# FLUCTUATIONS OF INSTANTANEOUS VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT IN THE SURF ZONE

R.D. Kos'yan[1], M.V. Krylenko[2], C.E. Vincent[3]

Peculiarities and mechanisms of sand sediment suspension and vertical instantaneous distribution in the surf zone and on the scales of the wave period are discussed using data from field campaign “Novomikhailovka-03” and laboratory “Sistex-99” experiments.

## INTRODUCTION

At present there are no mathematical models that are sufficiently reliable for the prediction of spatial-temporal variability of suspended sediment concentration in the near shore zone where the most intensive suspension and sediment transport takes place. Many researchers currently rely on methods based on the utilization of time-averaged values of concentration and water velocity for calculation of sediment discharge in the near shore zone. However it is generally accepted that such methods are inexact from physical point of view as far as they do not take into actual mechanisms of sediment suspension and do not include the temporal fluctuations in both the suspended sediment flux and the water velocity.

The importance of the fluctuation component in the estimation of net flux of suspended sediment has been proved by many filed and laboratory experiments (Vincent and Green 1990; Kos’yan et al. 1996, 1997; Van Rijn et al. 1993). Now detailed knowledge of high-frequency fluctuations of vertical field of suspended sediment are necessary for the improvement of numerical modeling of vertical distribution of suspended sediment concentration under deformed and surf waves.

## EXPERIMENTS

The field experiment “Novomikhailovka-03” was carried out on the Russian section of the Black Sea coast in winter 2003 near the settlement of Novomikhailovka which has a long sandy beach. The submerged slope and beach are composed of fine-grained sand with median diameter from 0.21-0.24 mm. Measurement were fulfilled from the trestle, 300 m long. Synchronous recording of suspended sediment concentration, near-bottom water velocity and elevation of the free surface was carried out at the depths between 0.7 and 1.2 m. Measuring equipment was placed on a special carrier which was buried in the sand beneath the trestle. A schematic of the equipment positions on the carrier, vertical and horizontal distance between the devices is shown in Fig. 1.

Measurements of suspended sediment concentration was done with the help of 7 turbidimeters, which were spreaded in vertical and horizontal direction. In vertical direction 4 turbidimeters were placed at the horizons from 2-4 to 30 cm above the bottom. Measurements of cross-shore, along-shore and vertical components of water velocity were fulfilled with the help of electro-magnetic gauge of curent velocity and acoustic three-component measurer of current velocity “Vector”. Synchronous measurements of suspended sand concentration, components of water velocity and elevation of free surface were fulfilled in series from 20 minutes to one hour with the frequency of inquiry of turbidimeters and electro-magnetic sensors being 18.2 Hz, and that for the acoustic current meter “Vector” being 15.92 Hz.

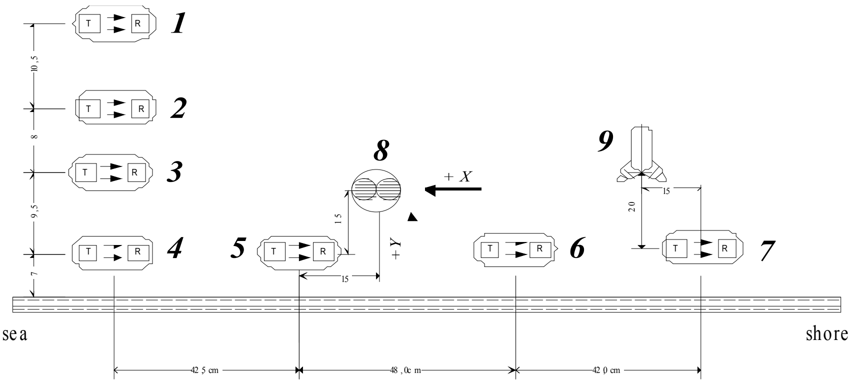


**Figure 1. A mobile carriage was use for equipment. The separation and heights of the sensors are shown. 1-7 are optical turbidimeters; 8 is a 2D (vertical and cross-shore) electro-magnetic current meter; 9 is a “Vector” acoustical current meter. A sand level gauge was buried into the sand.**

The “Sistex-99” laboratory experiments (Vincent, Hanes 2002) took place in large wave channel at the University of Hanover in Germany. The total length of the channel is 300 m; it is 5m wide is and 7 m deep although water depths of only 4-5m were used in Sistex-99. A sand bed 0.57m thick was formed of well-sorted sand, with a median diameter of 0.24 mm. Waves were generated by means of mobile wave plates. A sand beach with a slope of 6 degree absorbs wave energy at the end of the channel.

