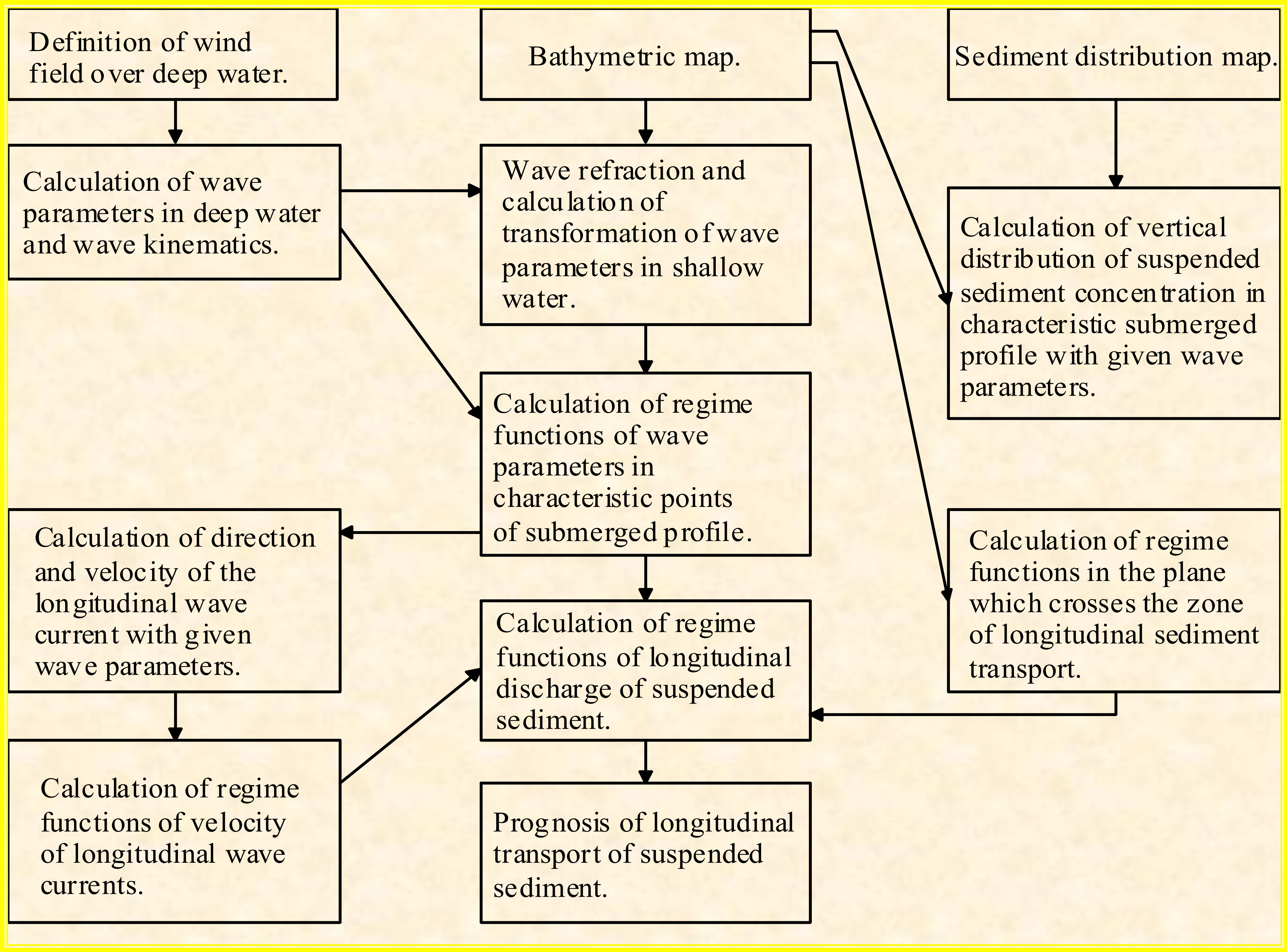
# Sediment transport in the nearshore zone

Ruben Kos'yan

# The modular scheme for calculation of longshore transport of suspended sediment.



# 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).

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

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

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

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; Qx and Qy - 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 + Cw + Cl + C', (2)

U(x,y,z)= U + Uw + Ul + U', (3)

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V(x,y,z)= V + Vw + Vl + V', (4)

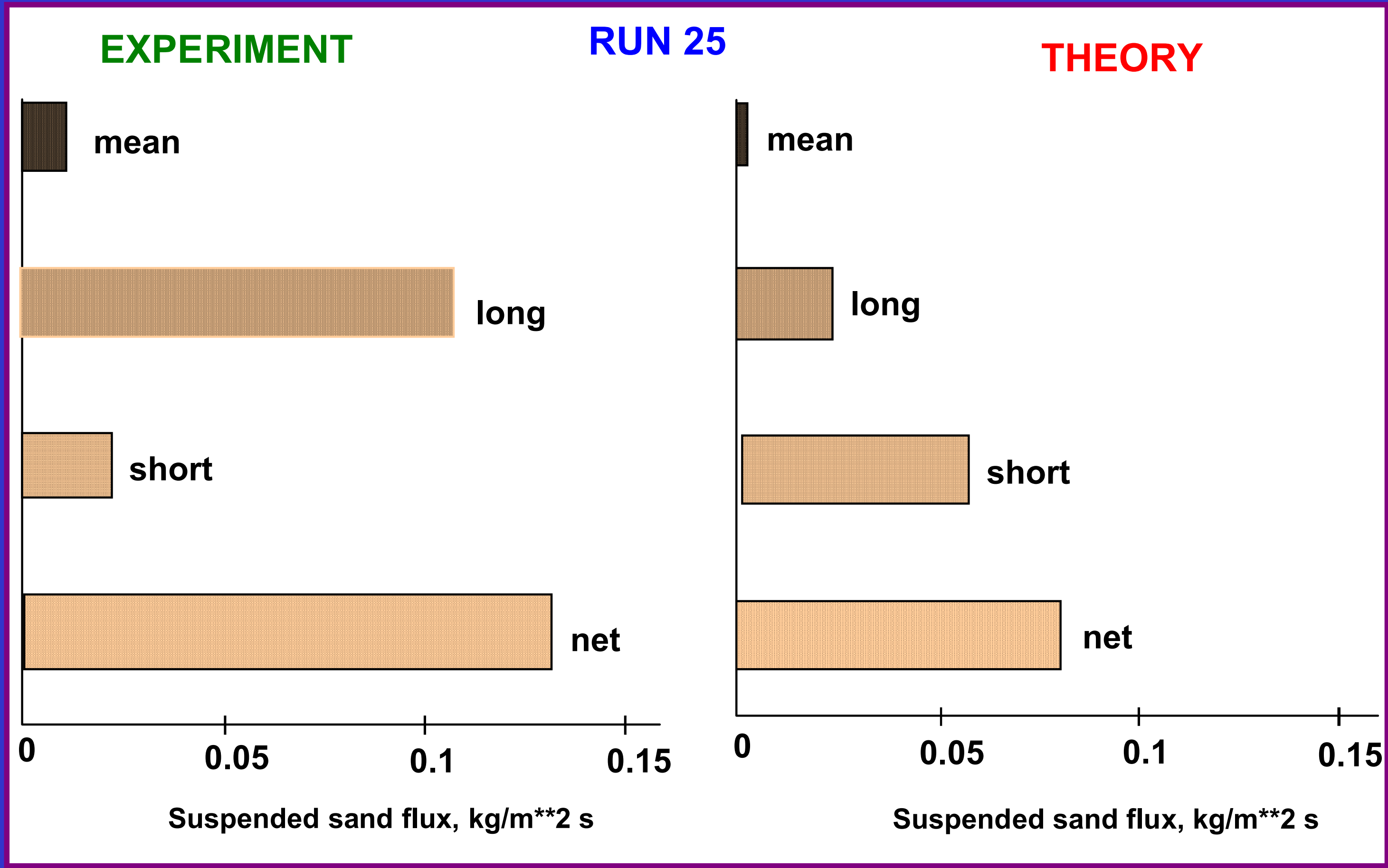
where U and V are mean for time period T values of sediment concentration and water velocity components in the cross-shore and longshore directions; Cw, Uw, Vw are fluctuations of those characteristics in gravity band of the spectrum of irregular waves; Cl, Ul, Vl - fluctuations of sediment concentration 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. 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**

$$qx = C\ U + C_w U_w + C_l U_l + C'U' \qquad (5)$$

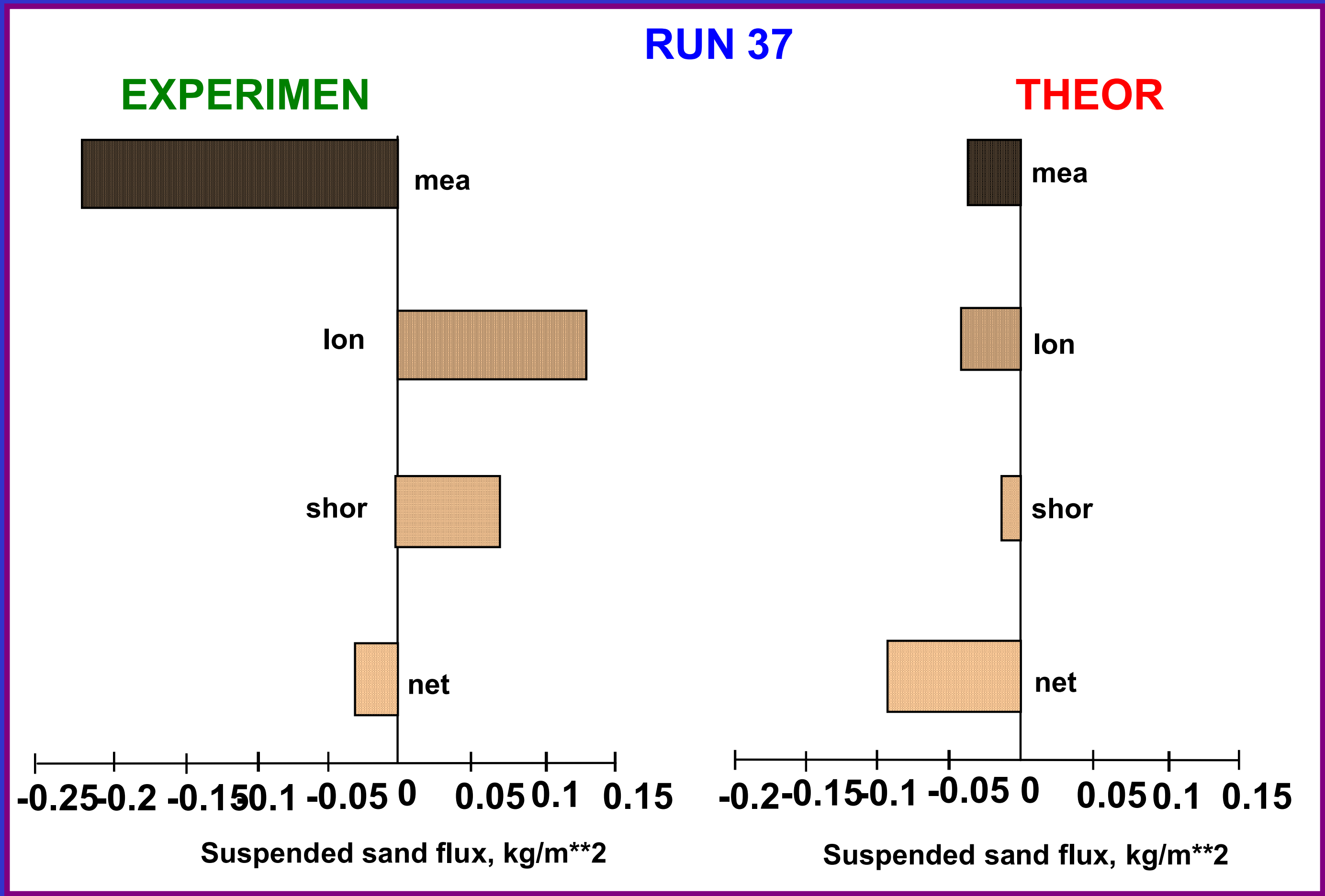
$$qy = C\ V + C_w V_w + C_l V_l + C'V' \qquad (6)$$

**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, but it is still a long way off for its solution.**




**The experimental and theoretical values of net suspended sand flux, time mean flux and fluxes by short and long waves for run 25.**

