LARGE-SCALE LABORATORY MODELING OF SUSPENDED SAND CONCENTRATION FLUCTUATIONS UNDER IRREGULAR WAVES

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Abstract: The paper describes large-scale laboratory experiments performed with simultaneous measurements of suspended sand concentrations, free surface elevations and three-component velocities (including turbulent fluctuations) at several levels above the sea bed. The data from these experiments are used to develop a more correct description of the contribution of vertical velocity to the convective sand flux and the relationships between fluctuations of turbulent kinetic energy and wave energy dissipation for the estimation of local sand suspending and advection to the temporal variation of suspended sediment concentration.

INTRODUCTION

In traditional models only the time averaged characteristics of water circulation, sediment and pollutant transport processes are considered, without taking into account the group structure of waves, their transformation within the coastal zone and contribution of phase shifts between sediments and the fluid at different frequencies of an irregular wave spectrum. Some advances have been achieved as a result of field research in the last years, which show that the group structure of waves and infragravity waves have considerable influence upon the sediment transport in the zone of the wave transformation and breaking. Such investigations need to be continued with the emphasis on precise laboratory experiment using a broad range of parameters.

The hypothesis is that a physical model of temporal-spatial fluctuations of sand suspension and transport is possible on the basis of the mechanisms of convective suspension, determination of phase and amplitude ratios between the suspended sediment concentration (SSC), turbulent kinetic energy (TKE) and losses of wave energy due to wave breaking, allowing the estimation of the contribution of local convection, diffusion and advection of sediments to form the concentration field over rippled and plane beds.

Existing data allow neither the correct discrimination of the contribution of vertical velocity to the convective sand flux nor the relationships between fluctuations of turbulent kinetic energy and wave energy dissipation, to the estimation of local sand suspending and advection to the temporal variations of SSC (Kos'yan et al, 2001). Therefore in 2006 new large-scale laboratory experiments ("Hannover-2006") were performed in the LARGE WAVE CHANNEL (GWK) of the Coastal Research Centre (FZK) in Hannover. Simultaneous measurements of SSC, free surface elevations and three-component velocities (including turbulent fluctuations) were carried out at several levels above the sea bed.

LARGE – SCALE EXPERIMENTS

The physical simulation of dynamic processes in the coastal zone at prototype scale is extremely important to keep the similarity of both hydrodynamic and lithodynamic processes. The LARGE WAVE CHANNEL (GWK) of the Coastal Research Centre (FZK) in Hannover has a total length of 303 m, a width of 5 m, a total depth of 7 m and the maximum water depth is 5 m. For the experiments a sand bed was installed (Fig. 1). The wave generator is absorption controlled and allows waves up to 2 m depending of the local water depth along the channel. The measuring equipment used for the experiments consists of:

- Wave gauges (resistance wire type) for measurement of surface elevation along the wave channel (Fig.1)
- Optical turbidimeters for measurement of suspended sediment concentration at 4 different levels above the sea bottom (Fig. 2A);
- 3-component acoustic velocity sensors (type Vector) for measurement of wave induced currents at 2 different levels above sea bottom (Fig. 2 B);
- Sediment accumulators at different levels (Fig. 2E)

The analog sensor signals were sampled by a parallel 80-channel analog-to-digital converter (ADC) with a frequency of 40 Hz and recorded on a computer. A sample and hold modus guaranteed synchronization of all measured signals.

