Modelling of the vertical distribution of suspended sediment concentration under waves with a group structure

Kos'yan R.D., Divinskiy B.V., Krylenko M.V., Vincent C.E.

Results of the modelling of the vertical distribution of suspended sediment concentration under the influence of waves with a pronounced group structure are presented in this paper. The reliability of the model has been checked against laboratory data from the SISTEX'99 experiment. Fluctuations of suspended sediment concentration, calculated by the model, correlate very well with the experimental data and reproduce the form, number and duration of concentration peaks rather well.

Index Terms—**Coastal zone, modelling, sediments, waves**

I. 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 shore zone. However the most intensive suspension and sediment transport takes place in this zone. Due to difficulties in making measurements in real marine conditions quantitative assessment and prediction of suspended sediment distribution in the coastal zone has been done by mathematical modelling, with the use of parameters obtained under laboratory conditions. To date, many models have been constructed of the distribution of time-averaged concentrations of the suspended sediments under the action of waves; a full review of such models was undertaken by Antsyferov and Akivis [1]. But a method based on the use of time-average values of concentration and water velocity does not take into consideration temporal fluctuations of suspended sediment flow and the resultant calculation may differ from real values by a factor of ten.

Earlier field [4, 10, 11, 18] and laboratory [14, 15] research has shown that the fluctuation component of sediment suspension is very important to the resultant transport of suspended sediments. Many models of spatial-temporal fluctuations of suspended sediment concentration are based on the idea of turbulent diffusion priority [5, 7] without taking into consideration the mechanisms by which sediment is resuspended, and this results in differences between field and calculated data [10, 11, 12 and 13].

In some models [5, 6, 7] spatial-temporal fluctuations of suspended sediment concentration in the wave flow are described as function of the instantaneous value of Shields parameter. Such models satisfactorily correlate with experimental data only for monochromatic waves, showing the correct phase shift of sediment when sediments are moving as a narrow belt, 1-2 cm thick, above the flat bed.

Field and laboratory experiments have shown the necessity of taking into account an oscillatory motion of water and the phase lag between fluctuations of suspended sediment concentration and water velocity at different levels from the bottom [10, 12, 14, 15]. It was revealed that duration and frequency of concentration peaks depends on the periodicity of groups of high waves and that of the number of waves in certain groups [2].

Modelling of the variability in the vertical distribution of suspended sand concentration above the flat bottom under waves with pronounced group structure is presented in this paper. The reliability of the model presented here is checked against the results of laboratory experiment "SISTEX'99". A series of synchronous measurements of suspended sediment concentration, components of water velocity and elevation of free surface were selected for modelling and verification of the results for the case of waves with a group structure.

II. DESCRIPTION OF THE EXPERIMENT

Data for modelling were obtained in the course of laboratory experiment "SISTEX'99" performed in the large wave canal at Hanover University in Germany [17]. The total length of the canal is 300 m, its width is 5 m, depth 7 m. The sandy bottom of the canal is composed of well-sorted sand with a mean diameter of 0.24 mm. Waves in the canal are generated with a system of mobile wave plates with dynamic back coupling which decreases the influence of reflected waves.

Tests with irregular waves, waves with a clear group structure and monochromatic waves were carried out during the experiment. A vertical profile of suspended sediment concentration, two components of water velocity (vertical and

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Manuscript received March 27, 2007. The work is carried out under financial support of the Russian Foundation of Basicl Research, grant № 05-05-64145 and grant NATO CLG98/587.

R. D. Kos'yan is with the Southern Branch of the Institute of Oceanology, RAS, Gelendzhik, Krasnodar region, Russia (phone: +7614128069; e-mail: kosyan@coastdyn.ru).

B. V. Divinskiy is with The Southern Branch of the Institute of Oceanology, RAS,Gelendzhik, Krasnodar region, Russia. (e-mail: divin@sbsio.coast.ru).

M. V. Krylenko is with the Southern Branch of the Institute of Oceanology, RAS Gelendzhik, Krasnodar region, Russia (e-mail: mari@sbsio.coast.ru).