Tests were carried out using irregular waves, waves with clear group structure and monochromatic waves, in the course of the experiments. In every test a vertical profile of suspended sediment concentration, two components of water velocity and

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elevation of free surface were measured. Instruments for measurements of suspended sediment concentration and water velocity components were fixed on the frame cantilevered ~1m out from the channel wall. Measurements of water velocity were measured 10-15 cm above the bottom using an acoustic Doppler velocity meter (ADV). Wave-wires placed along the channel wall recorded the instantaneous position of the water surface. An acoustic backscatter sensor (ABS) was mounted ~0.45 m above the bottom to measure the suspended sediment concentration. Backscatter was measured at 101 points a vertical direction at 5 mm intervals with the frequency of 3.133 Hz. Acoustic backscatter profile, components of water velocity and elevation of free surface were recorded synchronously in time series of 2050 readings (~11 minutes). The ABS was subsequently calibrated in a recirculating tank using sand from the channel and the backscatter profiles converted to suspended sand concentration profiles.

## RESULTS

In the course of these experiments synchronous recordings of suspended sediment concentrations were measured at the different distances from the bottom, synchronous with elevations of the free surface and water velocity fluctuations. Fig. 2 shows time series of concentrations at 4 levels derived from the ABS; Fig. 3 show fragments of the recording from four turbidimeters placed at the different distances from the bottom and the synchronous water velocities from the "Vector" ADV.

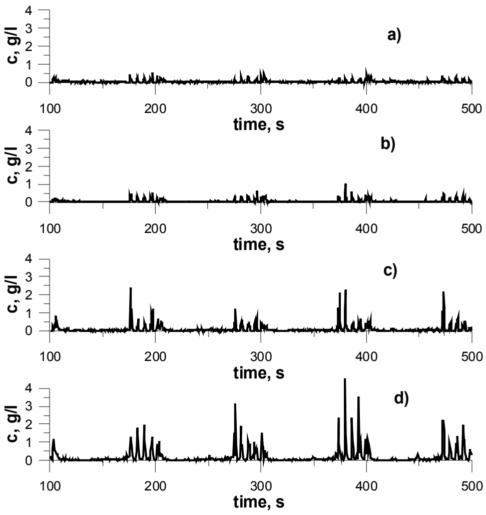



**Figure 2. Fragment of ABS recording of the suspended sediment concentration under a repeating group of waves (wave period 6.1s) of ~100s length, a) 10cm, b) 7cm, c) 4cm and d) 2cm from bed, "Sistex-99".**