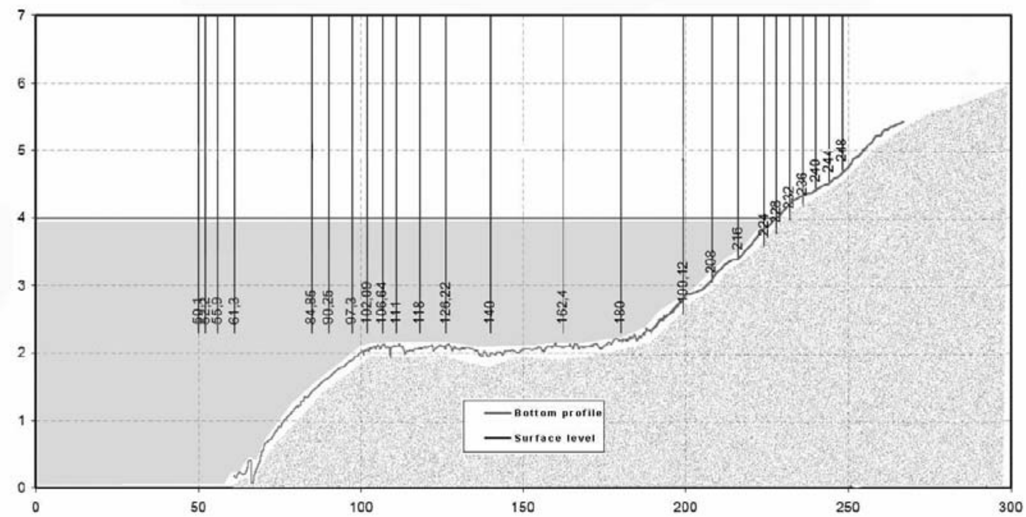

Fig.1. Longitudinal section of GWK with installed sand bed and wave gauges

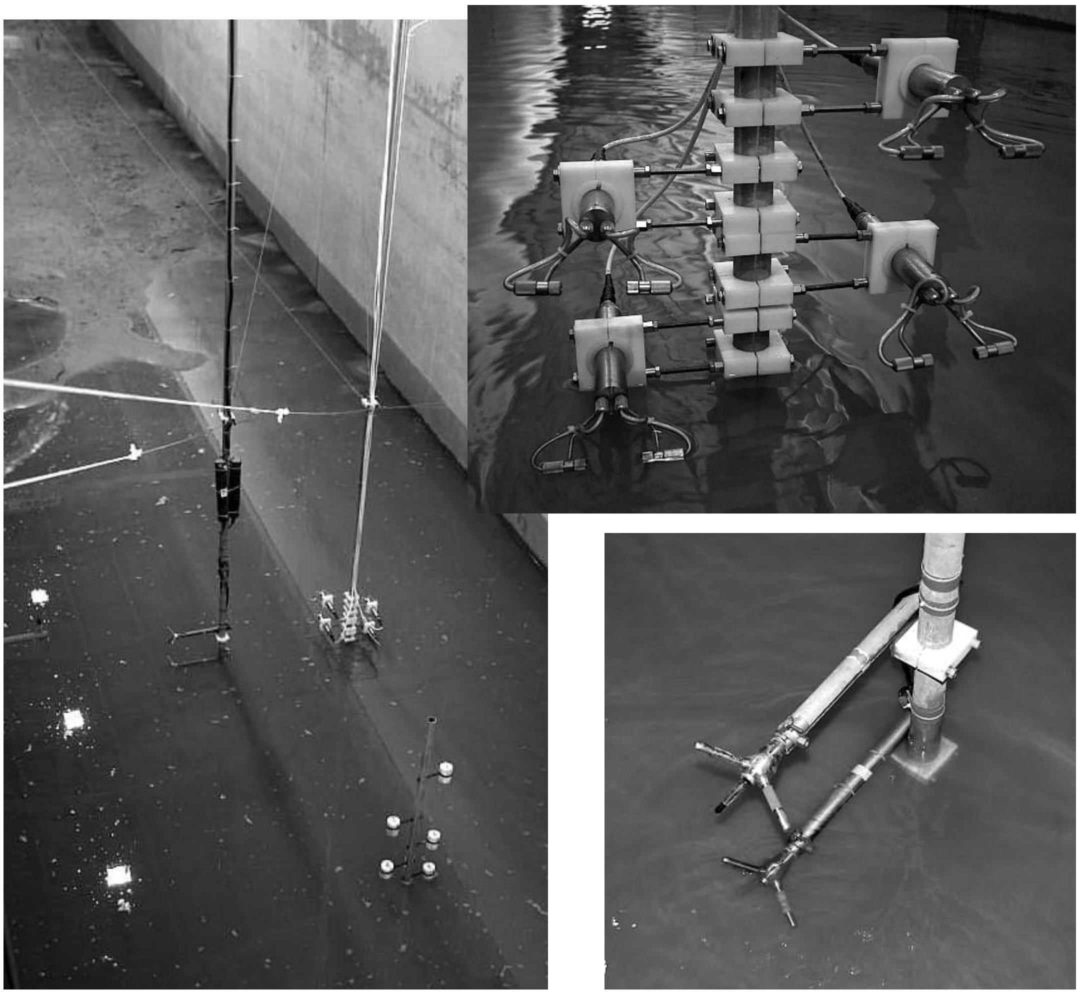
Fig. 2. Installed turbidimeters, velocity sensors (Nortek-Vector) and sediment accumulators (left hand photo). Positioning of turbidimeters (upper right photo) and velocity sensors (Nortek-Vector) (lower right photo)