C. E. Vincent is with the School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK (e-mail: c.vincent@uea.ac.uk).

along the axis of the flow) and elevation of free surface were measured in every test. Instruments for measuring the suspended sediment concentration and components of water velocity were installed on frames cantilevered out from the wall of the canal. Measurements of water velocity were made at a distance of 10-15 cm above the bottom with the help of Doppler acoustic measurer (ADV). Wave-wires, which recorded the location of the water surface, were mounted along the canal wall. Suspended sediment concentration was measured with the help of high-frequency (2, 4, 5, MHz) acoustic backscatter sensor (ABS) [16], which was installed at the distance of 35-40 cm from the bottom. Concentration of suspended sediments was measured in 101 points along the vertical line in every 5 mm with the frequency of 3.13 Hz. Synchronous measurements of suspended sand concentration, components of water velocity and elevation of free surface were done in bursts, each of which has 2050 readings.

III. MODEL OF SUSPENDED SEDIMENTS

The model is based on the diffusion equation for suspended sediment concentration:

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

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

According to this equation a change of concentration in time at any horizon from the bottom is defined by the change oin the balance between the vertical suspended sediment flux due to particle settling (the first term of the r.h.s of the equation), and the sediment re-suspended from the bottom (the second term on the r.h.s).

A. Determination of diffusion coefficient

The generalized diffusion coefficient of sediments is considered to be variable in vertical direction and is given by [9]:

$\varepsilon(z)=\varepsilon_1(z)+\varepsilon_2(z)+\varepsilon_3(z)$.

Here $\varepsilon_1(z)$ is the contribution of the orbital motion,

$$\varepsilon_1(z)=\frac{\pi H^2\sinh^2 kz}{2\sqrt{2}T\sinh^2 kh},$$

$\varepsilon_2(z)$ is the contribution of the wave flow,

$$\varepsilon_2(z)=\frac{\pi\chi^2H^2}{36T\sinh^2 kh}\frac{\sinh^3 2kz}{\cosh^2 2kz},$$

$\varepsilon_3(z)$ is the contribution of diffusion in near bottom layer,

$$\varepsilon_3(z)=\frac{b(u_g-w_s)\frac{z}{\delta}}{1+0.06\frac{z}{\delta}\exp(\frac{z}{\delta})},$$

where coefficient *b* is defined as $b=116\left[\frac{\rho}{\rho_s-\rho}\right]\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}}$.

u_g is the maximum value of bottom orbital velocity with components

$$U=\frac{HTg}{2\lambda}\frac{\cosh(2\pi\frac{\delta+h}{\lambda})}{\cosh(2\pi\frac{h}{\lambda})},$$

$$W=\frac{HTg}{2\lambda}\frac{\sinh(2\pi\frac{\delta+h}{\lambda})}{\cosh(2\pi\frac{h}{\lambda})}.$$

δ is the thickness of boundary layer from Johnson's equation [8]:

$$\frac{\delta}{z_0}\lg\left(\frac{\delta}{z_0}\right)=0.6\frac{H}{D\sinh kh},$$

where z_0 is the roughness parameter, $z_0=\frac{z_N}{30}$, z_N is the effective roughness of the bed, which for a smooth sandy bottom is equal to the $z_N=2.5\overline{d}_{50}$ where d_{50} is the mean diameter of sandy particles on the bottom). *H, T,* λ are the height, period and length of the wave, and *h* is water depth.

B. Boundary conditions

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

$$\varepsilon_s\cdot\frac{\partial C}{\partial z}+w_s\cdot C=0$$

At the bottom boundary suspended sediment concentration is described by C(0,t)=*A p*(t), where *p(t)* is a function of local ejection of suspended sediment (pick-up function) [20], defined by

$$p(t)=3.3\left(\frac{\theta(t)-\theta_{cr}}{\theta_{cr}}\right)^{1.5}\frac{(s-1)^{0.6}g^{0.6}d^{0.8}}{\nu^{0.2}},$$ where

$s=\frac{\rho_s}{\rho}$ is the relative density of sediments.

