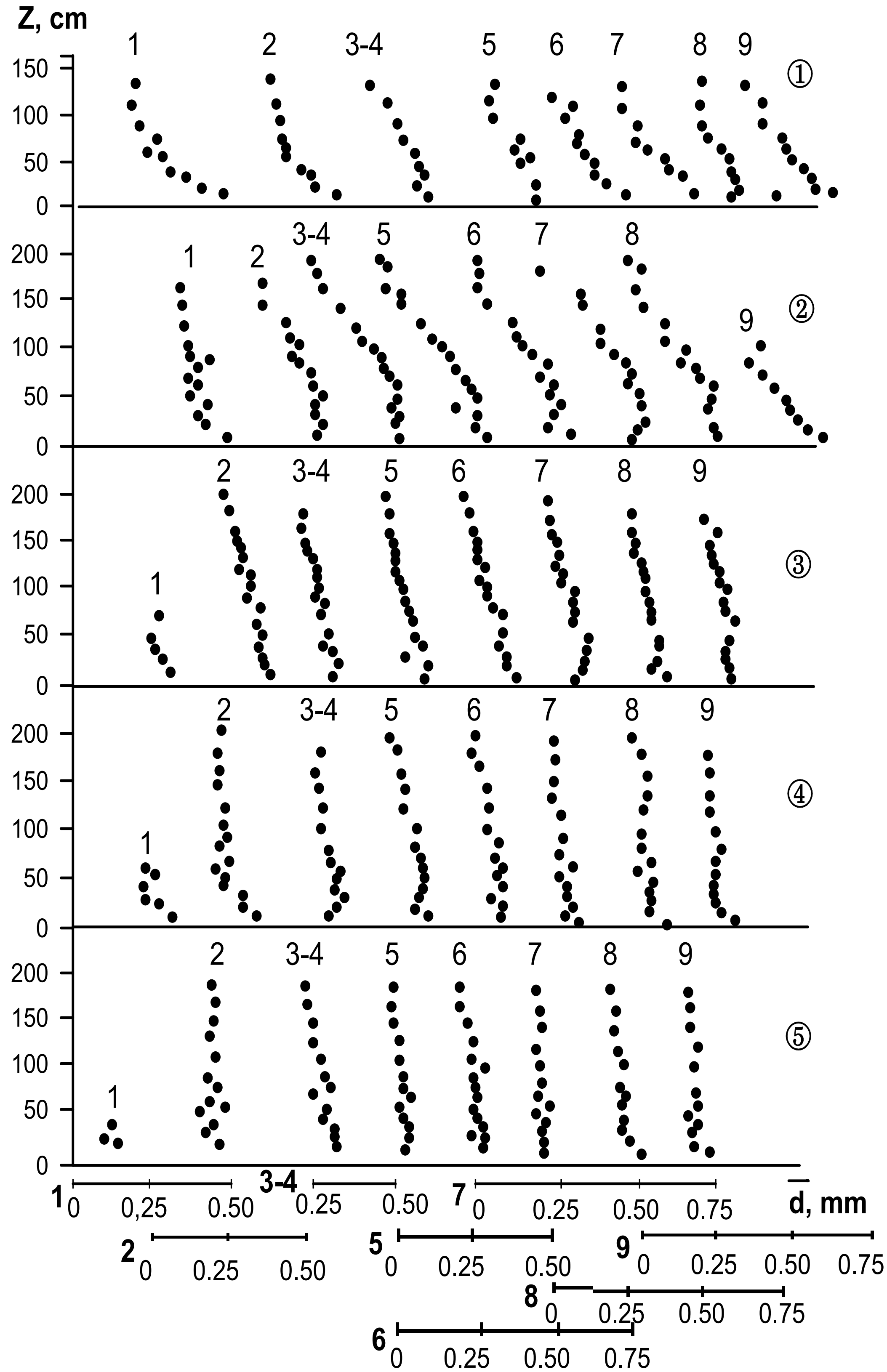

Fig.7. The vertical profiles of suspended sediment median diameter during storm («Kamchia» site).

SEDIMENT CONCENTRATION IN THE BREAKING ZONE

Taking into account an important role of the wave breaking zone in the formation of the sedimentary flux, the detailed measuring of the peculiarities of the suspended sand vertical distribution in its different sections - from the beginning of the wave breaking to the water edge- has been made (Kos'yan, 1985).

Different types of vertical profiles of concentration are established for the weakly deformed waves, for the greatly deformed but unbroken waves, for the waves, breaking by spilling, by plunging and for the bore zone (the inner part of the surf zone). Fig.8 presents the distribution of the suspended sand concentration at different horizons along the swell wave breaking zone. The wave breaking by plunging began at the distance of 32 m from the water edge (point 9). The measuring of concentration was done at 10 points simultaneously. The location of these points is shown in the figure. The largest amount of the sand is suspending 2-3m shoreward from the wave plunging point, and a monotonous reduction of the concentration is observed on the both sides from it.