Two main test series were performed with respect to the simulated wave spectra:

- Irregular waves with spectra characteristics occurring at the Black Sea
- Irregular waves with artificial spectra where the peak periods were kept constant (Tp = 5 s) and the significant wave heights and spectral steepnesses were changed consecutively (H_{sig} = 0.9 to1.1m, wave spectrum steepness index γ =1.0 to 10.0).

RESULTS

In the following some first results from the ongoing analysis are described. In Fig. 3 examples of synchronously recorded time histories for some sensor signals are plotted. The time histories in Fig. 3 show the suspended sediment concentration fluctuations measured at distances of 7, 15, 25 and 40cm above sea bottom (1 – 4), the surface elevation H (5) and the wave induced velocities, where v_x is the horizontal cross-shore component (6) and v_y the vertical component (7).

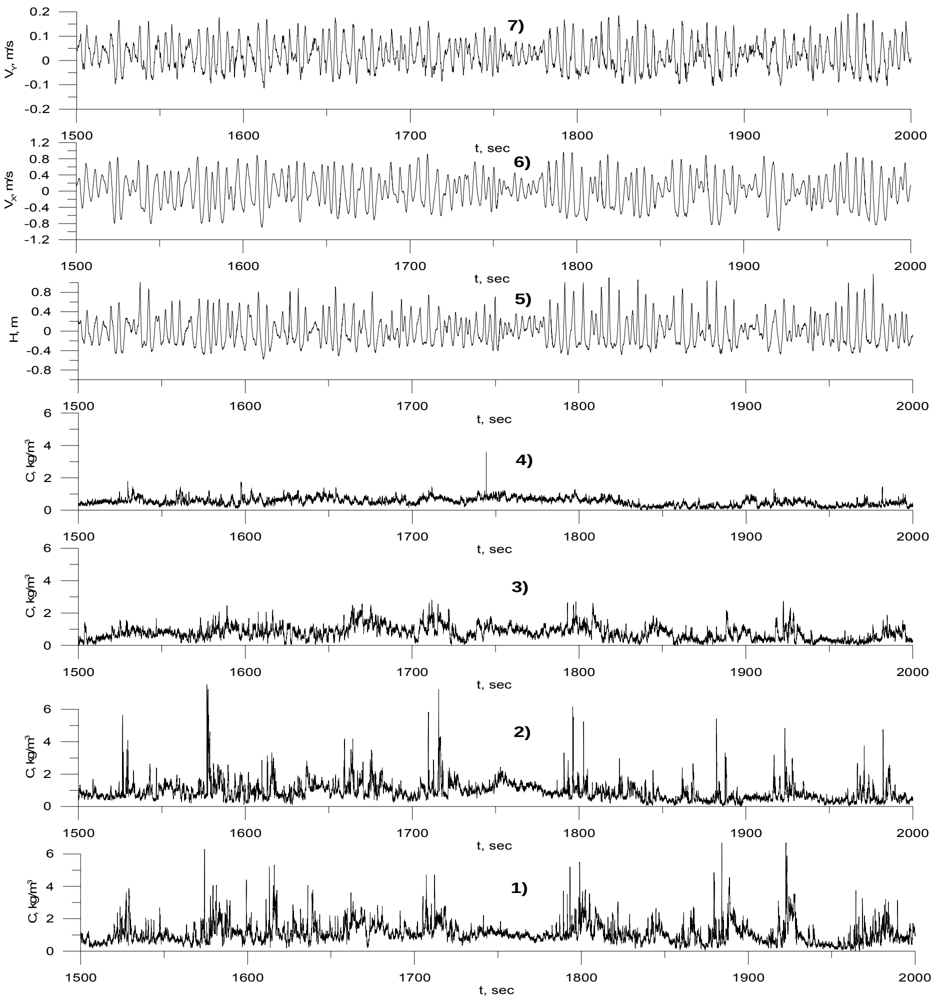

Fig. 3. Fragments of the recorded suspended sediment concentration fluctuations (turbidimeters 1-4 from 7, 15, 25, 40cm above sea bottom), the synchronous free surface elevation H (5) and the water velocities from the Vector sensor, where v_x is the cross-shore (6) and v_y the vertical component (7) of velocity.