When individual waves are passing sediment suspendion takes place not during the whole period but as a quick ejection of a cloud of suspended sediment. The analysis of experimental data has shown that one ejection happens during the phase decrease from maximum to zero of the horizontal component of velocity. Group structure of waves greatly influences the process of vertical profile formation under certain waves within the group. Intensification of sediment suspension under wave groups tends to occur after the passage of maximum waves in the group and then gradually decays towards the trough of the geometric envelop of wave group [21]. These facts are taken into consideration by coefficient *A,* that changes from $0\le A\le 1$, and is equal to 1 during the suspension phase and to zero at other times. It applies both to single waves and group of waves in terms of their envelop.

The instantaneous value of Shields parameter shows a balance between shearing and confining forces:

$$\theta(t)=\frac{u_*^2(t)}{((\rho_s-\rho)/\rho)\cdot g\cdot\overline{d}_{50}},$$

where d_{50} is a median diameter of sediments, $u_*(t)$ maximum shear velocity calculated from the flow velocity $U(t)$.

C. Determination of $u_*(t)$

In conditions of a strong turbulence of the wave boundary layer k_n=D, an iterative condition is fulfilled [19]

$$\frac{1}{x^{(n+1)}}=\left(\log_{10}\frac{A_{bm}}{k_n}-0.17\right)-\log_{10}\frac{1}{x^{(n)}}+0.24x^{(n)}$$

where the initial value of $x^{(0)}=0.4$, $A_{bm}=\dfrac{u(t)}{\omega}$ and $\omega=\dfrac{2\pi}{T}$. In this formula $x=4\sqrt{f_\omega}$, where f_ω is a factor of wave friction. Solution of the equation gives a value of the wave factor of friction of $f_w=\left(\dfrac{x^{(m)}}{4}\right)^2$ and that of maximum shear velocity $u_*(t)=\sqrt{\dfrac{f_w}{2}}u(t)$.

An evenly-spaced computational grid, in depth and in time, was used for calculation, with Δz=0.005 m and Δt=0.228 s. The following values of parameters were used in the model [2]: settling velocity w_s = 0.025 m/s, critical value of Shields parameter for initiation of sediments motion $\theta_{cr}=0.045$ for sand with a mean diameter of 0.24 mm, kinematic viscosity of water $\nu=10^{-6}$ m^2/s.

Estimation of vertical profile of generalized diffusion coefficient has shown that contribution of $\varepsilon_2(z)$ coefficient is two order less than that of the other components (Fig. 1) and may neglected as a contribution to the diffusion coefficient.

Six regions of suspension are clearly seen in Fig. 2, they correspond to groups of waves (number 1-6). Chronograms of horizontal velocity U), experimental (C_{exp}) and model (C_{mod}) concentrations for these groups are given in Fig. 3.

Averaging the vertical profiles of concentration for both experimental and model data was done within every group (Fig. 4). The profiles obtained can be approximated by the following exponential function:

$$C(z)\propto a\exp(-bz),$$

where a and b – are parameters controlling the slope and position of the function.

Fig. 5 and Fig. 6 show temporal changes of the experimental and model profiles of suspended sand concentration. The predicted and measured vertical profiles of concentration are coincide satisfactorily in time. The vertical distribution of suspended sediment concentration changes synchronous from a concave profile to a convex one. The convex shape of the vertical profile of suspended sediment concentration is consisted with the convective nature of suspension process.

Observed differences in the absolute values of suspended sediment concentration are probably caused by the fact that a this model does not take into consideration any advective transport of suspended sediments, fluctuations of granulometric composition of the sand and change of physical properties of the flow when suspended sediment concentration increases.

The results of spectral analysis of chronograms of horizontal component of flow velocity, elevation of level and suspended sediment concentration (experimental and model) are given in Fig. 7. All spectra are characterized by pronounced local maxima at the frequency of 0.13 and 0.26 Hz (Fig. 7.1). The phase lag between the experimental C_{exp} and calculated C_{mod} concentration at the same frequencies is close to zero. Fig. 7.2 demonstrates a high coherence between all considered parameters (U, C_{exp}, C_{mod}) both at low frequencies and frequencies of the maximum of spectral density. Thus, the modelled series of the suspended sediment concentration statistically agrees with experimental one.