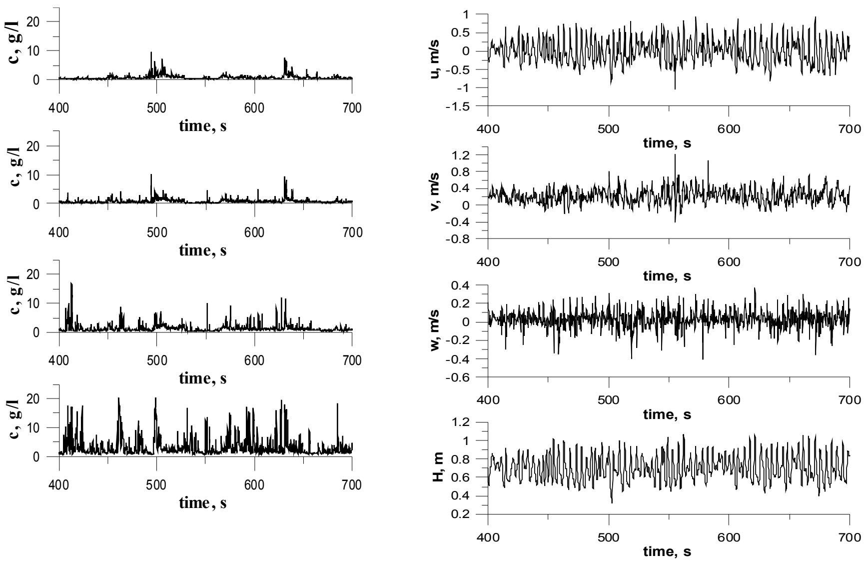



**Figure 3. Fragment of recording of suspended sediment concentration (turbidimeters 1-4 top-down) and the synchronous fragment of "Vector" recording from "Novomikhaiovka-03", where u- is the cross-shore, v- along-shore component, w- vertical component of velocity and H is the elevation of free surface.**

The form of vertical profiles of suspended sediment concentration change very quickly with time and deviate significantly from the mean of suspended sediment concentration (Fig. 4). When analyzing high-frequency fluctuations of vertical profile of suspended sediment concentration, we singled out several characteristic types of vertical distribution of concentration (Fig. 5).

As a general rule, a vertical profile close to logarithmic curve (Fig. 5a) is present under small waves between groups of large waves, when water velocities are not large and diffusion processes prevail in the formation of suspended sediment field.

In the second case (Fig. 5b) high values of suspended sediment concentration are observed at the level of 4 cm over the bed. They decrease sharply towards the surface. The concentration gradient decreases by ~1g/l per cm in height. Suspended sand only is restricted to near-bottom layer and it sand does not penetrate into superposed layers.

A third type of vertical distribution of concentration (Fig. 5c) is observed during the passage of large waves or during wave collapse when the vertical profile is nearly linear. Sand suspended from the bottom can rise at the height of several tens of centimeters above the bottom with maximum vertical gradients of concentration 20-30 cm above the bottom.

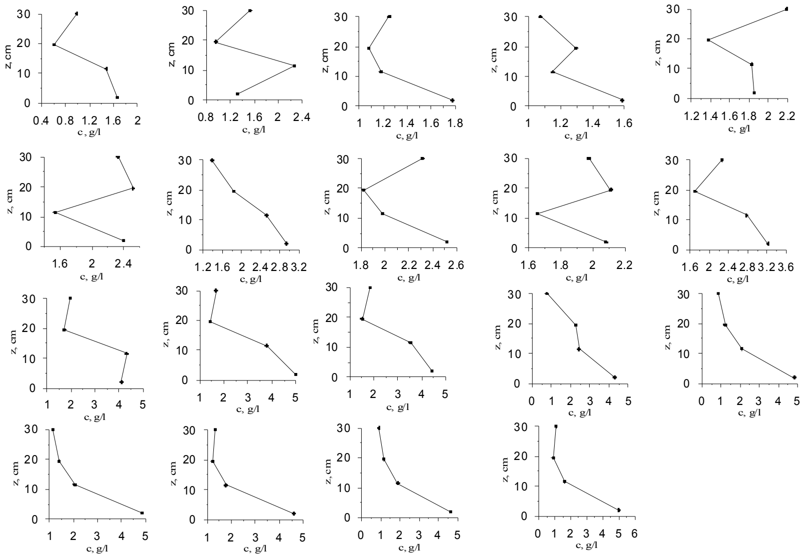



**Figure 4. High-frequency fluctuations of vertical profile of suspended sediment concentration during one second (frequency is 18.2 Hz).**

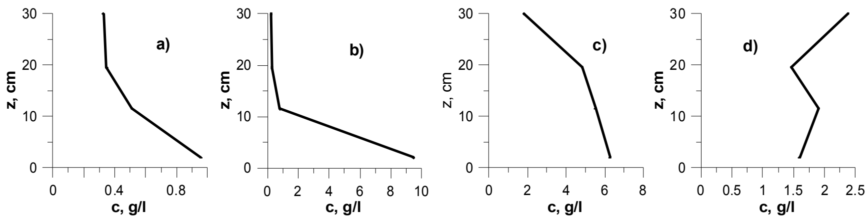



**Figure 5. Four characteristic types of vertical distribution of suspended sediment concentration from the field experiments "Novomikhaiovka-03".**