The shapes of vertical profiles of suspended sediment concentration (some examples are shown in Fig. 4) vary quickly with time and deviate significantly from the mean values of suspended sediment concentration. When analyzing high-frequency fluctuations of vertical profile of suspended sediment concentration, several characteristic types of vertical concentration distribution were found as plotted in Fig. 5.

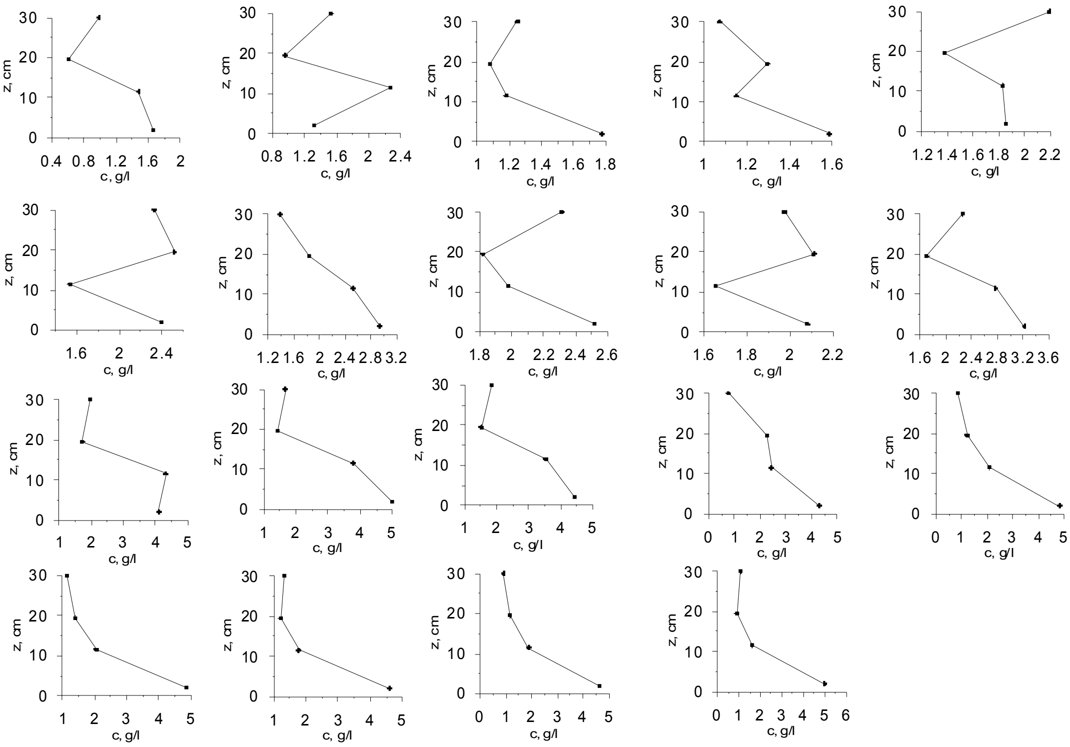

Fig. 4. High-frequency fluctuations of vertical profiles of suspended sediment concentration, each analyzed for a one second time segment from the time histories.

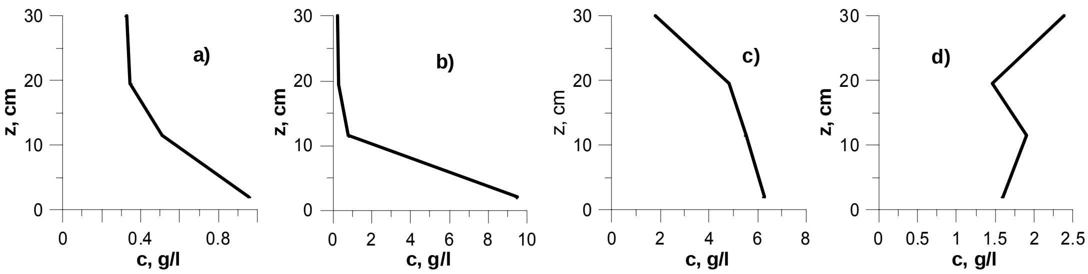

Fig. 5. Characteristic types of vertical distributions of suspended sediment concentration.