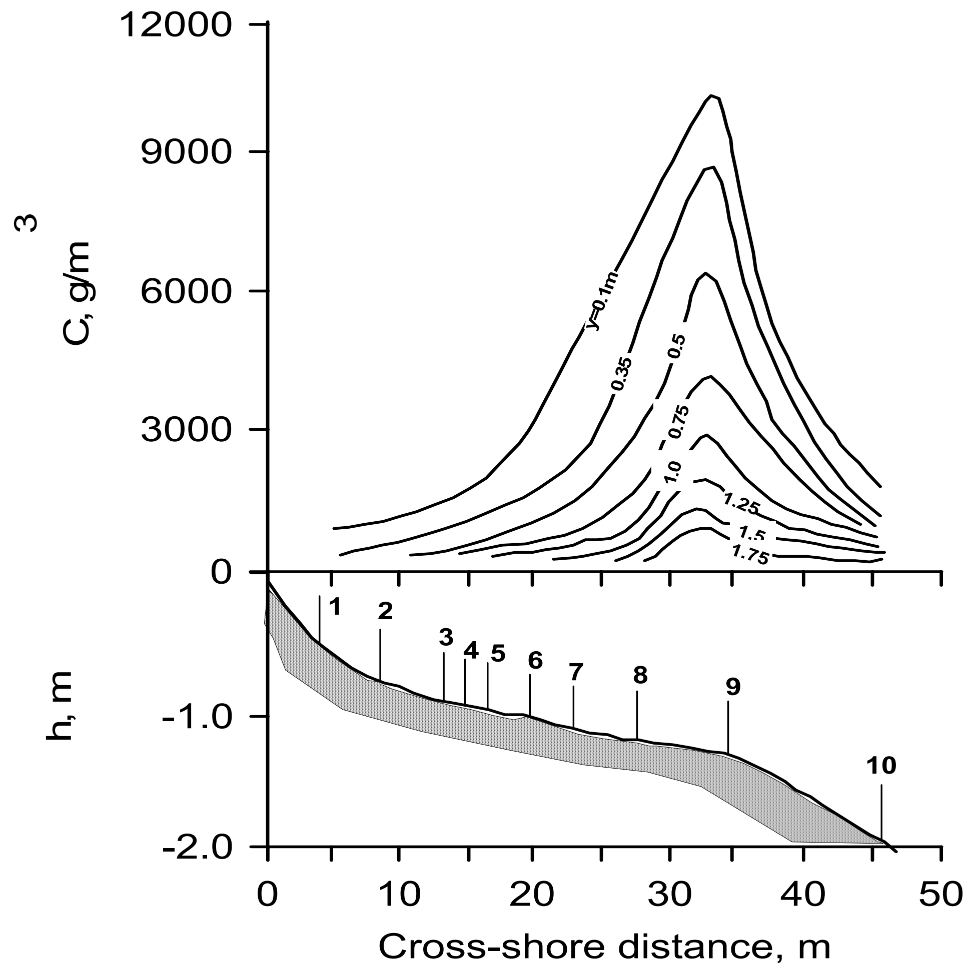

Fig.8. Spatial variation of suspended sediment concentration in the surf zone («Kamchia» site)

In the zone of weakly deformed waves most part of the sediment is suspended in the near-bottom layer. As wave height increases, suspended sediment is distributed over the whole depth with a large gradient in the near-bottom layer.

In the zone, where waves breaking by spilling the distribution of sediment is almost uniform with a slightly increasing gradient in the near-bottom layer. In the zone of plunging breaking waves the distribution is almost uniform over the entire depth. In the bore zone the sediment is distributed with a constant gradient in semi-logarithmic coordinates.

It should be noted that the breaking zone is also distinguished by the characteristics of suspended sediment composition. The vertical distribution of the main composition parameters is almost uniform while on the adjacent sites their variations are significant (Fig. 9). It can be assumed that the post-storm bed sediment composition in this zone will be more uniform than outside it.