Fig. 5d shows a fourth type of vertical distribution of suspended sand is an irregular profile. Concentration of suspended sediment in the most remote from the bottom layer may be higher than that near the bottom. Alternation of layers with high and low values of suspended sediment concentration is typical. Such a kind of vertical profile of concentration prevails after the passing of high waves when a cloud of suspended sand separated from the bottom is transported by the flow and gradually disperses and settles. Fig. 6 shows a cloud of suspended sediments during one second which passes the gauges under the wave trough at the distance of 15 cm from the sea bed. In this moment there is no sand suspension from the bottom. Advection processes play a major role in formation of such a vertical distribution of sediments.

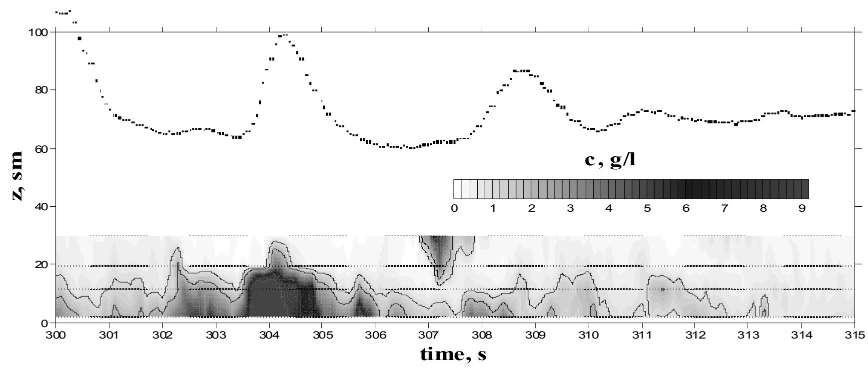



**Figure 6. Chronogram of temporal fluctuations of the field of suspended sediment concentration and elevation of water surface.**

Analysis of chronograms of suspended sediment concentration at different horizons suggests that sediment suspension occurs in pulses 5-10 seconds long (Fig. 7). Concentration peaks appear almost simultaneously at all horizons without obvious time delay between horizons, which testifies to a convective nature of sand suspension from the bottom. Peaks occur mainly around the time of passage of the crest of large waves. The height to which the cloud of suspended sediment rises above the bottom varies but, as a rule, it does exceed 10 cm.

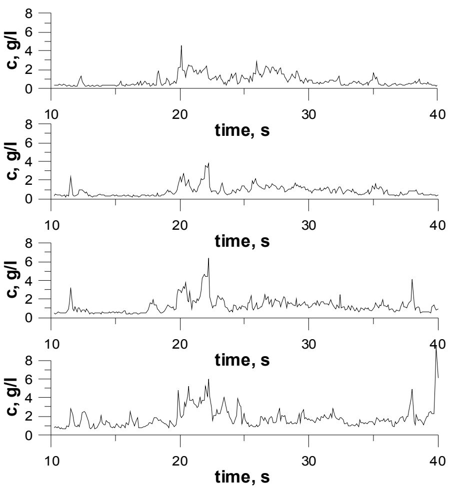



**Figure 7. 30-second fragment of recording of suspended sediment concentration. Turbidimeters 1-4 top-down, "Novomikhaiovka-03".**

Fig. 8 shows temporal changes of the profile of suspended sand concentration as a pulse of suspended sand concentration develops and decays, from concave profile at the beginning of the pulse to a convex one in the moments around the largest concentration within the peak. The convex shape of the vertical profile of suspended sediment concentration is consisted with the convective nature of suspension process. It supports the hypothesis of Nielsen (Nielsen 1979) that sand suspending from the bottom is distribution through the water column occurs due to its capture and transport of by vortexes under passing waves (Kos'yan et al. 2003).

The analysis of both laboratory and experimental data has shown that group structure of waves greatly influences the process of vertical profile formation under certain waves within the group. This influence of group wave structure upon the formation of the field of suspended sediment concentration under individual waves has been noted previously (Vincent & Hanes 2002; Williams et al. 2001).