In general a vertical profile close to a logarithmic curve (Fig. 5a) is present under small waves between groups of large waves, when wave induced velocities are small 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 sea bed. They decrease sharply towards the surface. The concentration gradient decreases by ~1g/l per cm in vertical height. Suspended sand is restricted to near-bottom layer and does not penetrate into higher layers. A third type of vertical concentration distribution (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 to heights of several tens of centimetres above the bottom with maximum vertical gradients of concentration 20-30 cm above the bottom.

Another type of vertical distribution is an irregular profile (Fig. 5d). Concentration of suspended sediment further away from the bottom layer may be higher than near to the bottom. Alternation of layers with high and low values of suspended sediment concentration is typical. Such vertical profiles of concentration prevail after the passage of high waves when a cloud of suspended sand separates from the bottom, is transported by the flow and gradually disperses and settles. In Fig. 6 a cloud of suspended sediments of about one second duration is shown between 307 and 308 on the time axis, which occurs under the wave trough at the distance of 15 cm from sea bed. At 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.

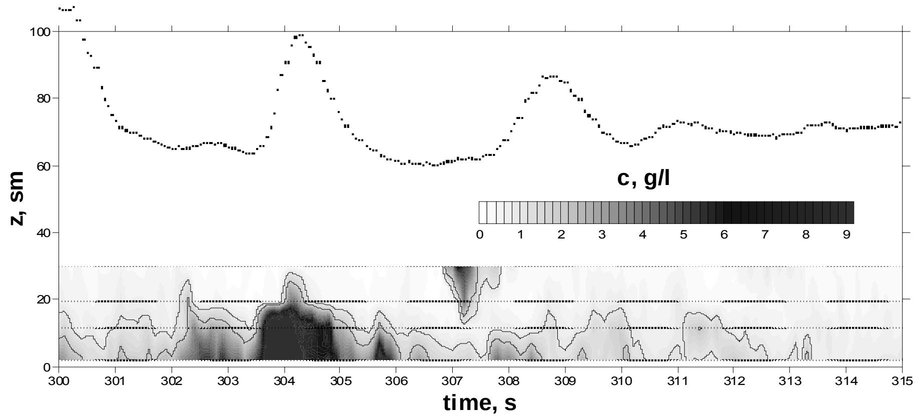

Fig.6. Chronogram of temporal fluctuations of the field of suspended sediment concentration and surface elevation

The analyzed data show that fluctuations of vertical distribution of suspended sediment concentration near the bottom is initiated by individual waves particularly under crests where water velocity is rather high. Penetration of clouds of suspended sand into the water column is not connected statistically with the passage 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 the vertical distribution of suspended sediment concentration is determined both by the parameters of individual waves and by low-frequency characteristics of the waves. The fluctuations of the vertical profiles of SSC described in detail in Kos'yan et al. (2007).

A model of the fluctuations of suspended sand concentration above a flat bottom under waves with pronounced group structure was constructed and checked against the results of our laboratory experiments "HANNOVER-2006" and those of

"SISTEX'99" (Ribberink et al., 2000). Series of synchronous recording of suspended sediment concentration, components of water velocity and elevation of free surface of waves with group structure were selected for modeling and verification of the model. The model is based on one-dimensional diffusion equation for suspended sediment concentration

$$\frac{\partial C}{\partial t} = w_s \cdot \frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\left(\varepsilon_s \cdot \frac{\partial C}{\partial z}\right) \qquad (1)$$

where C(z,t) is suspended sediment concentration, ε_s is a coefficient of turbulent diffusion of suspended particles, w_s is settling velocity, *t* is time and z is the vertical coordinate.

According to this equation a change of concentration in time at any horizon from the bottom is defined by the change of balance of suspended sediment flow in vertical direction owing to the particle settling (the first term on the right hand side of equation 1) and due to the suspended sediment flux from the bottom (the second term on the right hand side).

At the free water surface suspended sediment flow is considered to be equal to zero:

$$\varepsilon_s \cdot \frac{\partial C}{\partial z} + w_s \cdot C = 0 \qquad (2)$$

Near the bottom suspended sediment concentration is described by:

$$C(0,t)=A\ p(t), \qquad (3)$$

where p(t) is a function of local ejection of suspended sediment (pick-up function). When individual waves are passing, sediment suspension takes place not during the whole period, but as a quick ejection of a cloud of suspended sediment. The analysis of field data has shown that only one ejection happens during the phase of decrease from maximum to zero of the horizontal component of velocity. This fact is taken into consideration by coefficient A, that changes within $0 \le A \le 1$, and is equal to 1 during the suspension phase and is zero at other times. It applies to both single waves and to group of waves in terms of their envelope.