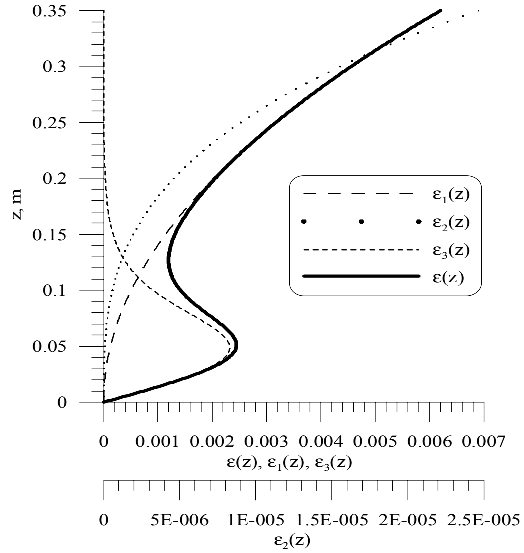

Fig. 1. Vertical profile of the diffusion coefficient.

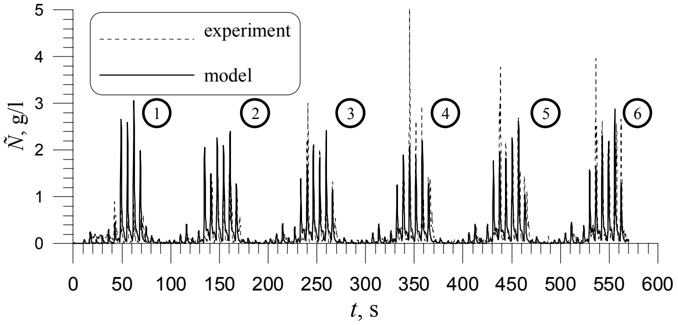

Fig. 2. Suspended sediment concentration at 5.5 cm from the bottom.