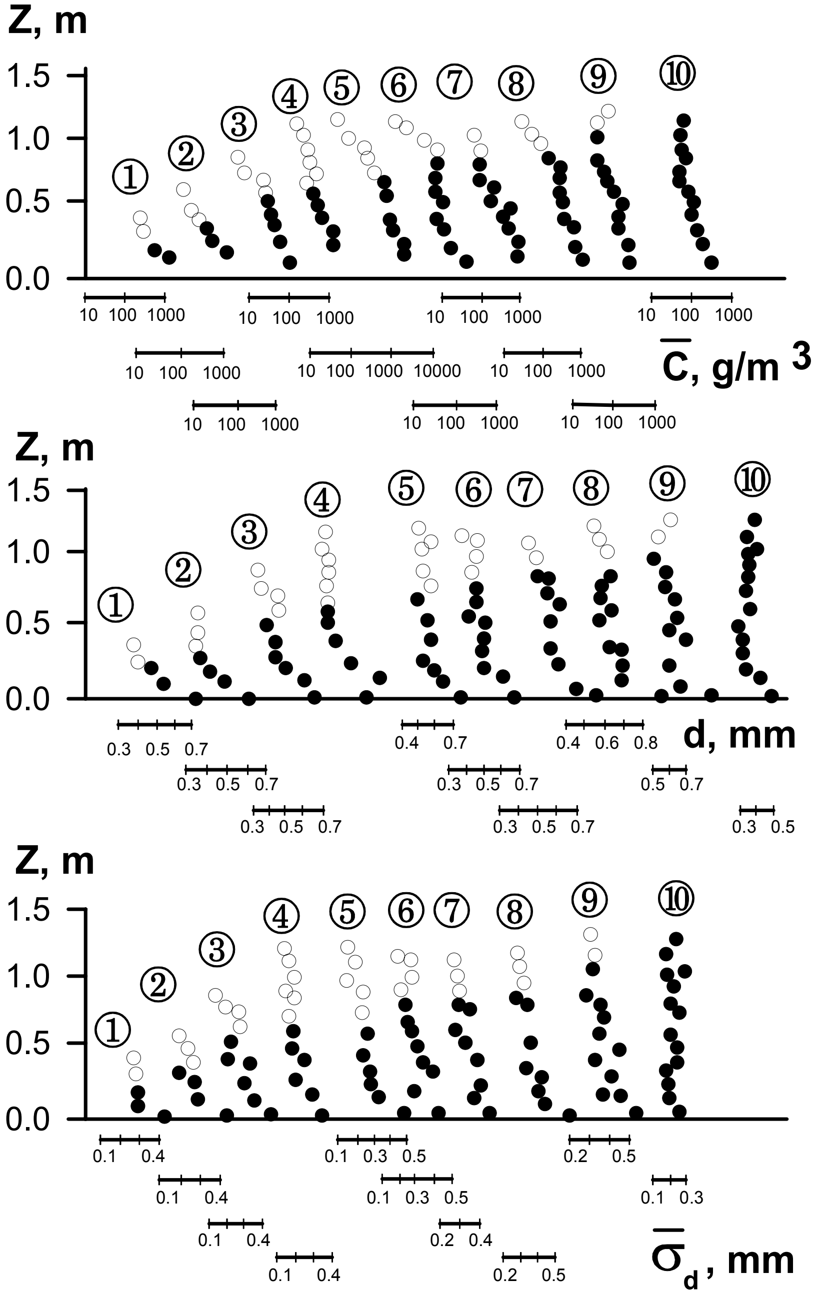

Fig.9. Vertical distribution of suspended sediment concentration (a), median diameter (b) and rms deviations from median diameter. Figures in circles show the numbers of measuring points.

In Fig.9, examples of the concentration profile during a storm are given at the same point of the underwater slope when the seaward border of the breaking zone migrated relative to the measuring point (Kos'yan, Dachev, Pykhov, 1980). The first profile was obtained when the weakly deformed waves were acting upon the bottom. The profiles 2, 3 and 9 were obtained when the greatly deformed unbroken waves were passing through the measuring point. For profiles 4 and 8 the point of observation was situated at the beginning of the breaking zone. For profiles 5 and 7 the point of observation was in the middle of the breaking zone. For profile 6 the point was at the end of the breaking zone. The suspended sediment concentration gradient is decreasing with increasing of the degree of the wave deformation.

THEORETICAL MODELS OF SEDIMENT SUSPENSION

For convenience all the models are considered in groups, according to physical premises used for their construction.

Movement of a Single Solid Particle.

It seems logical that theoretical study of motion of particulate sediment suspended in water flow should consist in study of regularities of a single particle movement with further extension to motion of a group of particles. The problem of a single solid body motion being solved, valuable information can be obtained for clarification of suspension mechanism, for determination of sediment discharge caused by presence of solid particles in liquid, etc.

Particle behavior in a turbulent flow depends largely on size of this particle in comparison with turbulence scale. If a particle is rather large, turbulence will mainly cause its greater resistance to flow and the particle will, at most, more or less follow large scale turbulent motion of liquid. But if a particle is small in comparison with the lowest scale of turbulence, it will tend to follow all the components of turbulence.

Most of theoretical schemes considering behavior of a single particle placed in a given liquid volume, assume it to be small enough to execute motions fully imitating turbulent pulsations of this volume.

Having reviewed the studies done under this limitation one has to admit that this route is far from practical realization. Detailed description of solid particle motion in viscous fluid, allowing simultaneously for effect of liquid velocity field on body motion, and for inverse effect, at present is still lacking. The studies under review generally consider motion of very fine particles. It is generally assumed that particle resistance to motion in liquid depends linearly on their relative velocity. Calculation methods allowing for square resistance law, more significant practically are too complex and even in first approximation result in huge formulae inconvenient in use.

The next step - extension of found regularities of a single particle behavior to group particle motion, - also presents significant difficulties.

Models Describing Two-Phase Flow As Motion Of Multi-Body System.

These models are only of theoretical interest because of principal possibility to solve the problem of strong irregular relative mass transport in physically rigorous terms. Line of research suggested by these models can not be realized in the near future as memory capacity and performance of modern computers do not permit to solve problems of this kind.

TWO-PHASE FLOW AS CONTINUOUS MEDIA MODELS

Two-phase flow models based on equations of continuous media mechanics. Practical interests call for sooner characterization of sediment transport parameters and, first of all, of regularities of vertical distribution of suspended sediment. When constructing theoretical models of suspended sediment transport by water flows, investigators have to face a number of difficulties:

1. When heavy suspended particles are present in a flow, problem of turbulence, far from solution as it is, becomes much more difficult. Complete theoretical description of such flows is absent, while experimental data on transport of heavy particles are scanty.

2. Full description of a single solid particle motion in viscous liquid possessing an arbitrary velocity field, simultaneously allowing for velocity field action on particle movement, and inverse action of body on liquid velocity field is still lacking.

3. There is no generally accepted theory of particle - particle and particle - liquid interaction.

4. Motion of particles relative to liquid further turbulizes the flow, which may result in additional dissipation of kinetic energy of turbulence. Particle action on flow turbulization is not estimated yet.

5. Action of time-variant orbital components of velocity on wave current turbulization is not estimated quantitatively.

6. As specifications of initial and boundary conditions of two-phase flow are random and approximate, only some probable characteristics of temporal and spatial development of this process can be discussed.

7. Continuous water flow erodes the bottom composed by discrete solid particles. Insufficient theoretical development of solid discrete media mechanics does not permit to introduce these real conditions into a model.

8. When interacting with bottom, flow itself regulates amount and composition of sediment transported in suspension, but principle of this self-regulation is not completely studied.

As the above difficulties can not be overcome yet, it seems impossible to construct a single, physically rigorous theory, valid for suspended flow in general, and to express it in a numerical form suitable for practical calculations. Thus, one has to construct simplified models of sediment transport limited in applicability to given conditions.

CALCULATION OF THE VERTICAL PROFILES OF THE CONCENTRATION

From above it is obvious that it is not possible yet to create physically strict theory suitable for description of the suspended particle flux in the flow, especially in the wave flow. It is also evident the absence of possibility to construct a universal method for practical calculation of solid particle transport. Therefore all known solutions are acceptable only in limited borders

Taking into consideration all above sated we set an object to choose relatively simple model of the transport of sediments suspended above the bed under unbroken waves. Let's begin with the problem of the value of rating concentration $z=b$.