The results of measurements of the velocity profile, the elevation of the level and suspended sediment concentration under waves with a pronounced group structure were taken as input data. The convective sediment flux is described by formula based on the field and laboratory data. The sediment entrainment from the bottom is represented by a pick-up function that takes into account the phase shift between the suspended sand concentration and the flow velocity.

Mean parameters of the waves, necessary for calculation, were found from the spectral characteristics of waves. An even grid pitch in depth and in time, was used for calculation with $\Delta z = 0.005$ m and $\Delta t = 0.228$ s.

Fig 7 shows a comparison of concentration chronograms calculated using the model, with those measured at 5.5 cm from the bottom. Discrepancy in absolute values of the concentration peaks obtained by experiment and model can be explained by the fact that the model assumes a constant granulometric composition of suspended sediment in vertical direction and median diameter of suspended particles. This effects the particle settling velocity. In the course of our experiments it was confirmed that median diameter of suspended particles becomes smaller when moving away from the bottom, and consequently the value of settling velocity decreases. This fact will be taken into account in the future modelling. Six regions of suspension are clearly seen in Fig. 7, corresponding to the passage of groups of waves (labelled 1-6 in Fig. 7).

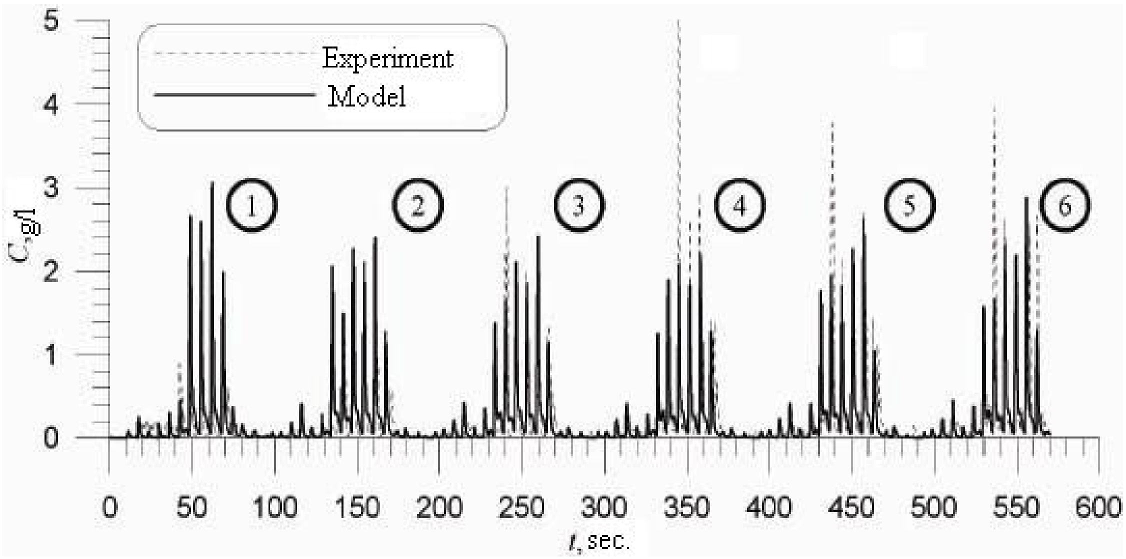

Fig.7. Comparison of concentration chronograms calculated on the model with those measured at 5.5 cm above sea bottom

The results obtained demonstrate a rather high coherence between modelled and observed suspended sand both at low frequencies and frequencies of the maximum of spectral density. This modelled time series of suspended sediment concentration agrees statistically with the experimental one so we can conclude that the model has been successfully elaborated for calculation of the fluctuations of suspended sediment concentration above a flat bottom under the influence of groups of waves. It takes into account the influence of group structure of waves and phases of individual waves upon the sediment suspension which is very important for modelling of fluctuations of suspended sediment concentration. The model demonstrates very well all qualitative peculiarities of sediment suspension in these given conditions. The predicted and measured concentrations coincide satisfactorily in time. The peaks coincide with the inflexion points on the vertical profile of velocity in the bottom boundary layer. This model is described more fully in Kos'yan et al, (2006).