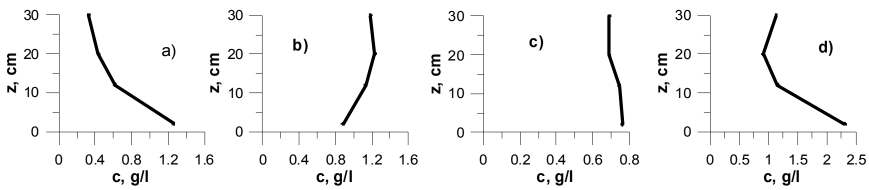



**Figure 8. Changes of vertical profile of suspended sand concentration during the development and decay of a concentration peak over ~10 seconds (a– beginning; b, c– middle, d- end of the peak).**

Intensification of sediment suspension under groups of large waves tends to occur after the passing of maximum waves in group and then gradually decays towards the trough of the geometric envelop of wave group (Fig. 9). Owing to this, vertical distribution of suspended sediment concentration under waves of the same height can be essentially different depending of the wave position in the group. Fig. 10 shows vertical profiles of distribution of suspended sediment concentration under two waves of approximately equal height, water velocity in the moments of passing of chosen waves is also similar. Values of suspended sediment concentration under the wave in the end of the group of large waves are several times larger than under similar wave in the beginning of the group. Analogous influence of group structure of waves upon the vertical profile of suspended sediment concentration can also be observed in real storm conditions (Fig. 11).

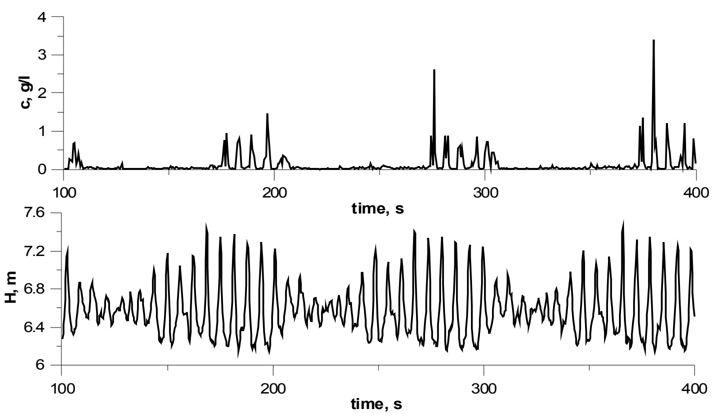



**Figure 9. Chronograms of suspended sediment concentration (C) at 2cm above the bed, and elevations of water surface from "Sistex-99".**

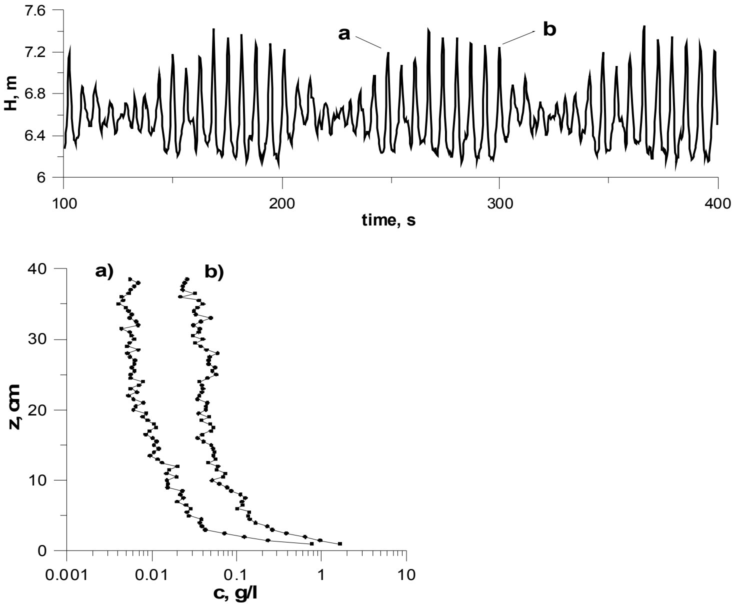
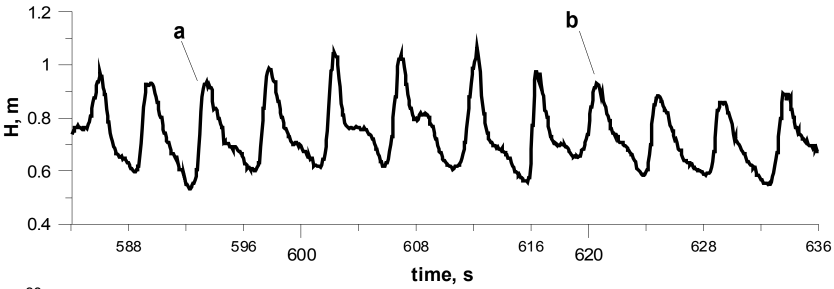