It is obvious that rating horizon should be found near the bottom, i.e. the source of sediments. There are various points of view what should be considered as near-bottom concentration. Without mentioning concrete papers, we state that several methods of choosing horizon b are proposed. Its choice at the bottom surface or on the upper boundary of near-bottom area is the most well-grounded from physical point of view. But for variety of reasons we managed to determine any reliable boundary and to measure precisely concentration there only in the course of rare precise laboratory experiments. Other approaches are for example the choice of fixed 0.3 or 1.0 m horizon (Clarke et al, 1982; Kos'yan, 1986) or relative horizon $0.1h$ where trustworthy measurements are executable. Empirical connection for C_b found by their results can be authorized by the necessity to construct solutions within relatively small range of depths. In this connection a suggestion was made to find a position of rating horizon depending n the characteristics of the flow (Antsyferov, Debolsky, 1997). And this afforded to expand a number of generalized data and to propose dependence for C_b in flows of different scale (Antsyferov, Katardzi, 2000). But this solution the same as previous ones is empirical and has not sufficient physical grounds. That's why a question about a method of calculation of this parameter keeps being open.

Now let's go to the second part – a problem of relative distribution of concentration.

As it was mentioned above the exponential distribution of the suspended sediment concentration with distance from the bottom is characteristic one (14):

$$\frac{C(z)}{C_b} = \exp\left\{-\int_b^z \frac{w_s}{k_b} dz\right\} \qquad (14)$$

where z is a vertical coordinate directed upwards from the sea floor, C_b is a value of a mean concentration on the $z = b$ horizon. On the basis of field measuring there was obtained a semiempirical dependence for the k_b coefficient on the particle parameters, at the depth of breaking and on a relative wave height, the values of which depend on the quantity of plunging waves. w_s is a settling velocity.

In summarizing monograph by Van Rijn (Van Rijn, 1993) the most well-known solutions of this task are adduced. Since there is no completely reliable theoretical basis for none of them, we won't analyze their initial suppositions but we only show their final shape in Table 1.

In the expressions adduced in this table: $a = 116 \cdot \rho_*^{-1} \cdot \left(\nu^2 g^{-1}\right)^{1/3}$; $k = 2\pi/\lambda$;

U_m - is and amplitude of near-bottom velocity of water particles; A_δ - is an orbital radius of liquid particle motion near the bottom, K_s - is a linear dimension of elements of bed roughness. H_r - is ripple height, $\omega = 2\pi / T$, δ_w - is the thickness of near-bottom boundary layer calculated from

$$\frac{30\delta_w}{K_s} \cdot \log\left(\frac{30\delta_w}{K_s}\right) = 1.2\frac{A_\delta}{K_s}$$

Results of analysis of comarisonf of this method with the data of laboratory experiment of Van Rijn have shown that a solution of Kos'yan (1985) better than others agree with the data of experiment, both for values of $C(z)/C_b$, and for gradient of this parameter in the main coumn of the flow (Antsyferov, 2001). We should note that rsults of a whole series of other, more interesting and detailed experiments better correlate with this model than with the other (Antsyferov, Kos'yan, 1986). All this afford to consider this model to be the most acceptable one, certainly when the choice of rating concentration is rather thorough.

A good number of formulae for the assessment of the suspended sediment concentration and discharge given in published works during last 30 years and the absence of universal dependencies testify to the lack of clear physical notions about the mechanisms of the sand suspending and transport under the irregular waves, which cannot be obtained only on the basis of measuring of mean values. Detailed measurements are necessary for the study of the processes of the sand suspending and transport in field conditions with the discreteness much smaller than the wave period. This is a long but the only possible way to obtain reliable and grounded from physical aspect models for calculation of the sediment transport and the bottom deformations.

Table 1. Main expressions for calculation of relative distribution of concentration

Authors	Formulae $C(z)/C_b =$
Homma, Horikawa, 1962	$\exp\left\{-\frac{w_s T \,\mathrm{sh}^3(kh)}{\alpha H^3 k^2}\left[\ln\frac{\mathrm{th}(kz/z)}{\mathrm{th}(kb/z)}+\frac{\mathrm{ch}(kz)}{\mathrm{sh}^2(kz)}-\frac{\mathrm{ch}(kb)}{\mathrm{sh}^2(kb)}\right]\right\}$, $\alpha \approx 10^2$
Bijker, 1967	$\left(\frac{b}{h-b}\frac{h-z}{z}\right)^{\varphi}$, $\varphi = \frac{w_s}{\kappa u_*}$
Lungren, 1973	$\exp\left\{-\frac{w_s}{0.4u_*}\left[\ln\frac{z}{b}+1.34\left(\frac{f_w}{2}\right)^{1/4}\left(e^{\frac{z}{\delta}}-e^{\frac{b}{\delta}}\right)\right]\right\}$
Nielsen, 1979	$\exp\left[-\frac{w_s}{\varepsilon}(z-b)\right]$, $\varepsilon_s = \begin{cases} 1.46\cdot 10^{-3} gT\left(\frac{A_\delta \omega}{w_s}\right)^{-0.32} & \text{для } \frac{A_\delta \omega}{w_s} \geq 25 \\ 3.5\cdot 10^{-4} gT\left(\frac{A_\delta \omega}{w_s}\right)^{0.68} & \text{для } \frac{A_\delta \omega}{w_s} < 25 \end{cases}$
Van Rijn, 1993	$\exp\left[-(z-b)\Big/\left(\frac{hu_*}{15w_s}\right)\right]$
Skafel, Krishnappan, 1984	$\exp\left\{-(z-b)\Big/\left[8.7A_\delta \frac{u_*}{w_s}\Big/\left(\frac{u_* d_{50}}{\nu}\right)^{2.2}\right]\right\}$
Kos'yan, 1983, Kos'yan, 1985	$\exp\left\{-w_s\int_b^z\left[\frac{\pi H^2}{2\sqrt{2}}\frac{\mathrm{sh}^2 kz}{T\,\mathrm{sh}^2 kh}+\frac{a(U_m-w_s)(z/\delta_w)}{1+0.06(z/\delta_w)\exp(z/\delta_w)}\right]^{-1}dz\right\}$

TIME SCALE OF SAND SUSPENSION BY IRREGULAR WAVES

Detailed measurement of mechanisms and time scales of sand suspension by irregular waves were carried out during field experiments «Novomikhailovka'93» at the Black Sea and «Norderney'94» at the North Sea (Pykhov et al, 1995; Kunz, Kos'yan, 1997).