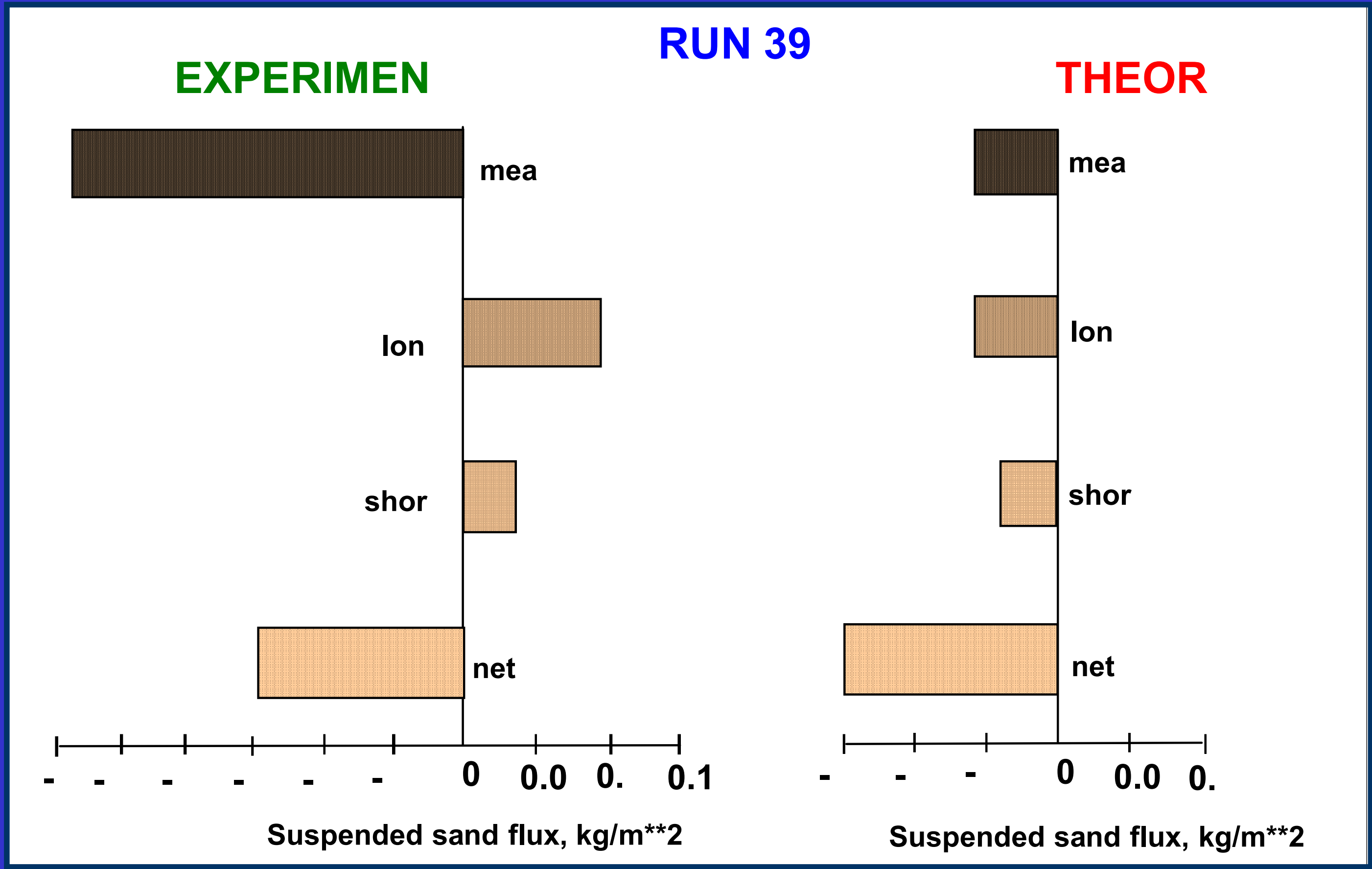
**The outflow velocity approaches zero and the main contribution to the net suspended sand flux derives from the infragravity waves. The rms values of the suspended sand fluctuations are equal to 1.15 kg/m$^2$s; this value is ten times more than the net flux.**




**The experimental and theoretical values of net suspended sand flux, time mean flux and fluxes by short and long waves for run 37**

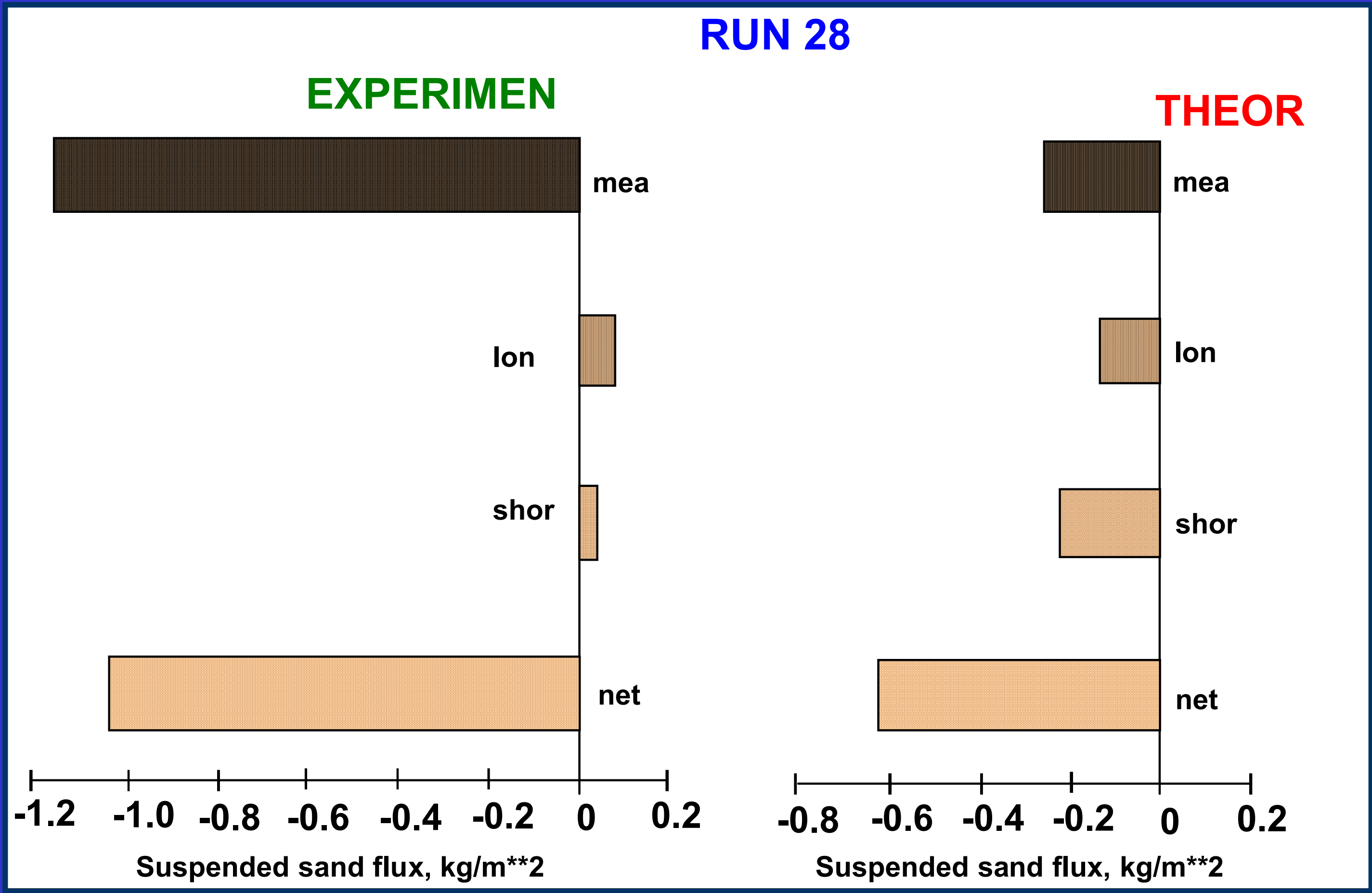
**The measured sand fluxes by short and long waves are directed onshore and almost completely compensates the offshore directed transport by the mean flow.**

**The rms values of suspended sand flux fluctuations are equal to 1.25 kg/m$^2$s. Predicted suspended sand fluxes by short and long waves are directed offshore, in contrary to the measured fluxes and the resulting net flux is three times higher than the measured net flux.**




**The experimental and theoretical values of net suspended sand flux, time mean flux and fluxes by short and long waves for run 39.**

**Predicted and measured net fluxes are nearly equal, but the predicted values and directions of fluxes by short, long waves and mean current are not coincident with the measured ones.**




The experimental and theoretical values of net suspended sand flux, time mean flux and fluxes by short and long waves for run.28.

The net flux completely depends on the mean flux and is directed offshore. Suspended sand fluxes by short and long waves are directed onshore too and contribute only about 10% to the net flux.

In contrary to the measured values, the calculated fluxes by short and long waves were directed offshore and contribute about 60% to the net cross-shore suspended sand flux.

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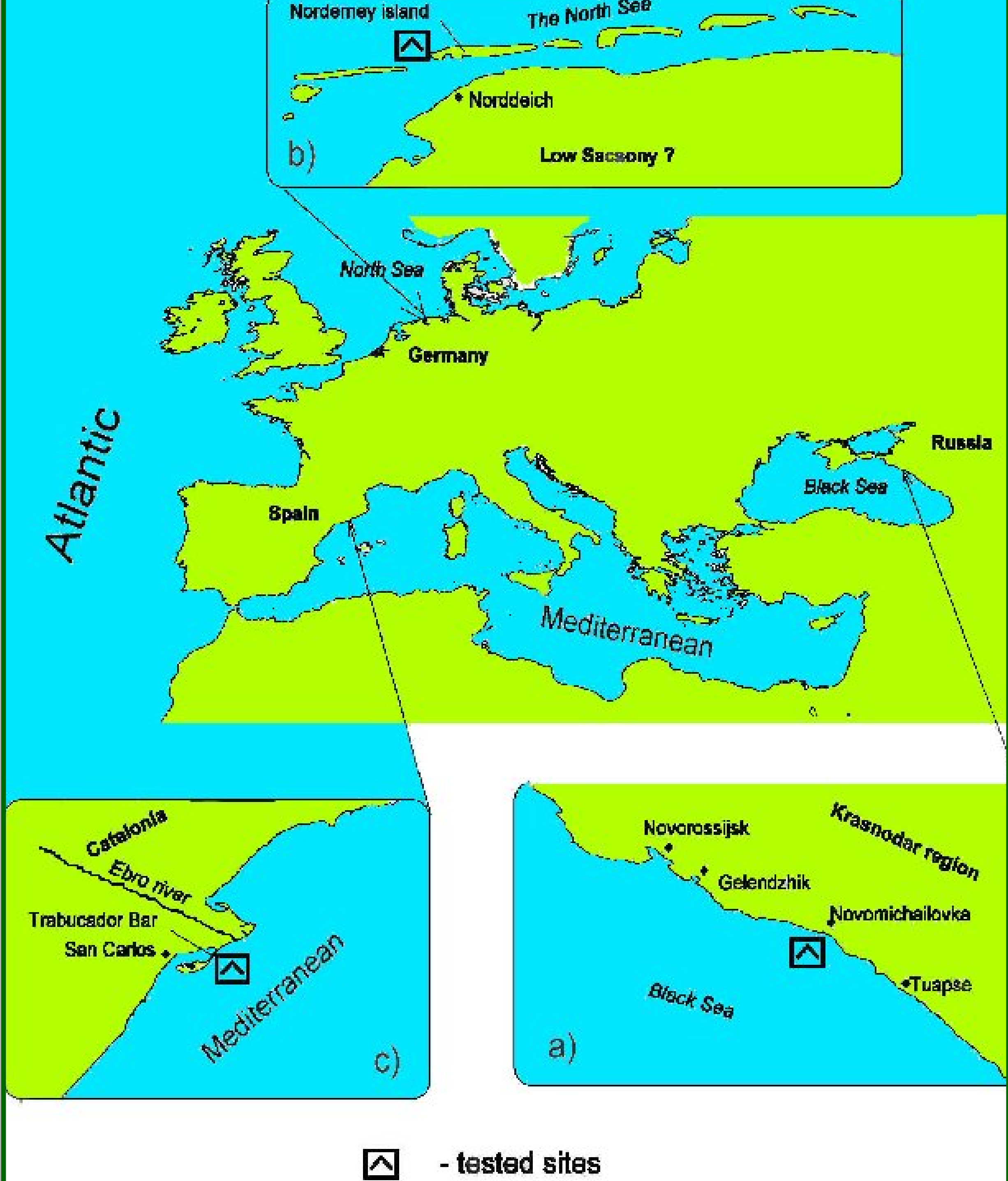
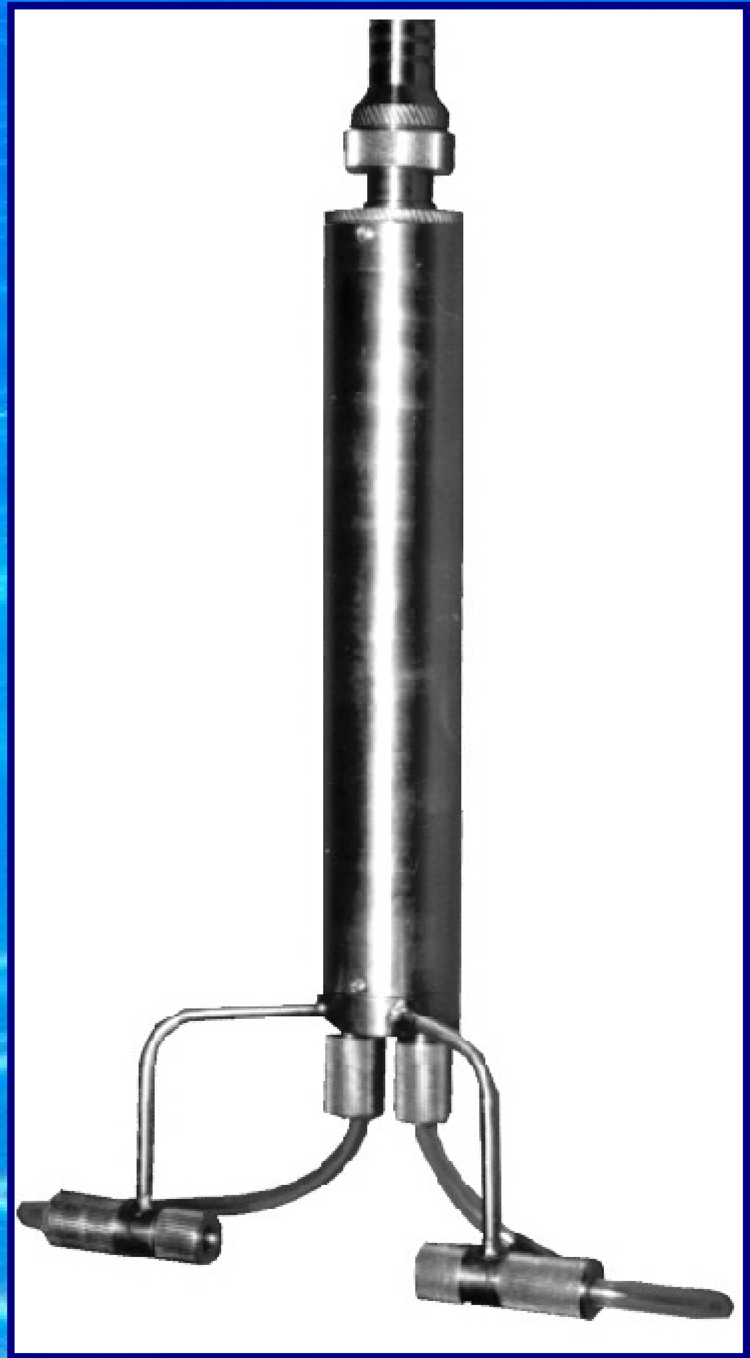
# The sites of the field experiments




The sites of the field experiments: a) - Novomichailovka'93, 99, 02
b) - Norderney'94; c) - Ebro Delta'96.