Real processes of sediment suspension are more complex than the mechanisms which are put into the model. The present model of suspension of bottom sediments will be improved as a result of further observations from both experimental and theoretical investigations.

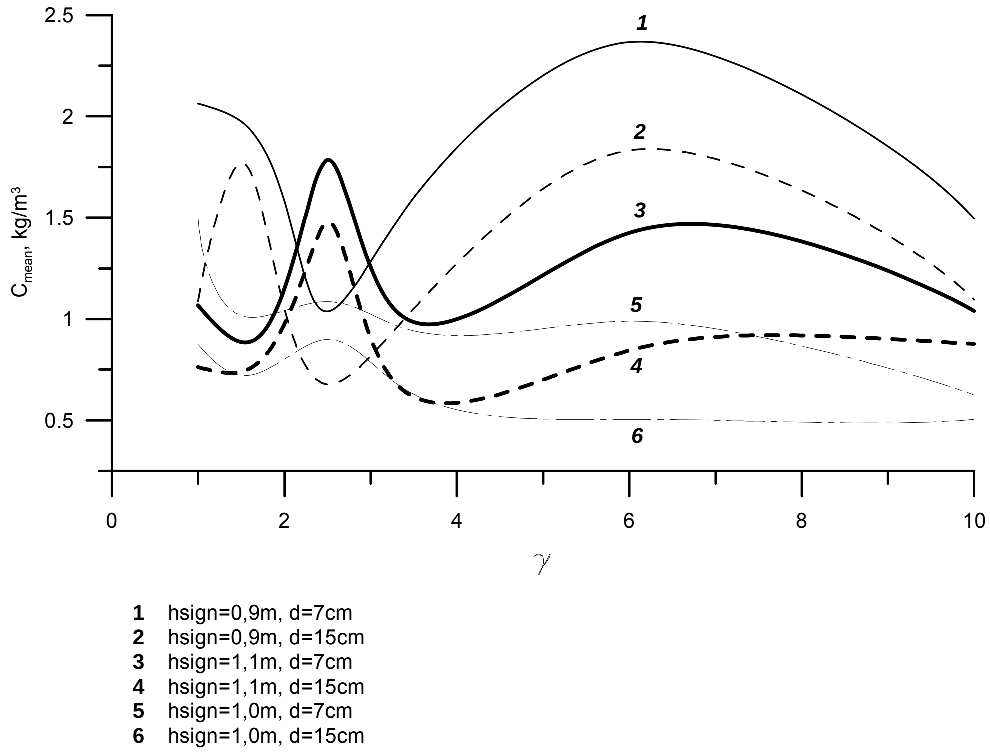

Fig. 8. Dependence of time averaged concentrations at two horizons (7 and 15 cm from sea bottom) for three significant waves heights (H_{sig} = 0.9, 1.0 and 1.1m) on spectral steepness.

One of the tasks of these experiments was to identify any dependence between values of suspended sediment concentration and the form of wave spectrum. Fig. 8 shows the dependence of averaged concentrations at two horizons (7 and 15 cm from the bottom) for three values of significant waves height (H_{sig}= 0.9, 1.0 and 1.1m) on spectral steepness. Fig. 9 shows spectra of suspended sediment concentration for different steepness (γ), and wave heights at the distance 7cm from the bottom.

From the figures it is seen that the form of wave spectrum greatly influences on the SSC values. With the same wave parameters the spectral steepness can alter the concentration by 2.5 times. There are some peaks of SSC values which occur at different steepnesses. Spectra of suspended sediment concentration also greatly depend on the wave spectra steepness. To explain and formulate any dependence we have to have many more new data.