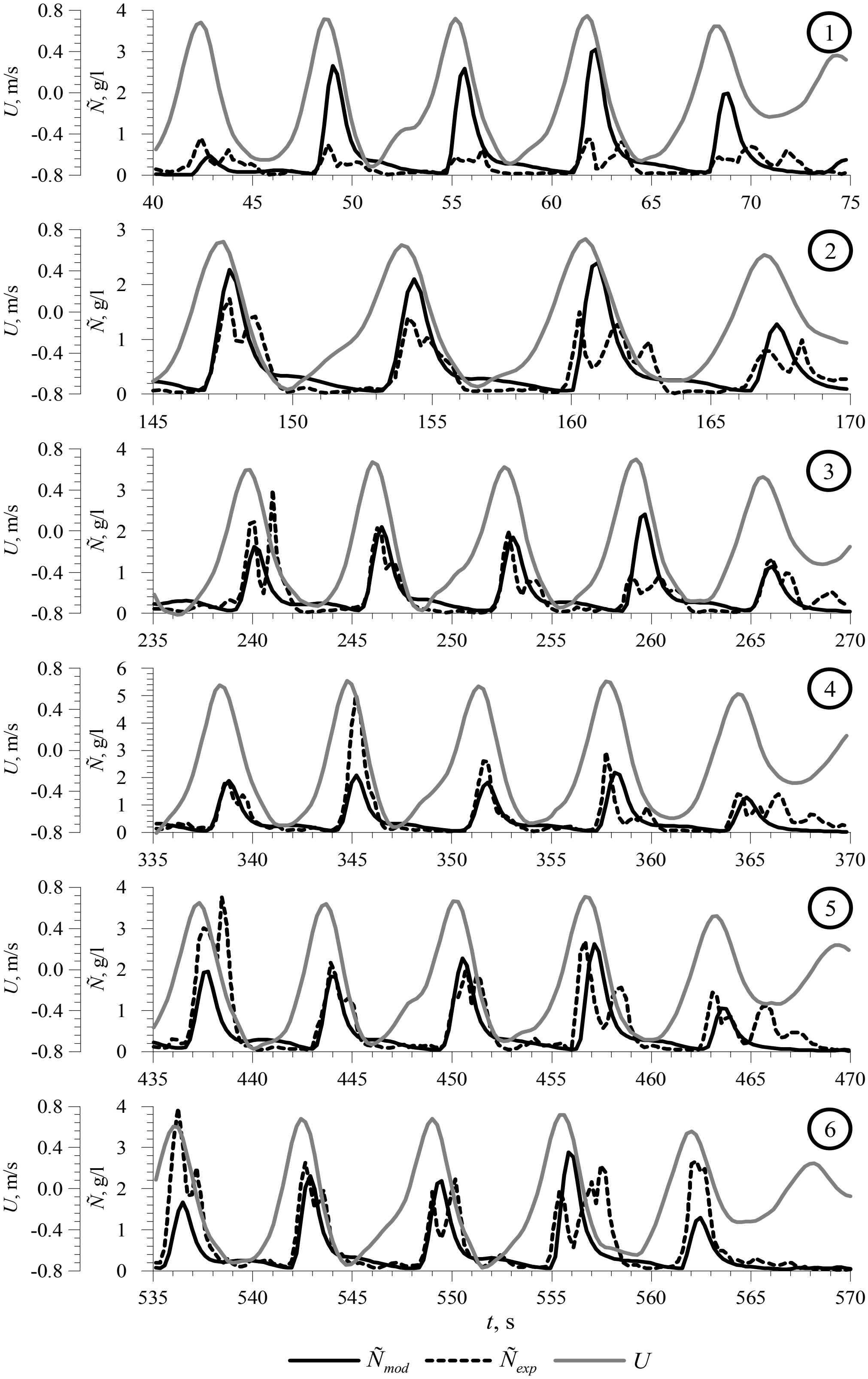

Fig. 3. Chronograms of horizontal velocity (U), experimental (C_{exp}) and model (C_{mod}) concentrations under wave groups.

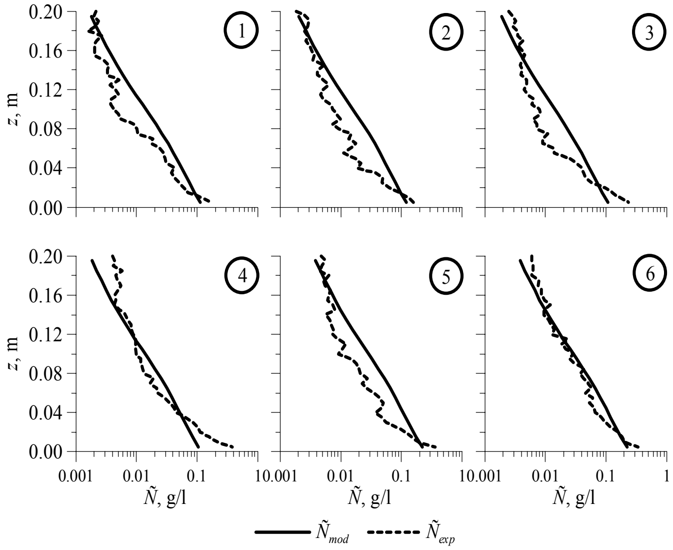

Fig. 4. Averaged vertical profiles of the experimental (C_{exp}) and model (C_{mod}) suspended sediment concentration under wave groups.

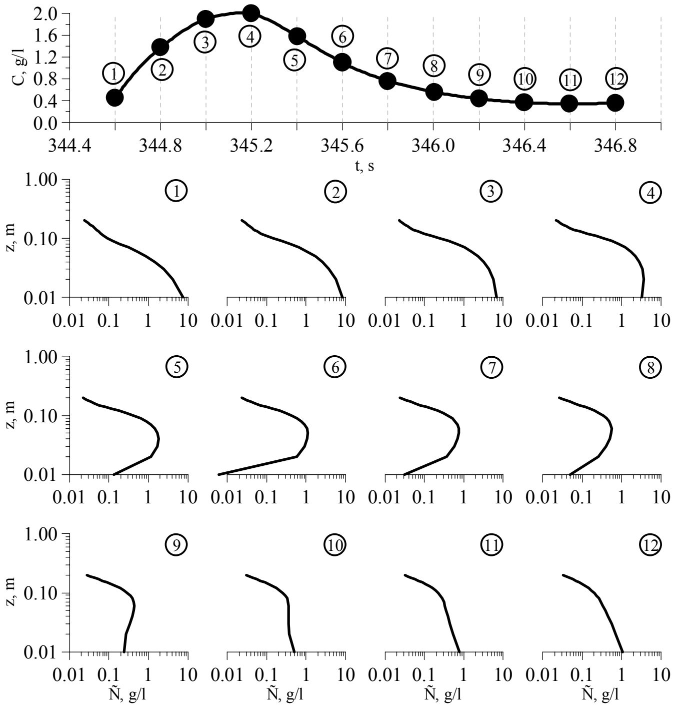

Fig. 5. High-frequency fluctuations of vertical profile of model suspended sediment concentration.