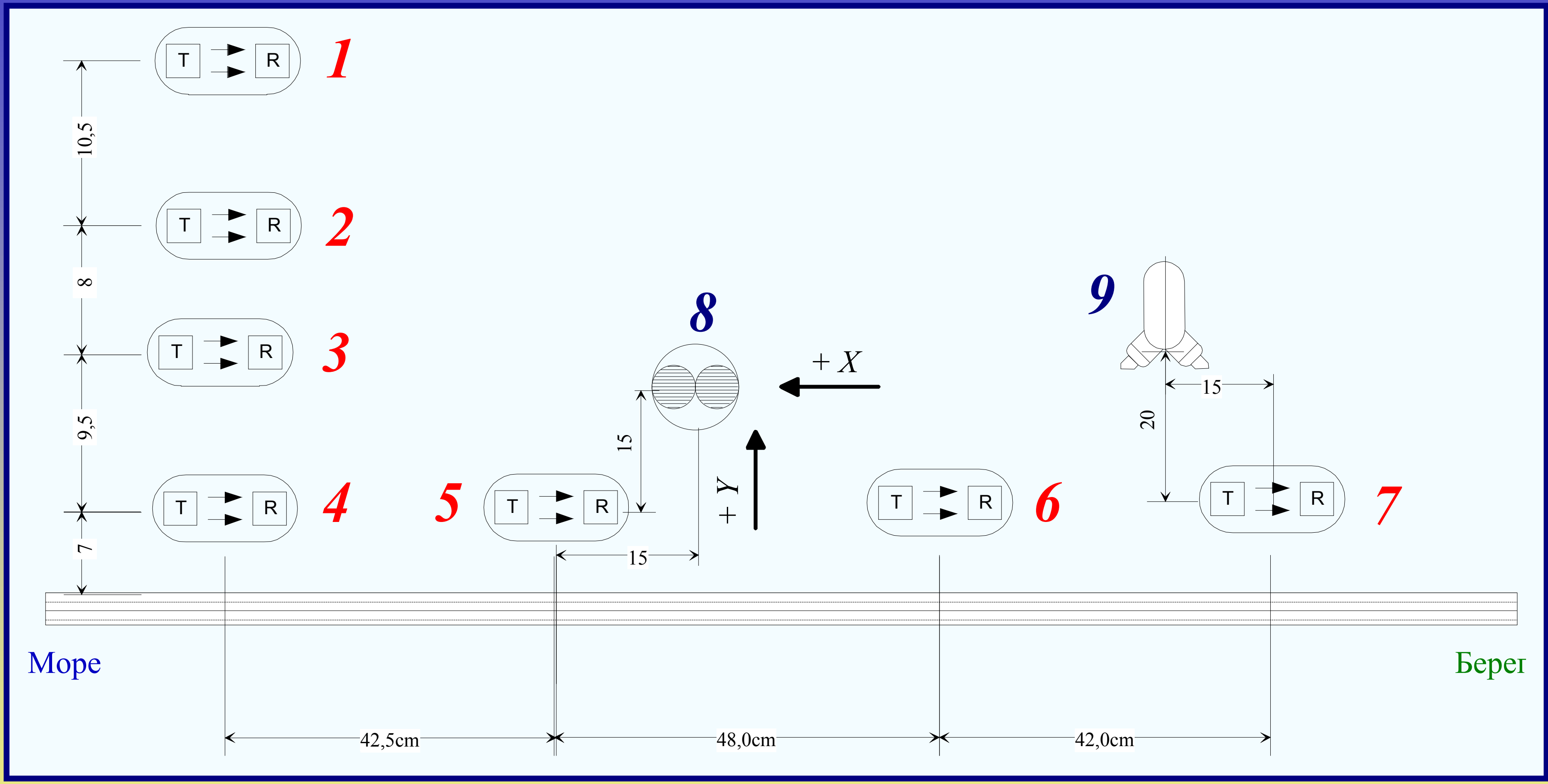
# Optical turbidimeter



**2D electriomagnetic velocitimeter “Stromungssensor Typ “S””**

**3 D acoustical currentmeter “Vector”.**

# Sand level gauge.




**Mobil carriage for equipment and the scheme of its displacement. Here: 1-7 – optical turbidimeters; 8 – 2D (vertical and cross shore) electro magnetic currentmeter; 9 – acoustical currentmeter “Vector”. Sand level gauge was buried into the sand.**

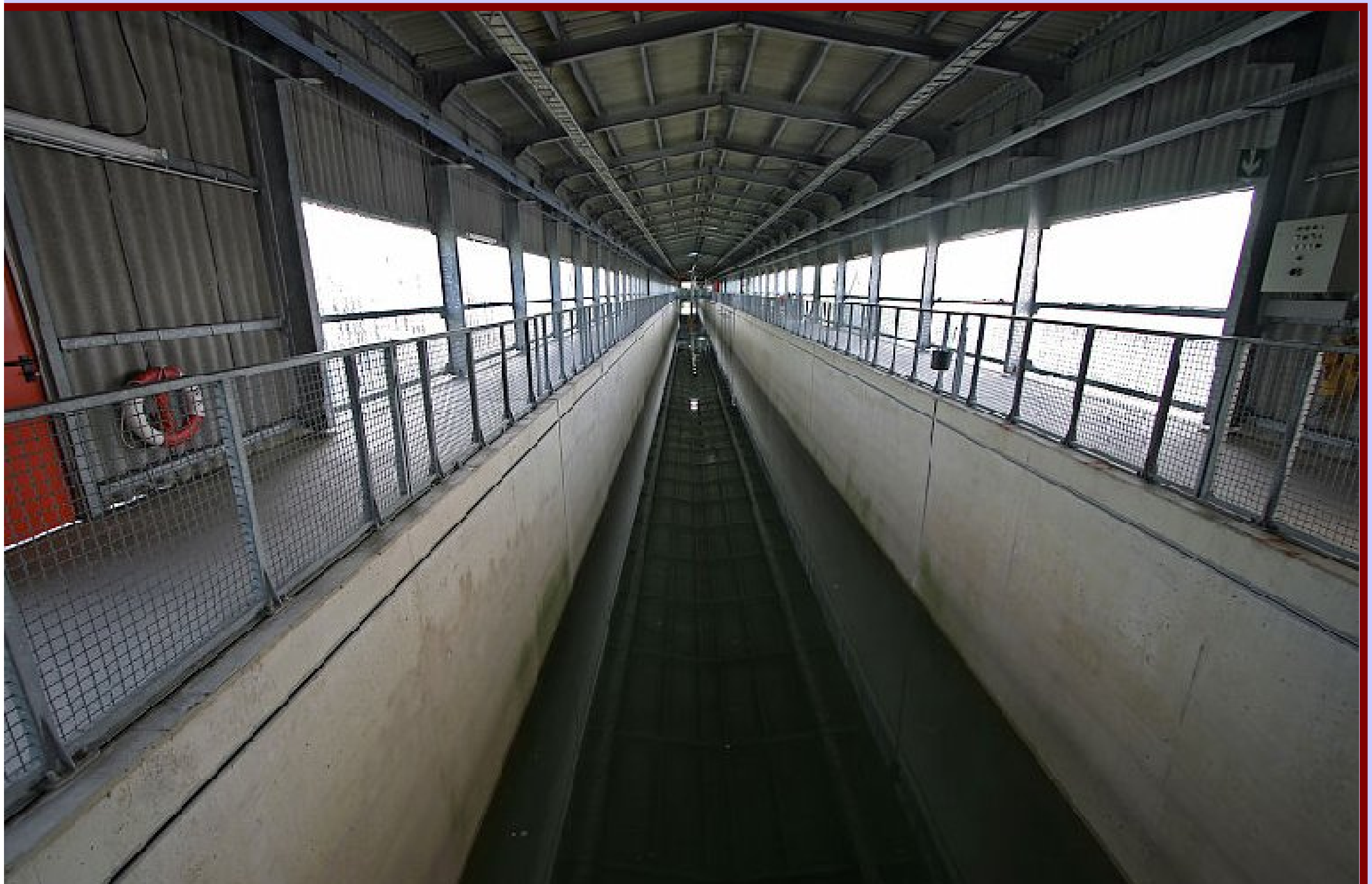
# LABORATORY EXPERIMENT "HANNOVER'2007"

From 8 August till 8 September, 2007 laboratory experiment was carried out under the project program. It was named "Hannover'2007". A place of experiment was Germany, Hannover, the Large Wave Channel (GWK)

# LARGE WAVE CHANNEL (GWK)

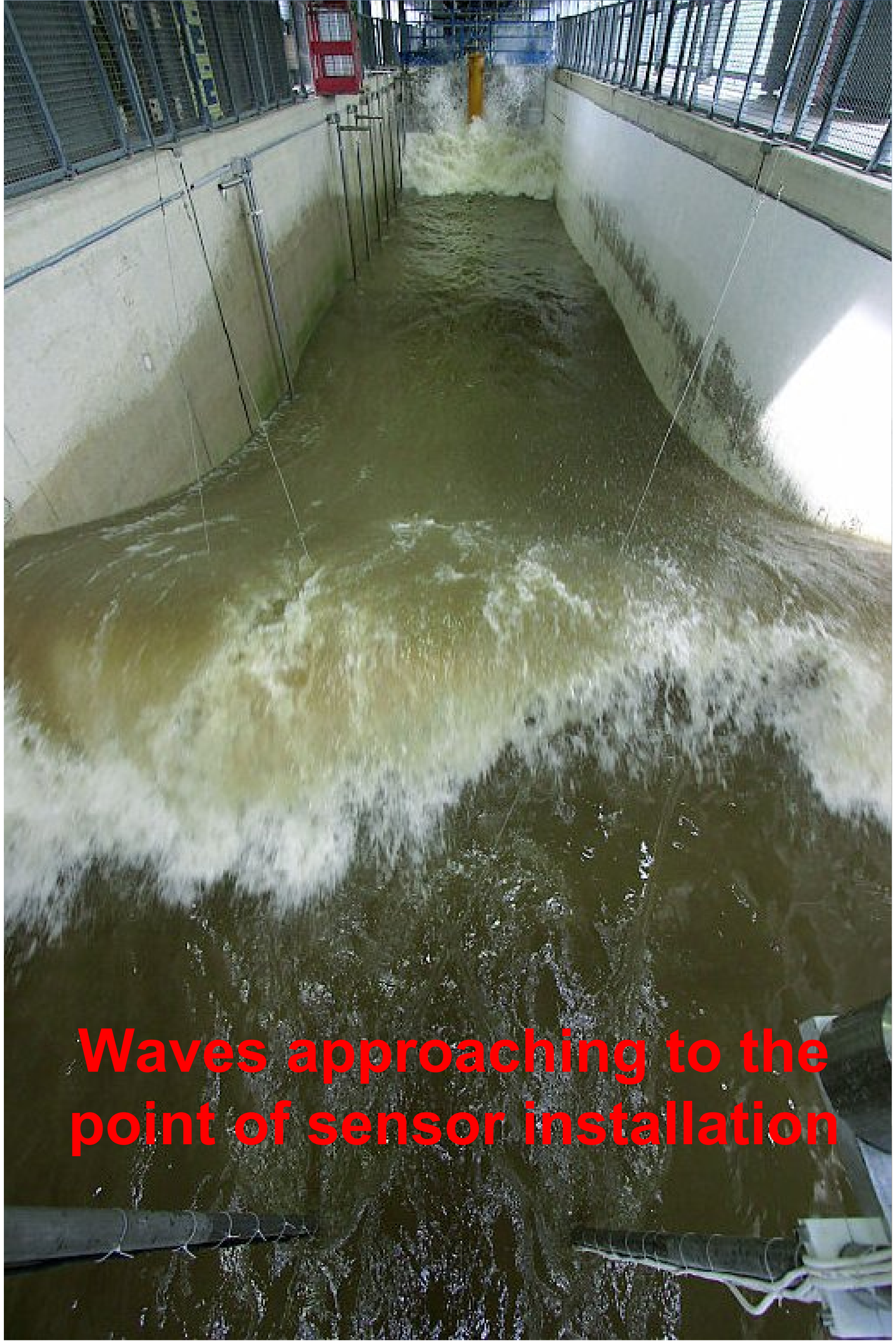
**The LARGE WAVE CHANNEL is the largest facility of its kind worldwide and the main experimental facility of the Coastal Research Centre (FZK) of Hannover University and Braunschweig Technical University.**