The processes which control the temporal variations in suspended sediment concentrations near the sand bottom have been examined by using field measurements of the suspended sand concentration and the horizontal current components. The field data had been measured by optical and electromagnetic sensors with sampling rate 20Hz.

Measurements during two moderate storms of the experiment, revealed, that there were fluctuations of concentration in a broad band of frequencies near the bottom. Under the influence of unbroken waves with a typical group structure, the sand suspension occurred in the moments when the high wave groups passed (Fig.10). Consecutive sand suspending under the influence of every wave in those groups resulted in the formation of broad-concentration peaks. The peak-duration depended on the quantity of waves in the group; it was in the order of several tens of seconds. The fluctuations of the sand-concentrations, with the same period as the waves, occurred within these peaks. A statistic reliability of the concentration fluctuations in these scales is confirmed by a rather high correlation coefficient for the field data between concentrations and cross-shore currents at the frequency of the approaching waves, as well as for the coherence between concentrations and the envelope of the cross-shore currents at the frequency of the wave groups. In this case the concentration spectrum of suspended sand is characterized by a local maximum at the frequency of the approaching waves and by a monotonous increase of the spectral density at the range of low frequencies, when they decrease. The latter can be explained by the fact that the spectrum of the envelope of the cross-shore currents is fairly wide and a local maximum is missing.

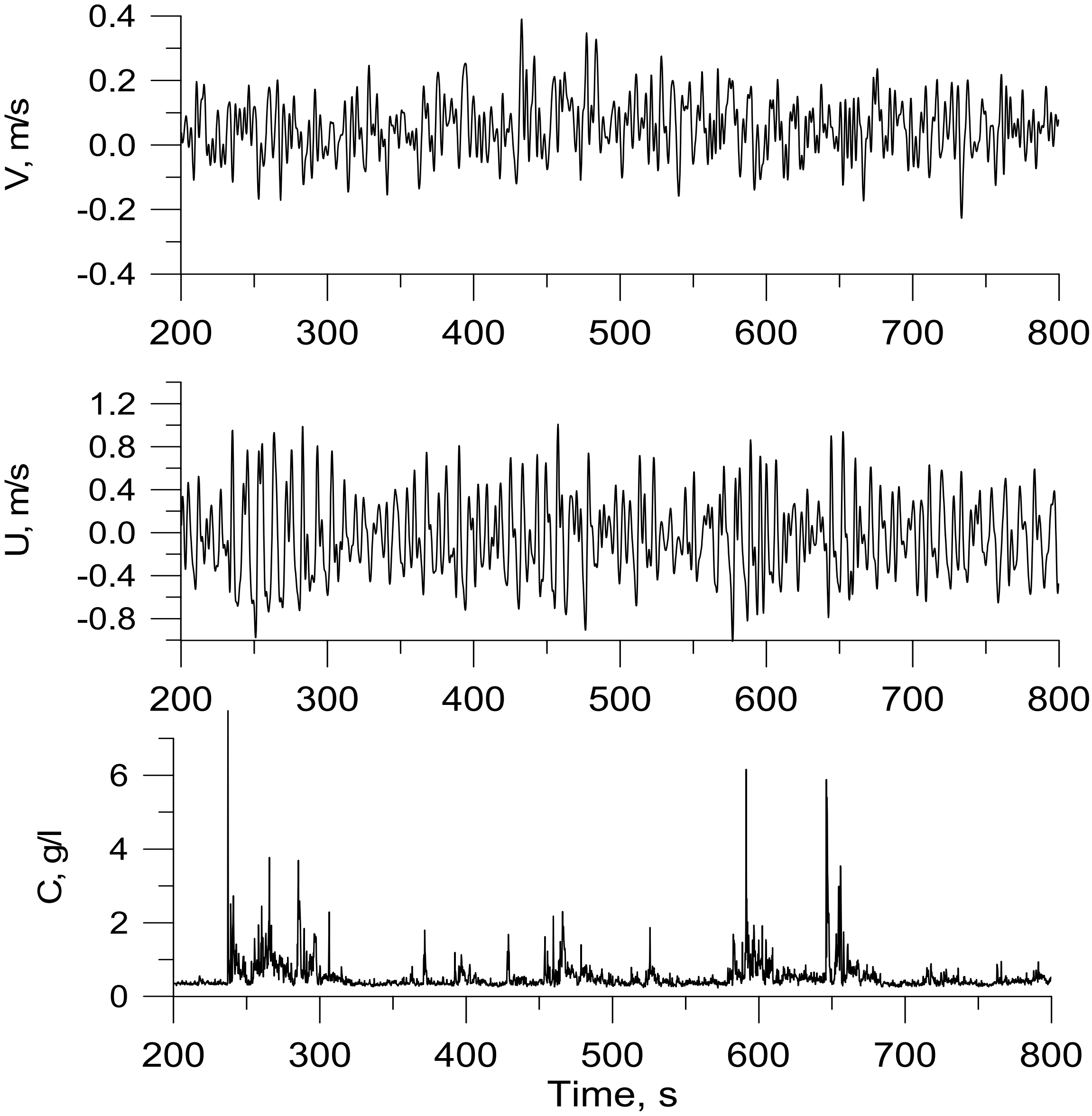

Fig. 10. Temporal variation of suspended sand concentration (c), cross-shore velocity (u), longshore velocity (v).