**Figure 10. Vertical distribution of suspended sediment concentration under waves with equal height in the beginning (wave is marked as *a*) and in the end (wave is marked as *b*), «Sistex-99». The period of averaging is 6 seconds.**

Examination of fluctuations in the shape and magnitude of the vertical profile of suspended sediment concentration on the scales of individual waves has shown that it can essentially change during a single wave period. Increase in suspension of sediment concentration within the nearbottom water layer generally happens around after the passage of a large wave crest (Fig. 12), during the phase of the flow deceleration due to turbulent vortexes which are formed behind the crests of the ripples. This correlates well with a hypothesis about ejection of turbulent vortexes from the ripple crests in the moment of change of sign of water velocity (Nielsen 1979, Black and Vincent 2001).

It was noted that, when values of Shields criterion do not exceed critical values under the wave crests, the vertical profile of concentration changes only slightly during the whole wave period. Concentration gradually decreased away from the bottom (Fig. 13).



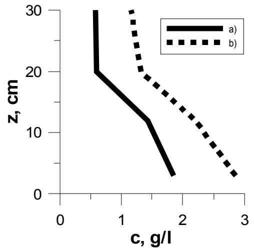




**Figure 11. Vertical distribution of suspended sediment concentration under waves with the equal height near the beginning (solid line, wave is marked as *a* above) and near the end of a wave group (dashed line, wave is marked as *b* above), "Novomikhailovka-03". The averaging period is 4 seconds.**

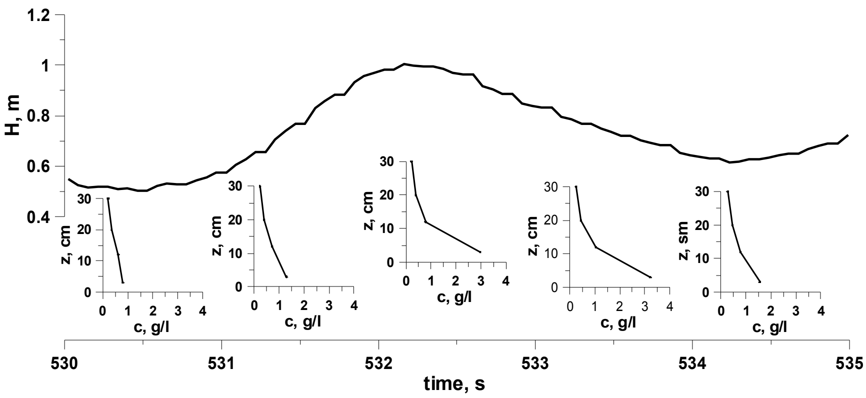



**Figure 12. Fluctuations of vertical profile of suspended sediment concentration during the wave period (interval of averaging is 1 s), z is distance from the bottom, c is concentration, "Novomikhailovka-03".**