**The channel is 300 long, 7 m deep and 5 m wide. Sand was filled down the bottom. The water depth varies from from 0 to 5 m.**

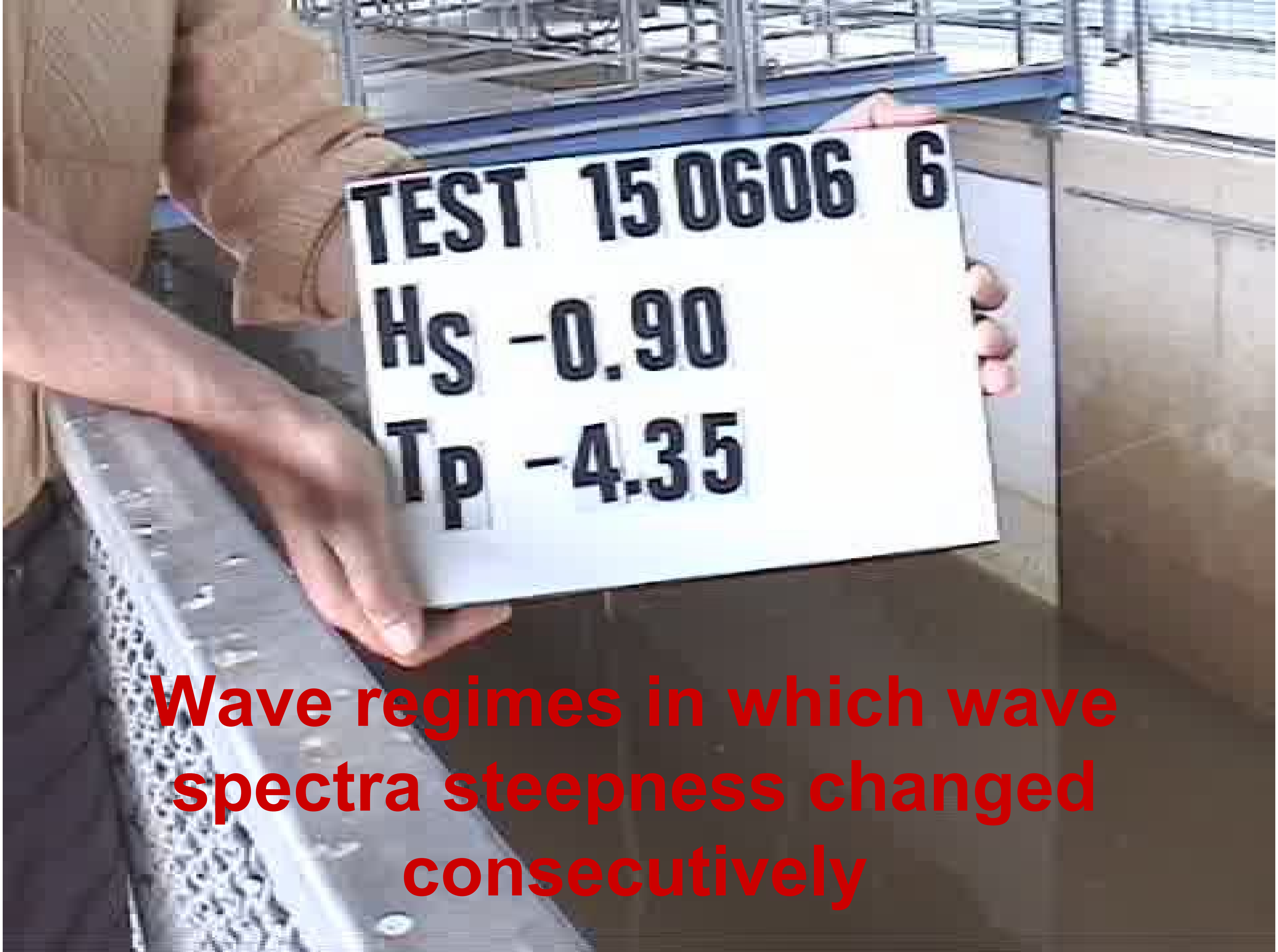


**GWK**

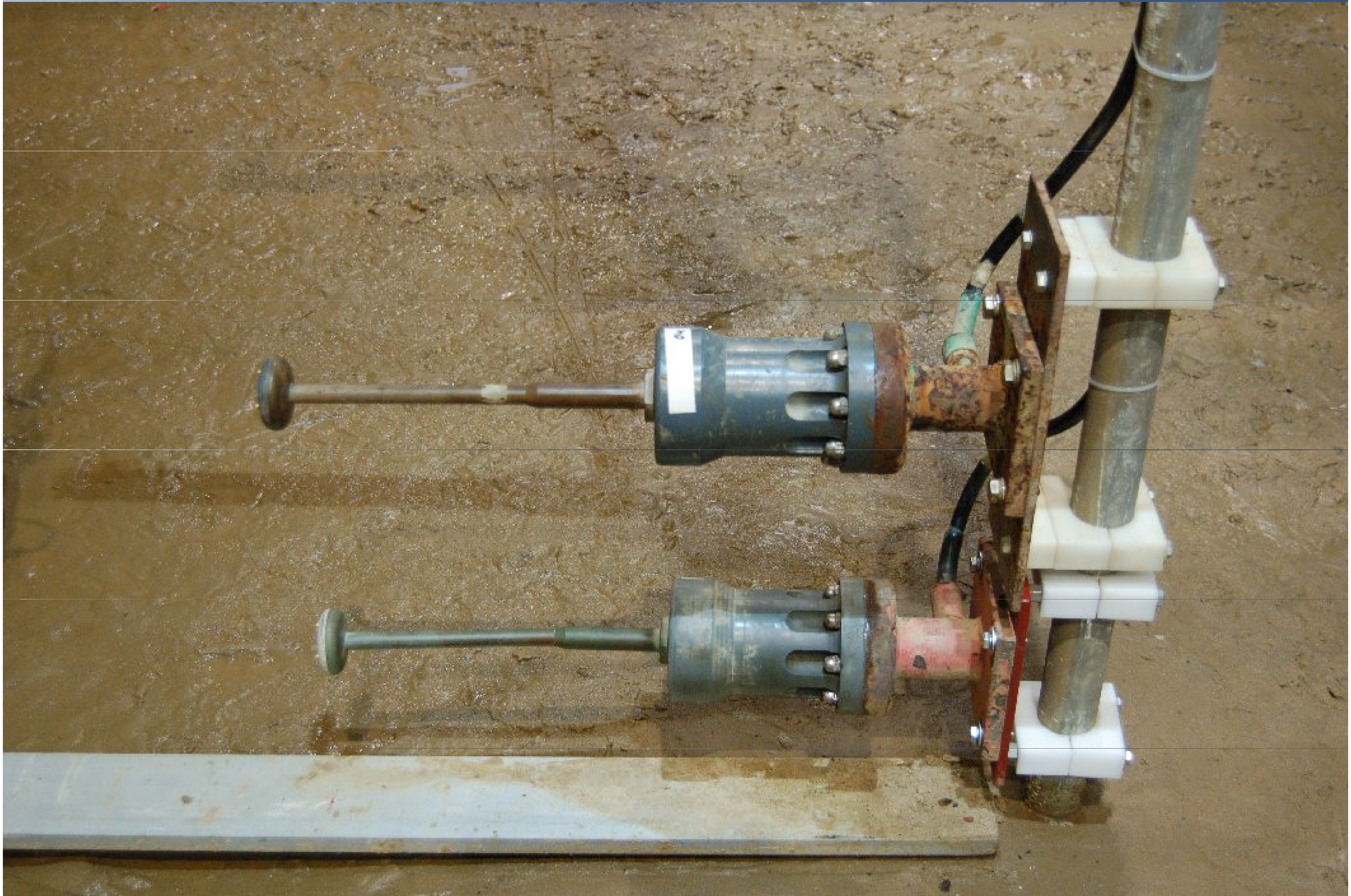
**View from the side of wave generator.**