In the breaking zone, where the group structure of waves degenerates because of energy dissipation (large waves are broken and the height of small waves decrease), the concentration fluctuations mainly take place in the infragravity wave band (Fig.11). Then, in some cases, significant values of the coherence between concentration and the cross-shore velocity of infragravity waves can be obtained. For most of the records, when sensors were placed in the middle part of the surf zone, the values of coherence between suspended sand concentration and cross-shore currents did not exceed 0.1 to 0.2 within the whole frequency band; that is close to the error of their determination. In these cases, the concentration spectra of the suspended sand have no local maxima and they are characterized by a monotonous increase of the spectral density when the frequency decreases.

The observed regularities can be explained by the fact, that the intensity and time scales of sand suspending in the breaking zone depends on the turbulence, which is induced from the water surface under breaking waves. Analyses of the concentration chronograms and the velocity components have shown that the emergence of sharp concentration-peaks is restricted to the moments, when the turbulent fluctuation of the cross- and longshore velocity starts (Fig.12). That testifies to the passing of a vortex or several vortexes through the measuring point. The appearance of such a rise of the turbulent velocity fluctuation and of corresponding peaks of sand concentration usually is not timed to a definite phase of the approaching waves and has no periodicity.

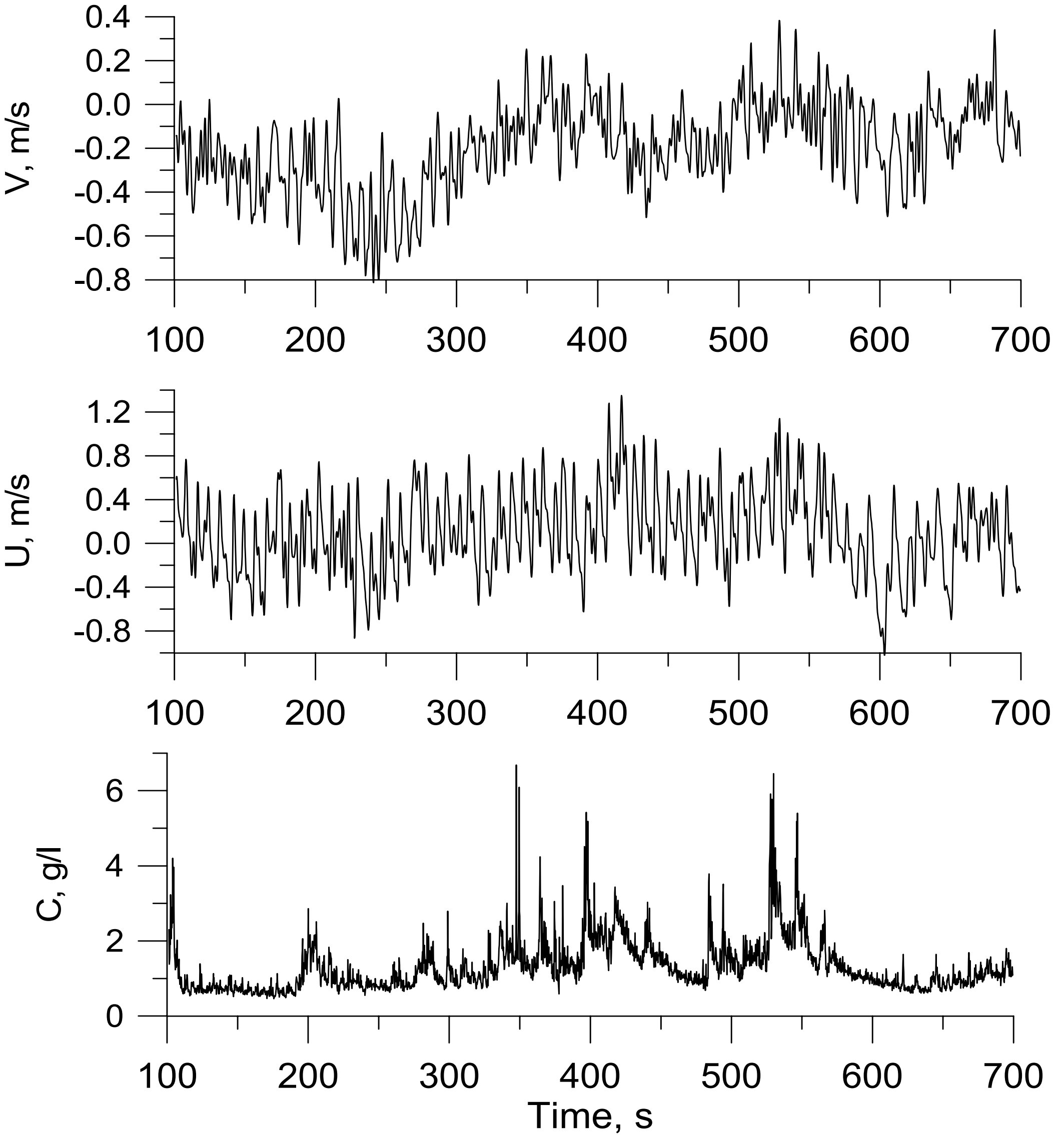

Fig.11. Temporal variation of suspended sand concentration (c), cross-shore velocity (u), longshore velocity (v).