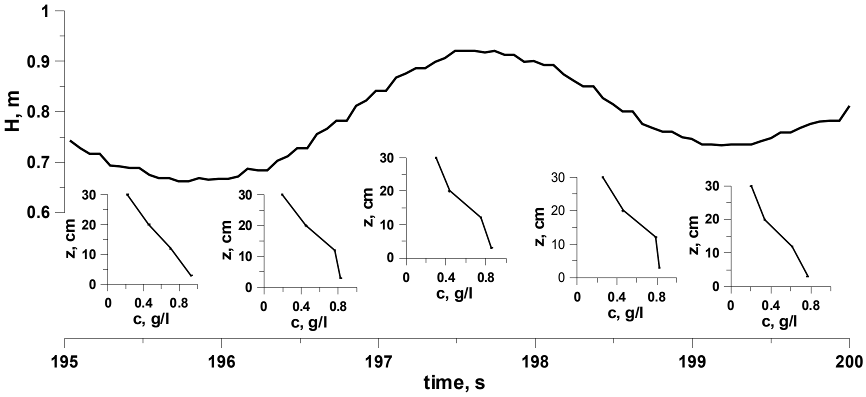



**Figure 13. Temporal variability of vertical distribution of suspended sediment concentration under deformed low waves (interval of averaging is 1 s), z is distance from the bottom and c concentration, "Novomikhailovka-03".**

When a wave is near the beginning of a group of large waves, suspended sediment concentration changes during the whole wave period mainly within the near bottom layer (Fig. 14). Intensification of sediment suspension was observed under large waves in the second part of the group after the change of sign of the water velocity (Fig. 15). Suspended sediment is captured from the bottom and penetrates for upwards for tens of centimeters; during the all phases of wave concentration is considerably higher than under individual waves in the beginning of the wave group.

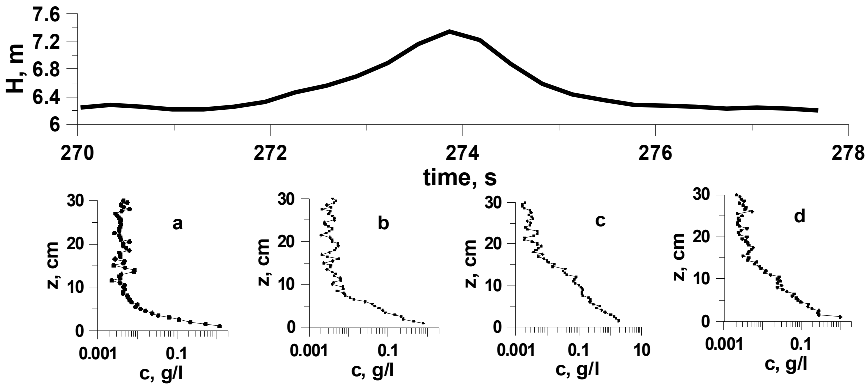



**Figure 14. Changes in the vertical profile of suspended sediment concentration under the wave near the beginning of the group of large waves. "Sistex-99", averaging period is 2 seconds.**

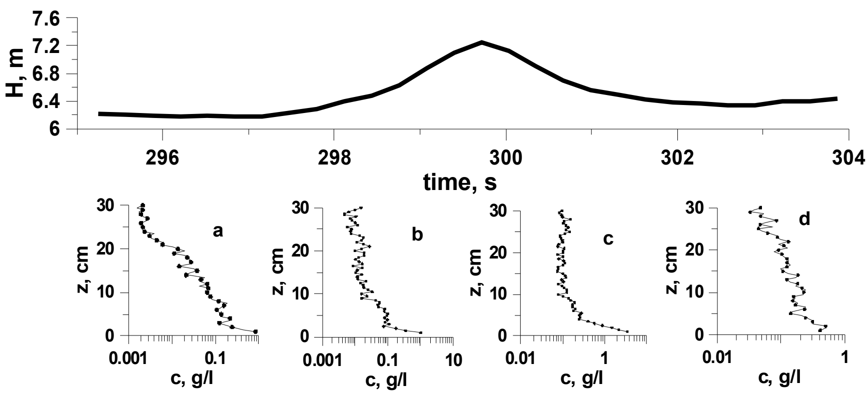



**Figure 15. Changes in the vertical profile of suspended sediment concentration under the wave near the end of the group of large waves. "Sistex-99", averaging period is 2 seconds.**

Fig. 16 shows chronograms of suspended sediment concentration at 4, 11, 20, 30 cm above the bottom and that of calculated turbulent energy. It is seen that a considerable increase of the level of turbulence occurs in the flow resulting in the appearing of a peak of suspended sediment concentration which covers all levels. The increase of turbulent energy lifts the suspended sediment to a height of tens of centimeters. The third type (Fig. 5 (c)) of vertical distribution of suspended sediment concentration is formed.