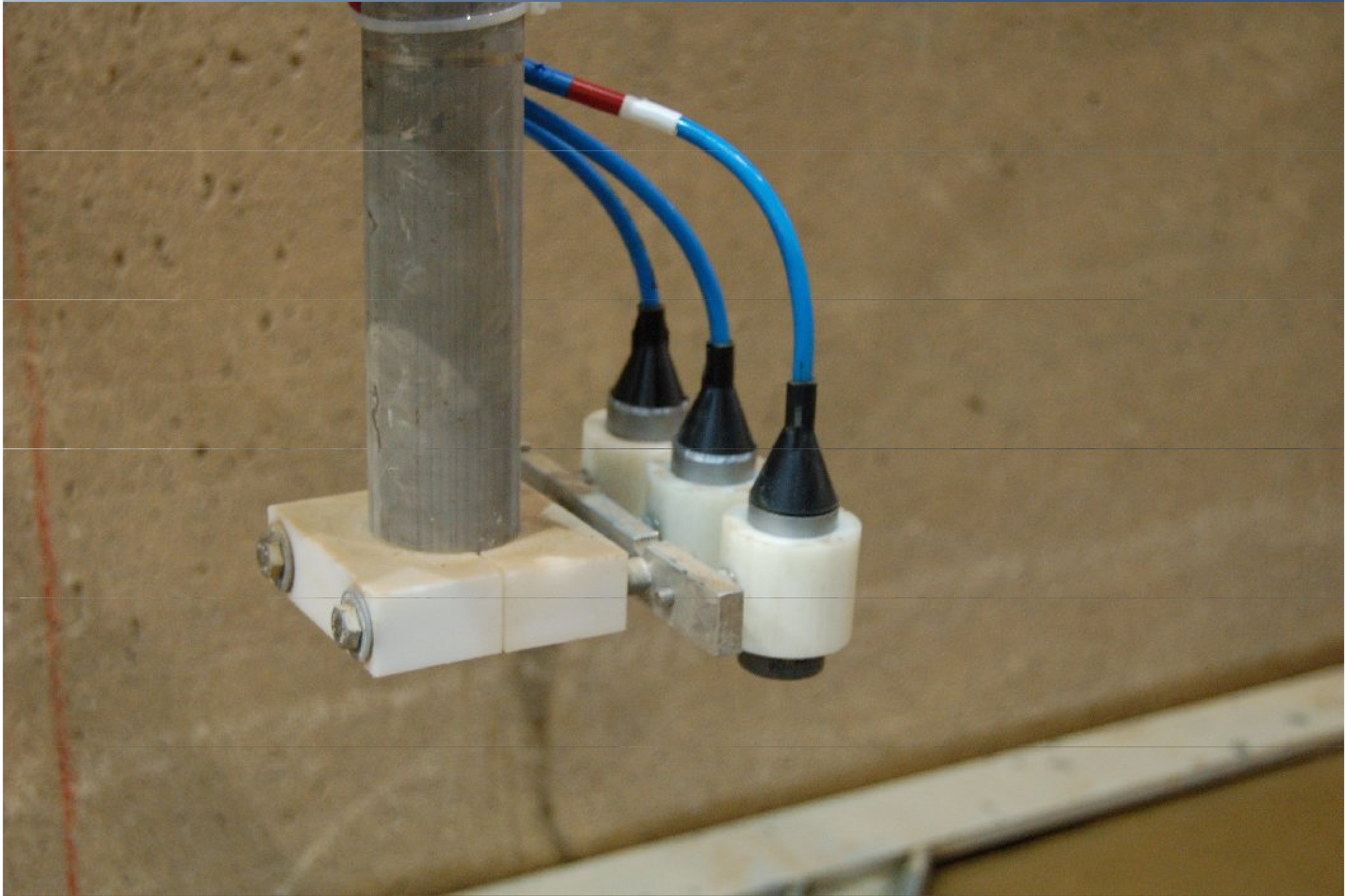

Waves approaching to the
point of sensor installation

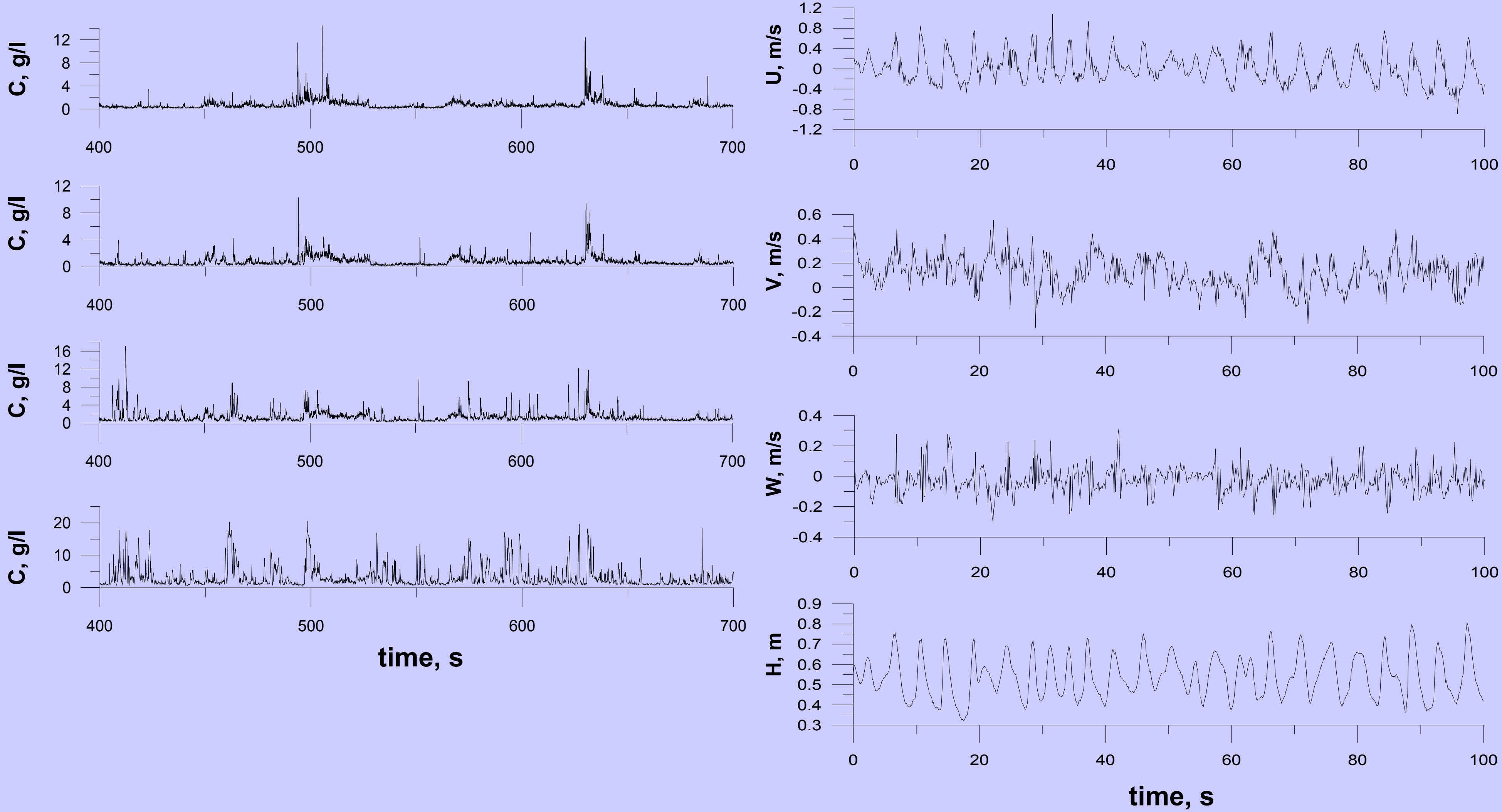
Formed ripples on the
beach bottom after water
discharge.



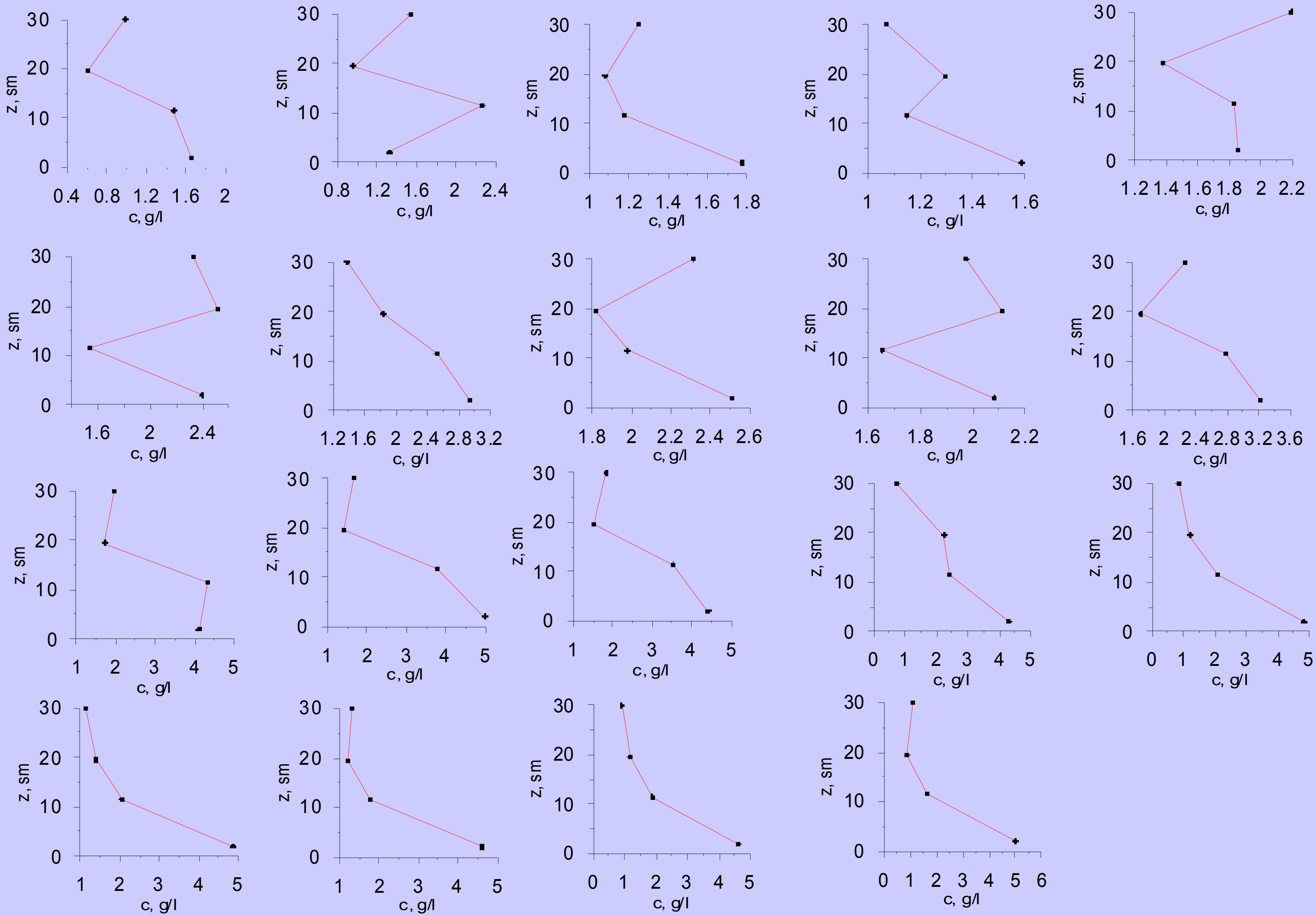

Wave regimes in which wave spectra steepness changed consecutively



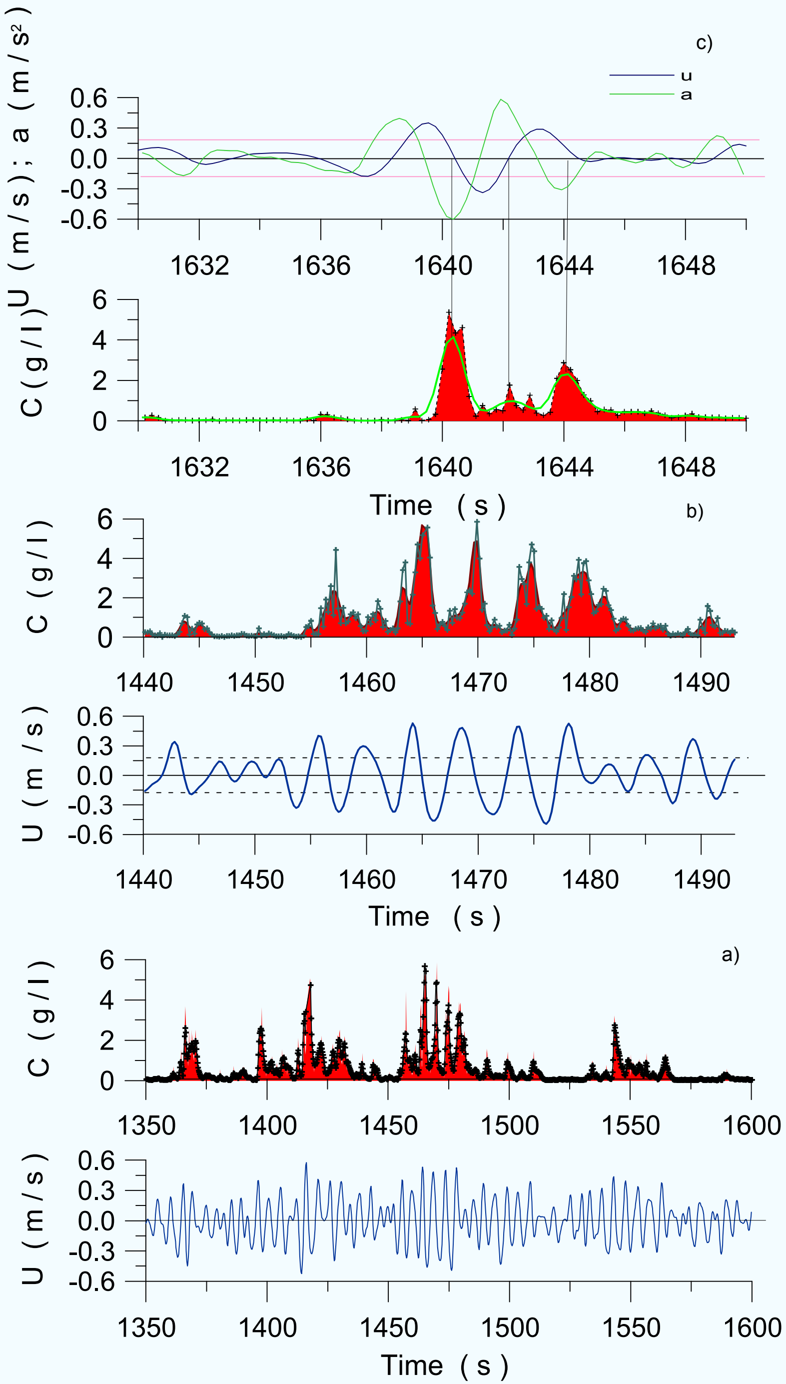





**Fragment of recording of suspended sediment concentration (t) and "Vector" record where u- cross-shore, v- along-shore, w- vertical component of velocity, H – elevation of free surface. From top to bottom turbidimeters placed at 30, 20, 11 and 4 cm from the bottom**