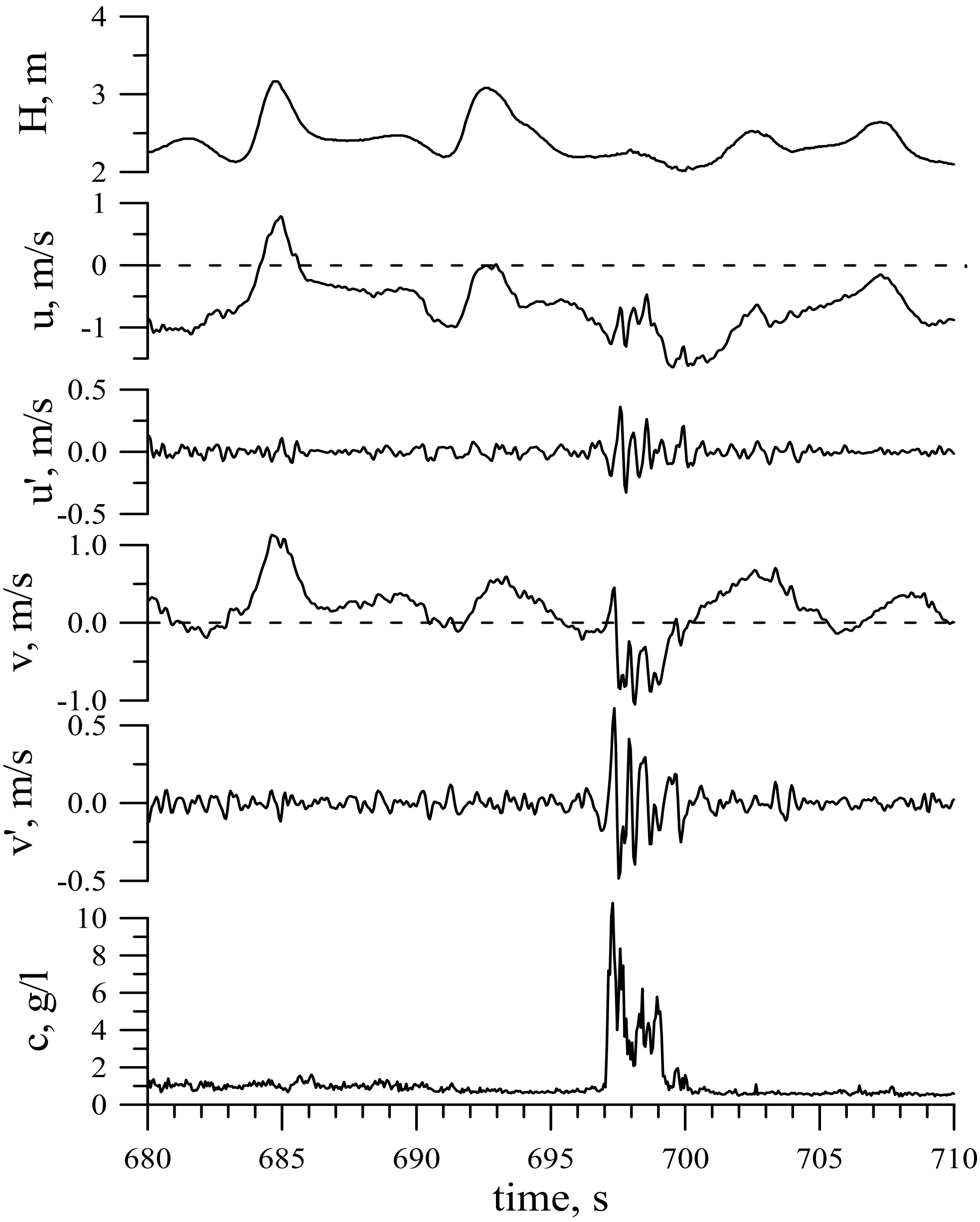

Fig.12. Temporal variation of suspended sand concentration (c), cross-shore velocity (u), longshore velocity (v) and its turbulent component u′, v′.

The analysis of the records has shown, that turbulent pulsations of velocities take place at frequencies of more than 0.8 Hz. Chronograms of the turbulent fluctuations were singled out by means of a digital filtering in the band of 0.8 Hz to 2.5 Hz. Sufficiently high correlations (coherence squared) between sand concentrations and turbulent fluctuations (instantaneous 2 D turbulent kinetic energy) at frequencies below 0.05 Hz show, that such a rise of turbulence within periods below 20 seconds is the basic factor of sand suspension at low frequencies. Such rises of turbulence in the wave breaking zone at low frequencies may depend either on vortexes penetrating from the surface water layer to the bottom during wave breaking, or on vortexes, which have been formed owing to hydrodynamic instabilities in the bottom boundary layer (Foster, Holman, Beach, 1994). The mechanism of their generation is poorly investigated up to now. The absence of an apparent periodicity of the sand concentration peak emergency and of a rise of turbulent pulsations in the breaking zone results in the formation of the concentration spectrum with the monotonous change of the spectral density, and, if there is no coherence between concentration and cross-shore velocities, also owing to the incoherence between turbulent velocity fluctuations and velocity fluctuations at the frequency of the approaching gravity and infragravity waves. Statistically significant values of the coherence between concentrations and cross-shore velocities have only been detected, when turbulent vortexes appeared periodically to a fixed wave phase, as usual for nonbroken waves, when local vortexes above the ripple bottom are rejected to the water column and the sign of the orbital velocity changes. This is confirmed by the shape of the co-spectrum of the concentration and the cross-shore velocities. The sand suspension in the moment when the velocity signal changes from positive to negative, results in an offshore sand transport. The sand is transported offshore with the same frequency as the group waves. This can be explained by the fact, that large waves with a long period and a lot of energy are present in velocity field, when the waves have a group structure. The crests of these waves are attached to the groups of low waves, and troughs are associated with the group of high waves. Therefore the suspended sand is more intensively transported offshore by the groups of large waves.