Functions of coherence between turbulent kinetic energy (TKE) and suspended sediment concentration are presented in Fig. 17. Values of coherence function are significant at the frequency of the wave group, and coherence increases when moving away from the bottom. This indicates the important role of low-frequency fluctuations of turbulent energy in the formation of the field of suspended sediment concentration at the horizons remote from the bottom.

The data presented show that fluctuations of vertical distribution of suspended sediment concentration near the bottom is very largely initiated by individual waves; water velocity under crests of which is rather high. Penetration of clouds of suspended sand into the water column is not connected statistically with the passing of individual waves. In this case hydro-dynamical processes at the frequency of group waves and features of a group wave structure are determining factors. Thus, high-frequency fluctuations of vertical distribution of suspended sediment concentration is determined both by parameters of individual waves and by low-frequency characteristics of the waves.

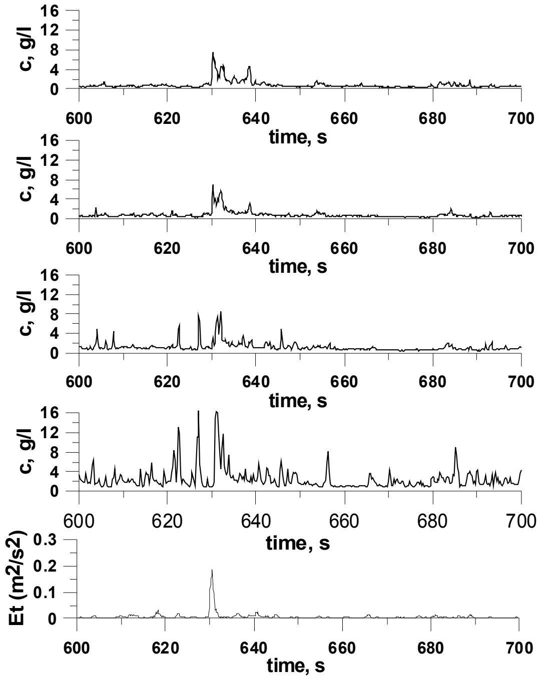



Figure 16. A fragment of recording from turbidimeters placed at the distance of 30, 20, 11 and 4 cm above the bottom and that of turbulent energy from top to down, “Novomikhailovka-03”.

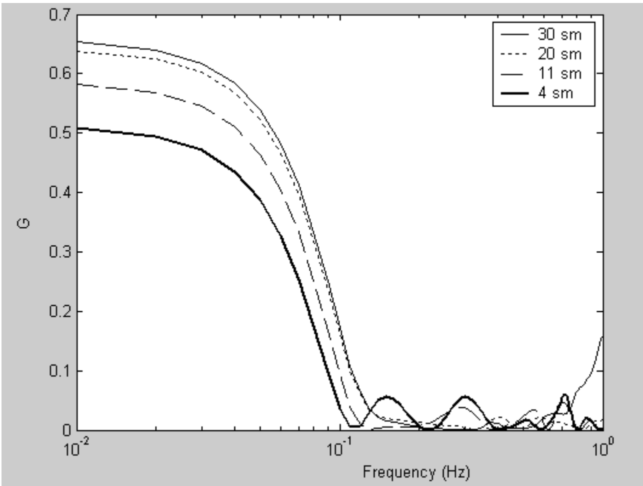



Figure 17. A square of coherence function between energy of coherence and suspended sediment concentration. A distance of a given horizon from the bottom is indicated in the description, “Novomikhailovka-03”.

**ACKNOWLEDGMENTS**

The work is carried out under financial support of the Russian Foundation of Basic Research, grant № 05-05-64145 and grant NATO CLG – Ref. 981587.

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KEYWORDS – ICCE 2006

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Abstract number - 106

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Surfzone processes
Sediment transport