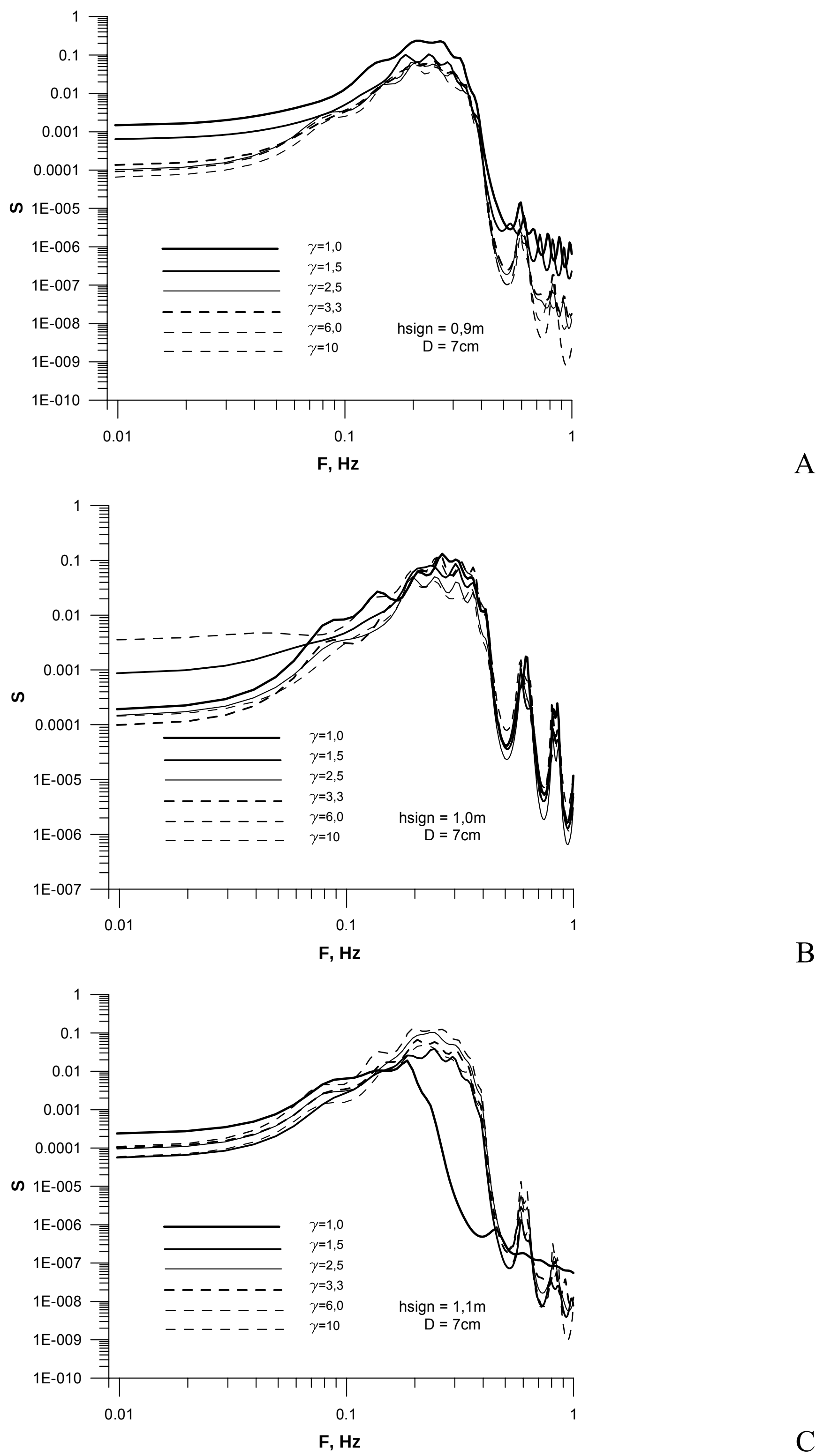

Fig.9. Spectra of suspended sediment concentration for different steepnesses (γ), and wave heights at 7cm above sea bottom. (A: H_{sig} = 0,9 m, B: H_{sig} = 1,0 m, C: H_{sig} = 1,1 m)

CONCLUSION

A series of investigations were conducted in the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Hannover which afforded an opportunity to model storm dynamic processes in the coastal zone at almost full-scale. This is most important because it turns out not to be possible to simultaneously similarity of hydrodynamic and lithodynamic processes under any scale of modelling. A data bank of unique experiments, modelling processes of an intensive storm was collected during a short experiment period. The analysis of this data bank gave the possibility of significantly advancing our understanding of storm dynamics and sediment flux in the coastal zone.

In the first stage of analysis of these observations we a) investigated the high-frequency fluctuations of the vertical profile of suspended sediment concentration; b) construct a model of which predicted the fluctuations of suspended sand concentration above a flat sandy bottom under waves with pronounced group structure and c) determined the dependence between values of suspended sediment concentration and the form of wave spectrum.

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