For the majority of the measuring series which had been carried out in the surf zone of Norderney, the oscillatory suspended sand flux was directed onshore, whereas the suspended sand flux associated with the time-mean current had been directed offshore. Basically, a value and direction of the net suspended sand flux (more than 80%) depended on the offshore directed undertow. In some cases, during low tide, the suspended sand flux in the offshore direction (associated with the averaged cross-shore currents) was practically completely compensated by the onshore directed oscillatory suspended sand flux. During the Northerner-experiment, the net cross-shore suspended sand flux at all points was directed offshore, almost all the time.

The lee vortex ejection is the basic mechanism of sand suspending for low energetic conditions, as they are existent in nearshore zones with slightly shoaling waves and rippled bed. The field measurements showed that suspension events coincide well with groups of high waves. For the 2D ripples case, the sand had only been suspended by waves with amplitude of the velocity which exceeded the rms-value for the investigated recording time interval (run). In this run such velocity corresponded to the shear stress of the bottom sand. The suspension events occurred twice per wave period and coincided with the time of the flow reversals during the deceleration and the acceleration phases.

Statistically significant values of coherence between the suspended sand and the cross-shore velocity fluctuations are recognized for the frequency of the wave spectrum peak and for the frequencies of the waves groups. At these frequencies the sediment concentration fluctuations lead the cross-shore velocity and its envelope. This leading has a magnitude of approximately $-\pi/2$ at the frequency of the wave spectrum peak and from $-\pi/2$ to 0 in the frequency band < 0.8 Hz.

With increasing wave shoaling and near-bottom velocity, the 2D bottom ripples transform into 3D ripples. In this case, the suspension events are formed at the measurement point only at the moment when the wave crest is passing and coincides with the flow reversal during the deceleration phase of the wave flow. From a comparison with the 2D ripples case we have observed some reductions of the coherence between the sediment concentration and the velocity envelope fluctuations for those frequencies which are smaller than 0.1 Hz. Concerning the frequency of the wave spectrum peak, the same conclusion applies for the phase lag between the suspended sediment concentration and the cross-shore velocity.

The mechanism of the vortex ejection due to the shear instability of the bottom boundary layer is the most probable reason for sand suspension from the bed in area which are located seaward of the wave breaking point. In those areas the waves are greatly deformed and the bottom is nearly flat. The suspension events coincide in time with the first half part of decelerating phase or with the flow reversal after the passing of the wave crest. For such conditions the statistically significant coherence between sediment concentration and cross-shore velocity is confirmed for the peak frequency of the wave spectrum and its first harmonic. The concentration follows the velocity fluctuations with phase lag of -□/4 at the frequency of wave spectrum peak. At the low frequency band (f<0.08 Hz) the sediment concentration poor correlate both with the velocity and its envelope.

The macroturbulent vortexes that are generated under plunging and spilling breakers are the driving forces for the mechanism of sand suspending in the surf zone. The most intensive suspension events are formed under plunging breaking waves. These events correspond in time to the forward front of cross-shore velocity. Because the wave induced vertical velocity at the moment of the steep forward front of the wave crest passing directed upward from the bottom, the suspended sediment flux is also directed away from the bottom. For the frequency of the wave spectrum peak and lower frequencies this is well confirmed by the Co-Spectra and the high coherence between the sediment concentration and the vertical component of the velocity. Inside the surf zone, where spilling breakers dominate, the high correlation between sediment concentration and turbulent kinetic energy is observed. Because the turbulence determinates the sediment suspending process and there is no direct dependency between the magnitudes of turbulent kinetic energy and the cross-shore velocity, it is no surprisingly that the correlation between the concentration and the velocity is very low, as demonstrated with the field data of the measurements. The most intensive suspension events are created by the largest turbulent vortexes. The presented examples for different recording runs demonstrate that at the moments of the most intensive suspension events the turbulent velocity in some times exceeds its r.m.s. value. This conclusion is in qualitatively agreement with the turbulence data under breaking waves, presented in the publications of Ting&Kirby (1995,1996), Cox&Kobayashi (1998) and Kos'yan et al (2001).

CONCLUSIONS

The analysis of field data, adduced above, affords to reveal the basic features of the spatial-temporal variability of the suspended sediment concentration in the nearshore zone. At time scales, when averaging is equal to the storm duration, the suspended sediment concentration increases monotonously, when the depth becomes less one. It is the largest in the wave breaking zone and then again it decreases when approaching the water edge. Seawards of the surf zone vertical profiles of the time-mean concentration and a mean diameter of suspended particles are characterized by large gradients in nearbottom layer, being 20-50 cm thick, and by its insufficient change above this layer when the distance increases. In this zone ripples on the bottom are present almost always. And sediment suspension depends of the blow-out of vortexes with sediments from behind the ripple crests to the water column up to several tens of centimeters above the bottom. This can explain the presence of high gradients of concentration in the nearbottom water layer.

Sand suspension above the rippled bottom occurs as sharp peaks of concentration at the frequency of approaching waves, and mainly groups of high waves. This is confirmed by statistically significant values of coherence between concentration, cross-shore velocity and its envelope. In the surf zone the suspended sediment concentration is distributed according to the exponential law with the distance from the bottom characteristic for the solution of the diffusion equation and a coefficient of the turbulent diffusion of particles being invariable, when the depth changes. The results of our research have shown that large vortexes formed near the water surface in the moments of the wave breaking are the main mechanism of sandy sediment suspending in this zone. Penetrating down the bottom such vortexes cause roughly even mixing of the water column. They, like tornado, suspend sediments above the bottom and distribute them at the depth according to the exponential law.

Modeling of vertical distribution of suspended sediments is limited by the absence of clear physical mechanisms of sediment suspension. The most effective way is the determination of relations between the suspended sediment concentration and turbulent kinetic energy, between which there are statistically significant values of coherence. To obtain such dependencies, the further research in field conditions of spatial-temporal variability of large-scale turbulence and sand suspension under irregular waves is necessary.

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