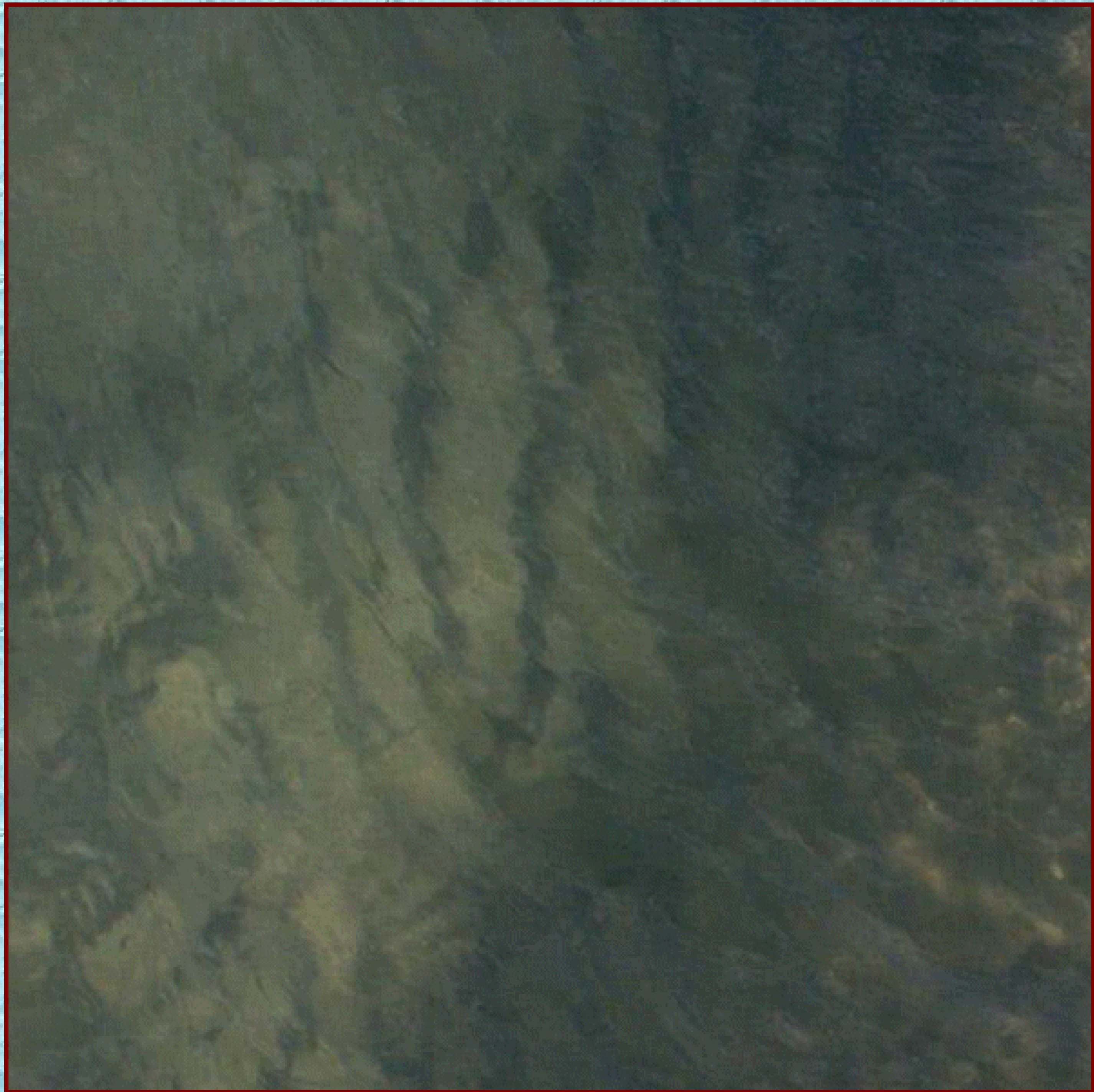


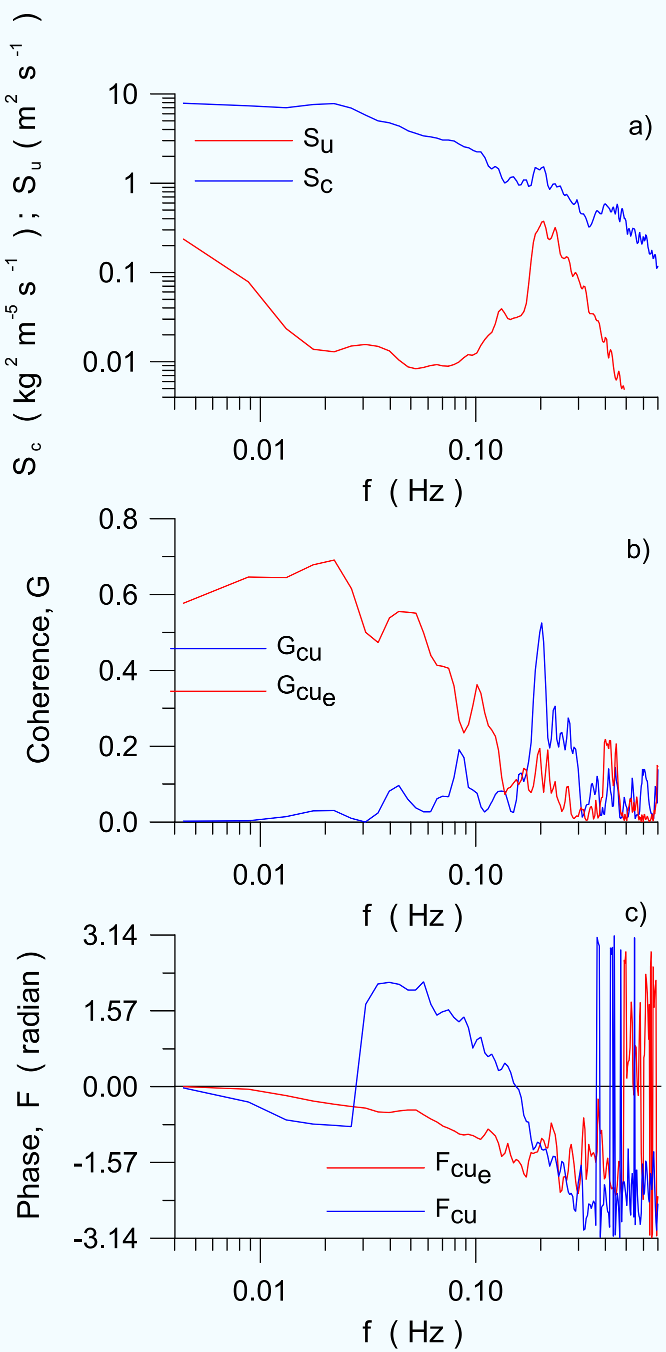

***High-frequency fluctuations of vertical profile of suspended sediment concentration during one second (frequency is 18.2 Hz)***



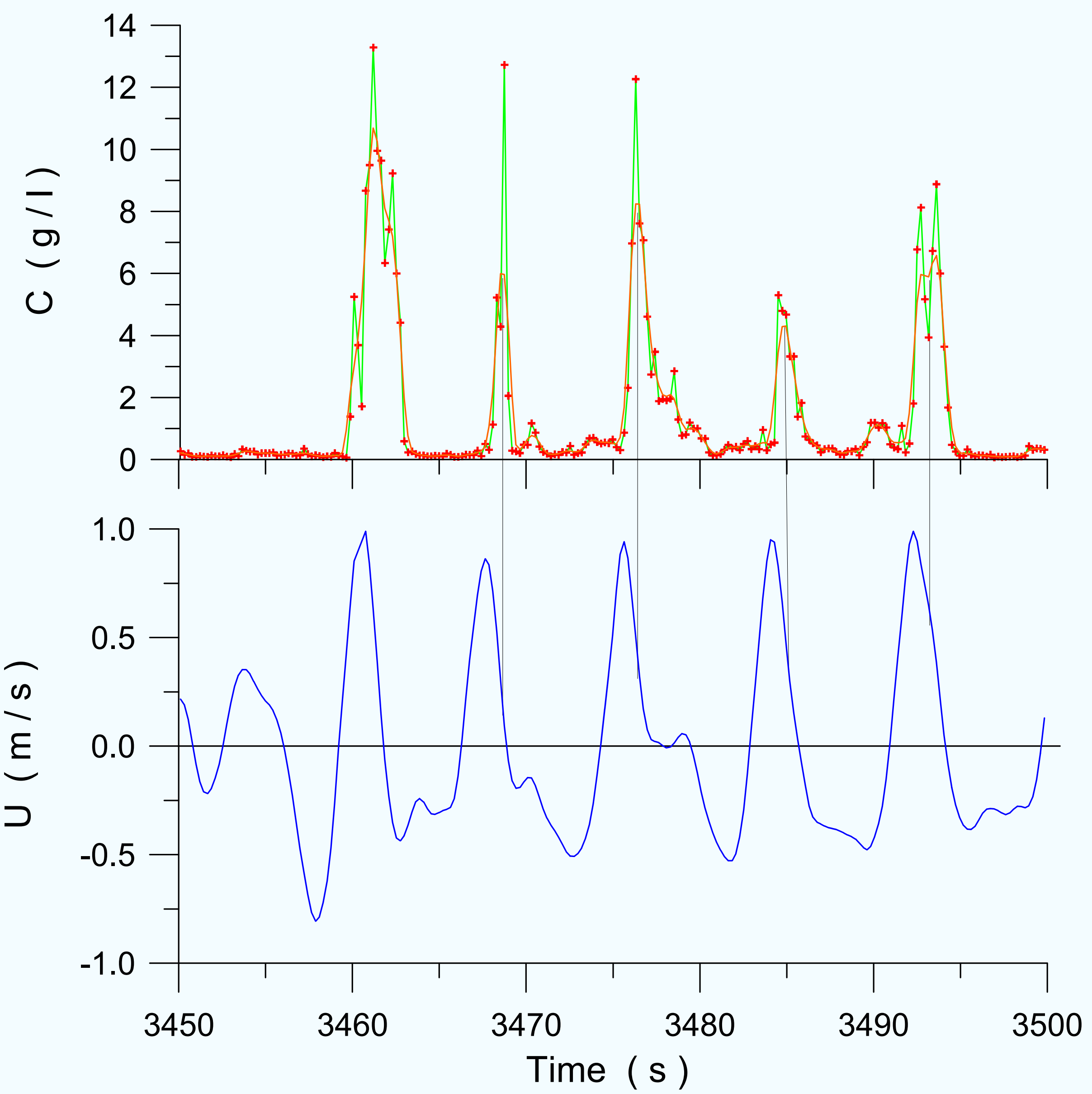

The example of the time series of the suspended sediment concentration (C) and cross-shore velocity (U) which illustrates the sediment concentration fluctuations induced: a) during the passing of the several groups of the high waves; b) by the individual waves inside the extended groups of the high waves; c) by the two waves in the group.

Dashed line with crosses - the sediment concentration, full line - the same without turbulent fluctuations at the frequencies more than 0.8 Hz. Horizontal dashed lines - r.m.s. value of the cross-shore velocity ($U_{rms}$). Full line at c) - cross-shore velocity (U), dashed line - cross-shore acceleration (a). The experiment “Novomichailovka’93”: significant wave height - $H_s$ = 0.48 m; wave period corresponding to the wave spectrum peak - $T_{p\,=}$ 4.5 s; the depth h = 2.7 m; the 2D bottom sand ripples with height - $\eta_r$ = 1.4 cm and length - $\lambda_r$ = 9.2 cm. The concentration was measured at the level 3 cm from the bottom and cross-shore velocity - at 25 cm.



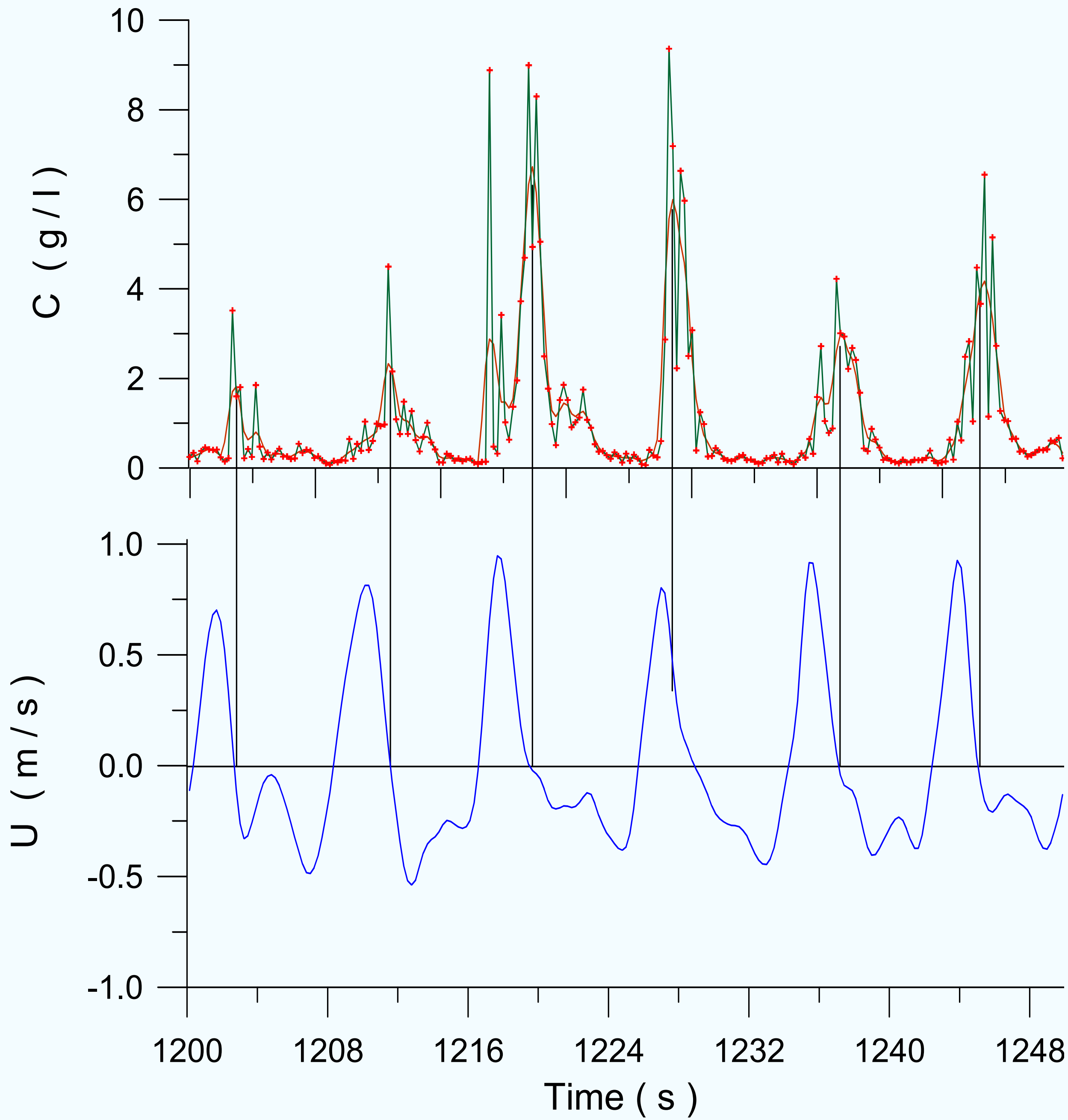



**The spectra of the suspended sediment concentration ($S_c$) and cross-shore velocity ($S_u$) - a); the coherence function and the phase shift between the sediment concentration and the cross-shore velocity ($G_{cu}$, $F_{cu}$) and between the sediment concentration and the cross-shore velocity envelope ($G_{cue}$, $F_{cue}$) - b), c), respectively.**