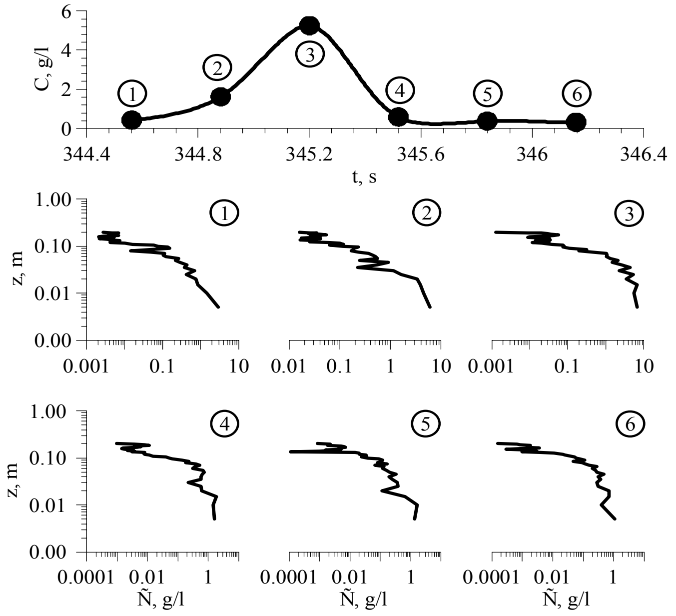

Fig. 6. High-frequency fluctuations of vertical profile of the experimental suspended sediment concentration.

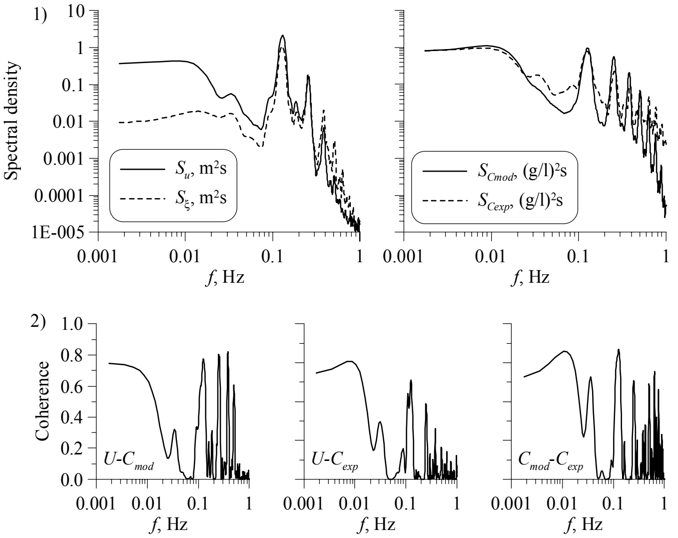

Fig. 7. Result of the spectrum analysis (C_{exp} – experimental and C_{mod} - model suspended sediment concentration).

IV. CONCLUSION

A model has been described for the calculation of the vertical distribution of suspended sediment concentration above a flat bottom under the influence of groups of waves. It takes into consideration the influence of group structure of waves and phases of individual waves upon the sediment suspension. This is very important for modelling the fluctuations of suspended sediment concentration. The model shows very well all qualitative peculiarities of sediment suspension under the given conditions.

Calculation of profile variability of the suspended sediment concentration is necessary for estimation of sediment transport in the coastal zone. The profiles obtained from the model of the concentration are supportive of the methodology suggested.

Real processes of sediment suspension are more complex than mechanisms which are put into the model. It is expected that this model for the suspension of bottom sediments will be improved with the involvement of additional processes and through further experimental and theoretical investigations.

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