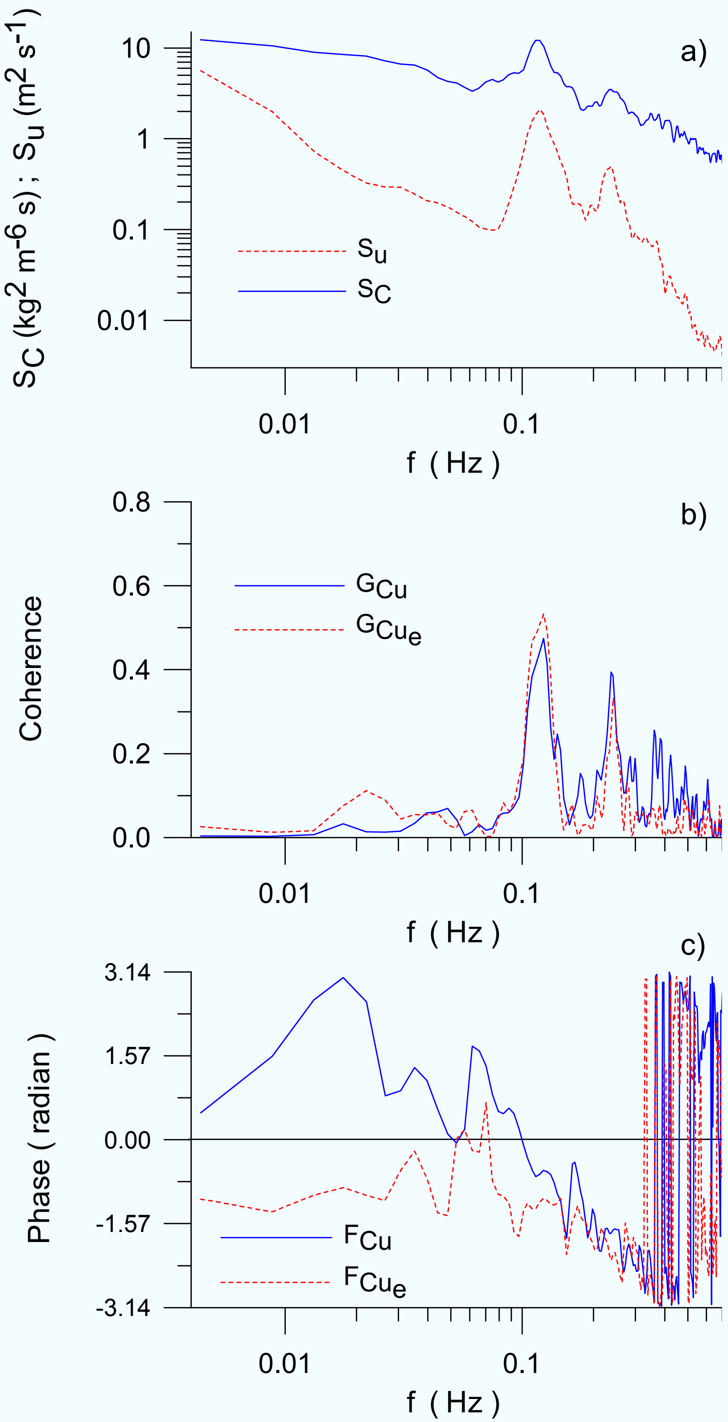



**A fragment of the temporal variability of suspended sediment concentration (C, dotted line shows measurements with discreteness of 0.055 s; solid line is the same without turbulent pulsations with frequency more than 1 Hz) and cross-shore water velocity (U). The "Novomikhailovka-93" experiment (the Black Sea).**

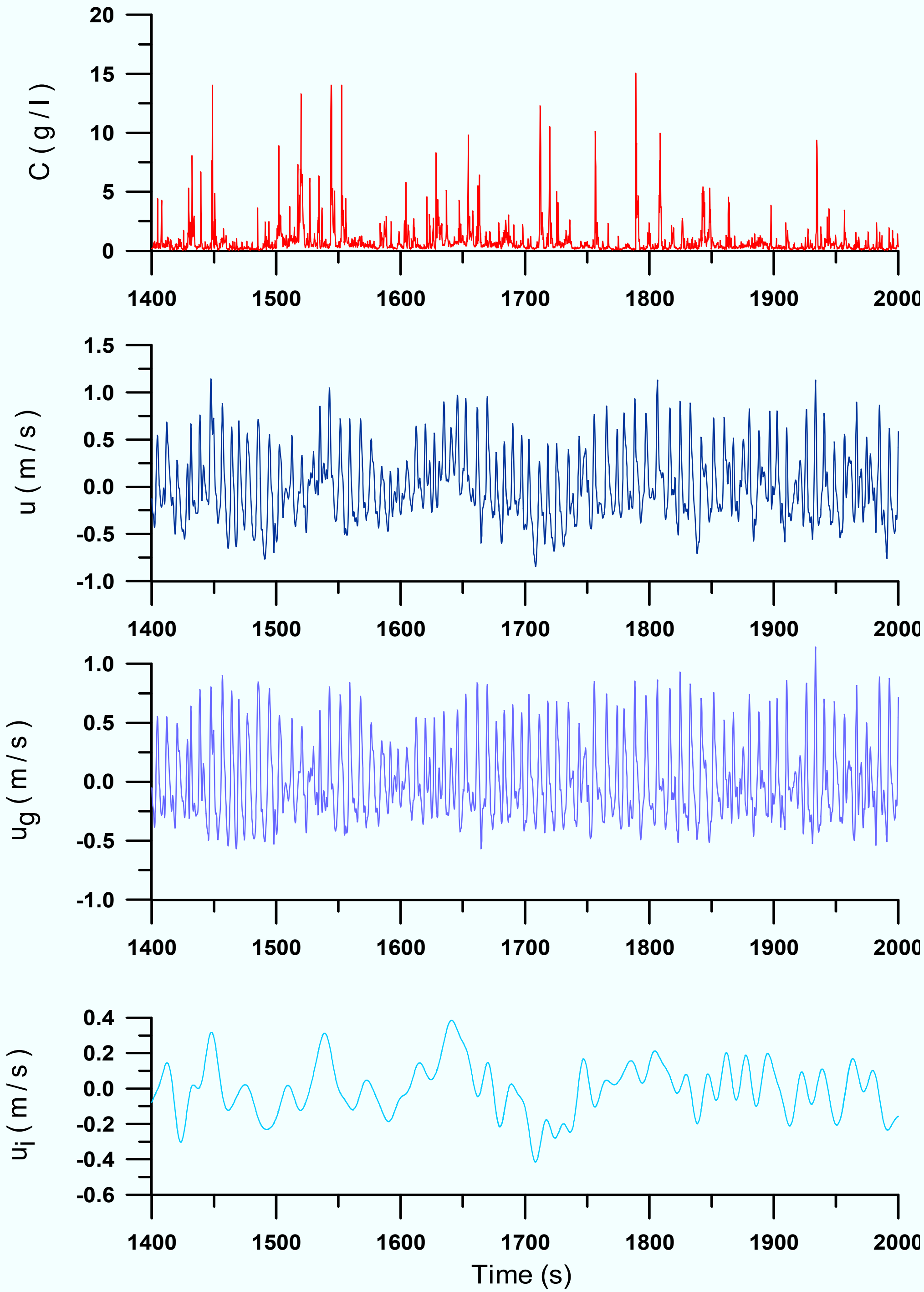
**Conditions of measurements. The height of significant waves is 0.85 m, the period of the spectrum peak is 8.3.s, depth is 2.7 m. Three-dimensional ripples with the slope less than 0.03 were on the bottom in the stage of obliteration. Suspended sediment concentration was recorded at the horizon of 7 cm, and water velocity - at the horizon of 25 cm above the bottom.**




**The same as previous picture, only with the less amplitude of velocity.**

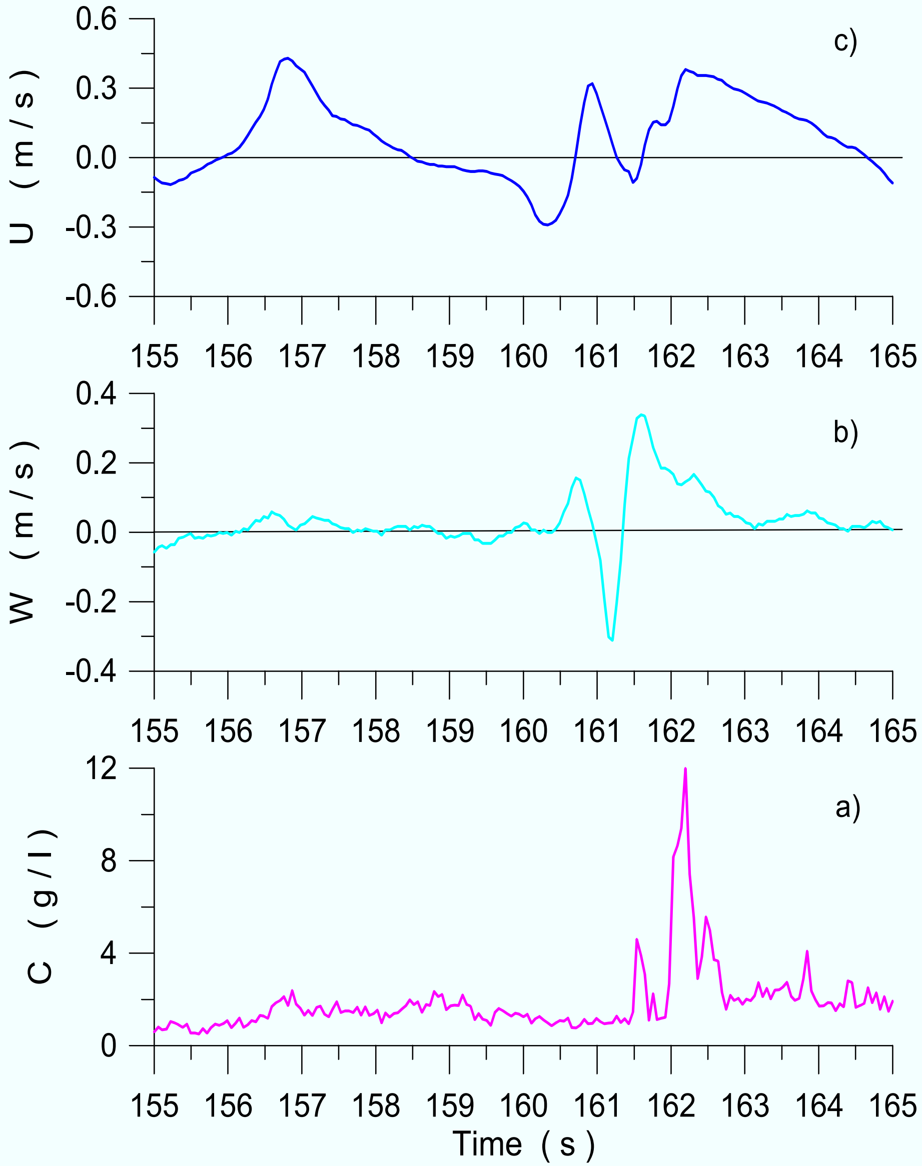



**Spectra of suspended sediments ($S_c$) and cross-shore water velocity ($S_u$) – a); coherence and phase shift between fluctuations of concentration and water velocity ($G_{cu}$, $F_{cu}$) and between concentration and envelope of water velocity ($G_{cue}$, $F_{cue}$) - b), c), consequently. Measuring conditions the same as in previous picture.**



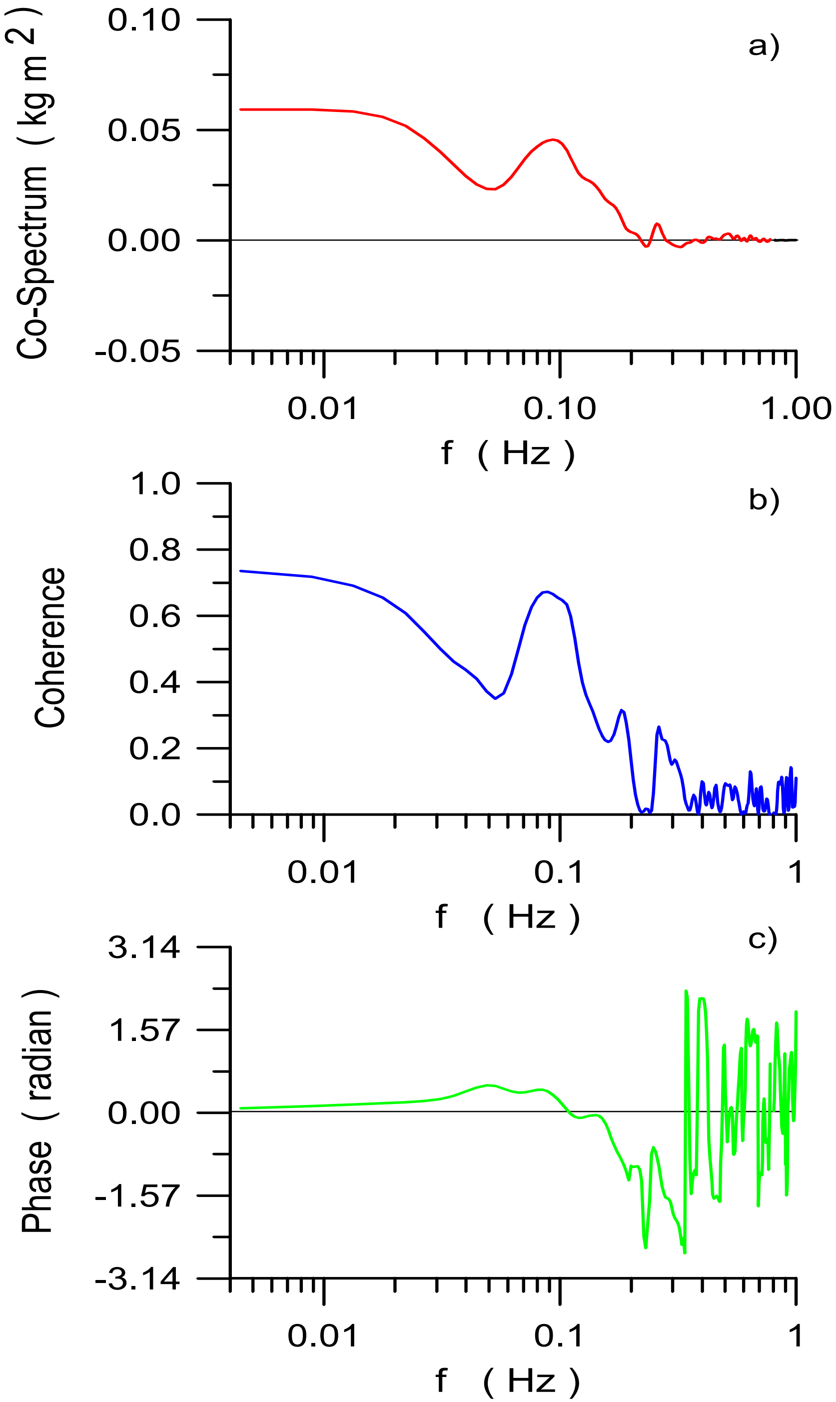

**A fragment of recording of suspended sediment concentration (C), cross-shore water velocity (U), its gravitational ($u_g$) and infragravitational ($u_i$) components, which illustrates their influence on the suspended sediment concentration.**

# Plunging type breaking



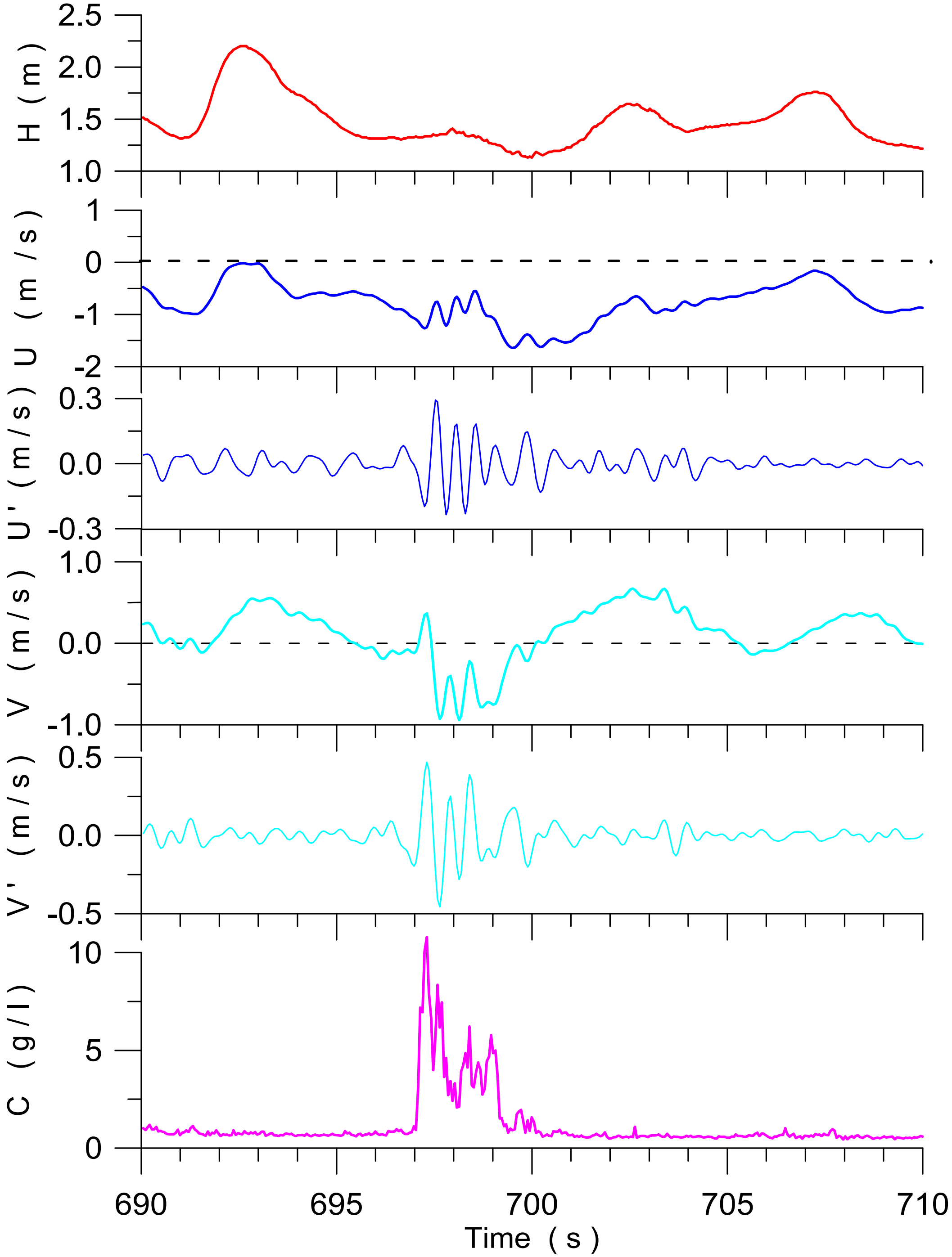

**The 10 s fragment of the time series of the suspended sediment concentration - a); vertical - b); and cross-shore velocity – c).**

**The presented data testify to the fact, that the vertical velocity determines the suspended sand flux from the bottom. The peaks of the concentration (a, b) are coincided in time with the increased magnitudes of the turbulent fluctuations of the vertical velocity and the zigzag form of the forward front of the cross-shore velocity (a, c).**

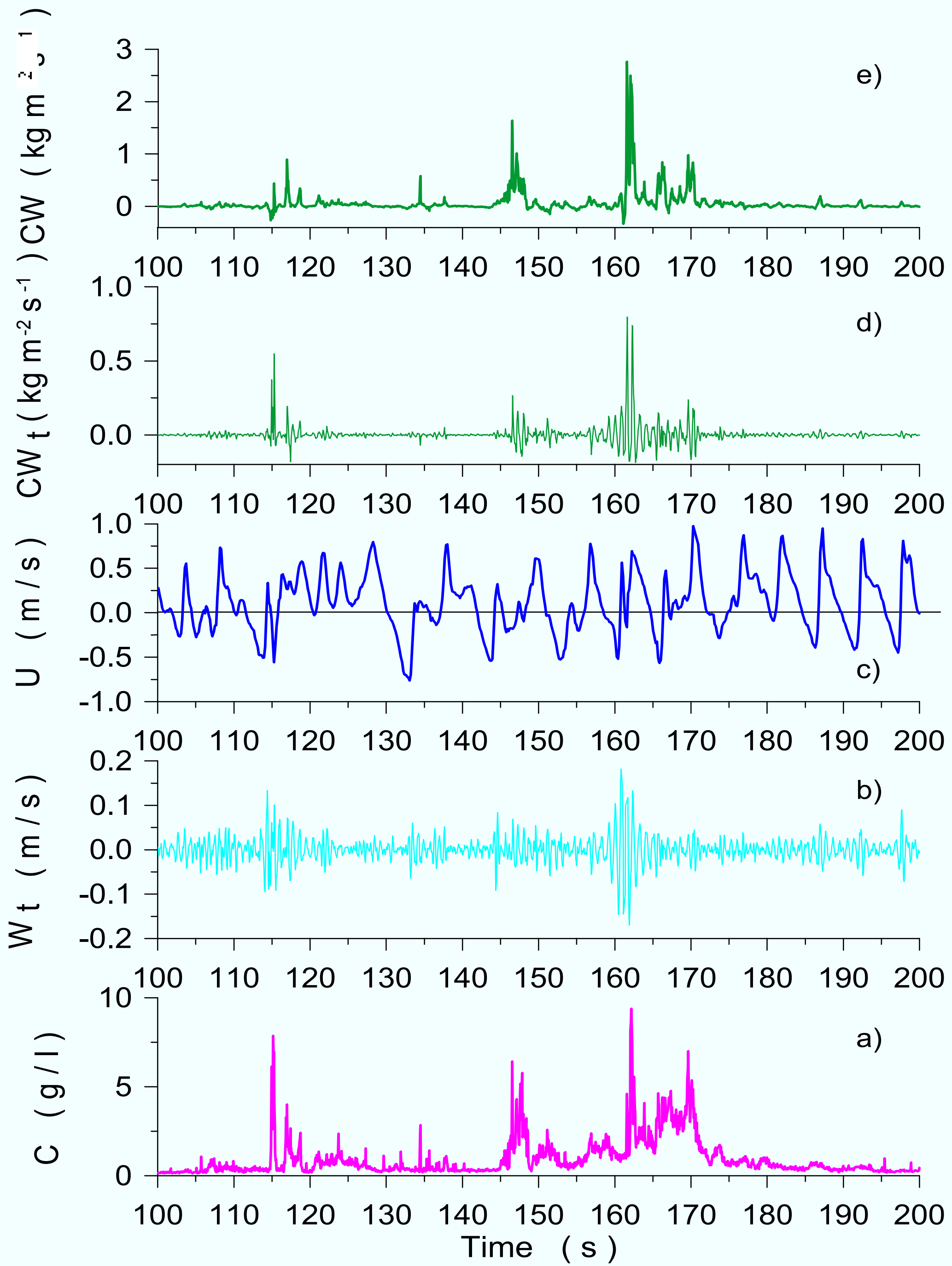



**The Co-spectra – (a), coherence – (b), and phase shift – (c) between the suspended sand concentration and the wave vertical velocity.**

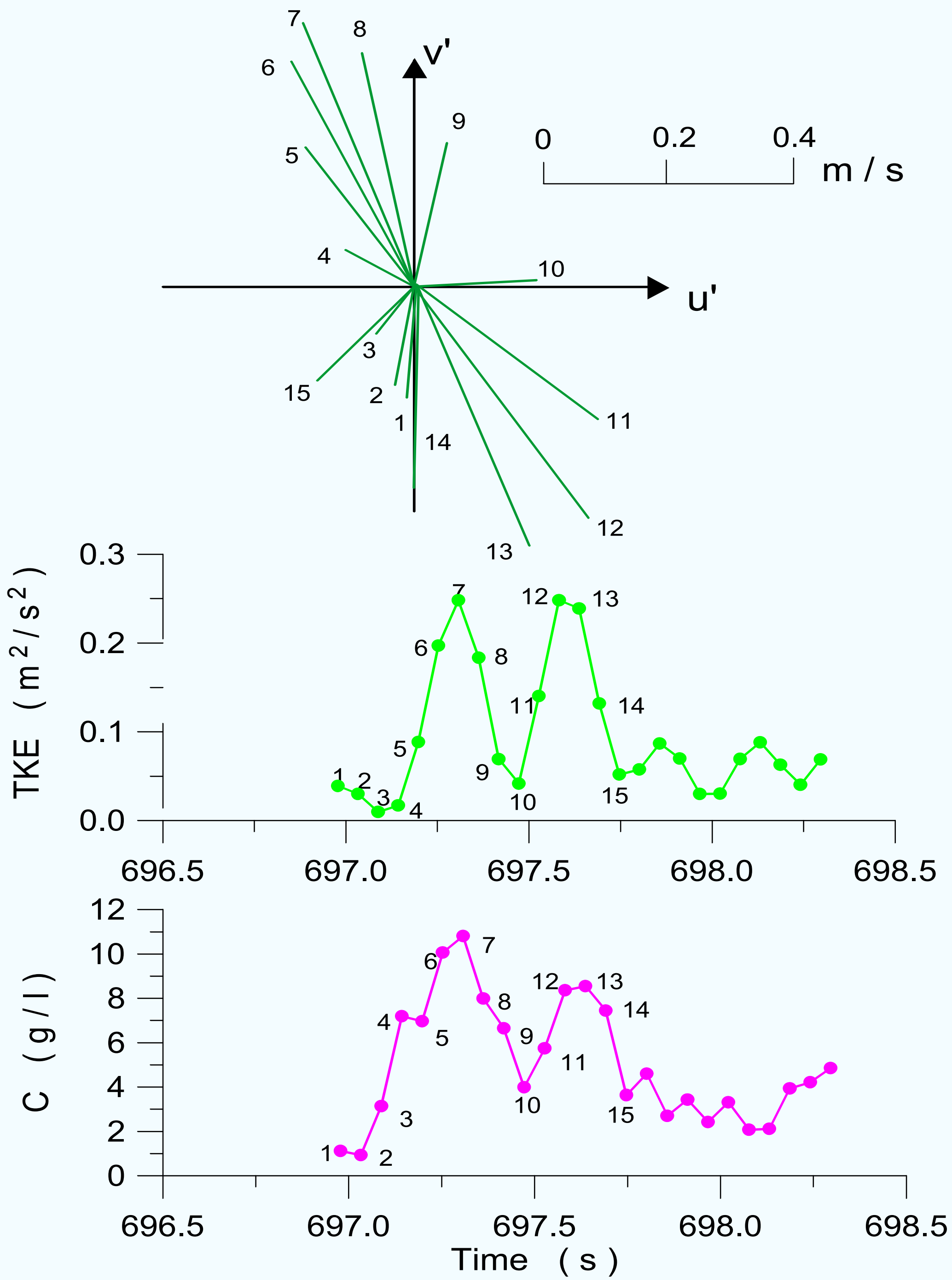
# Spilling type breaking



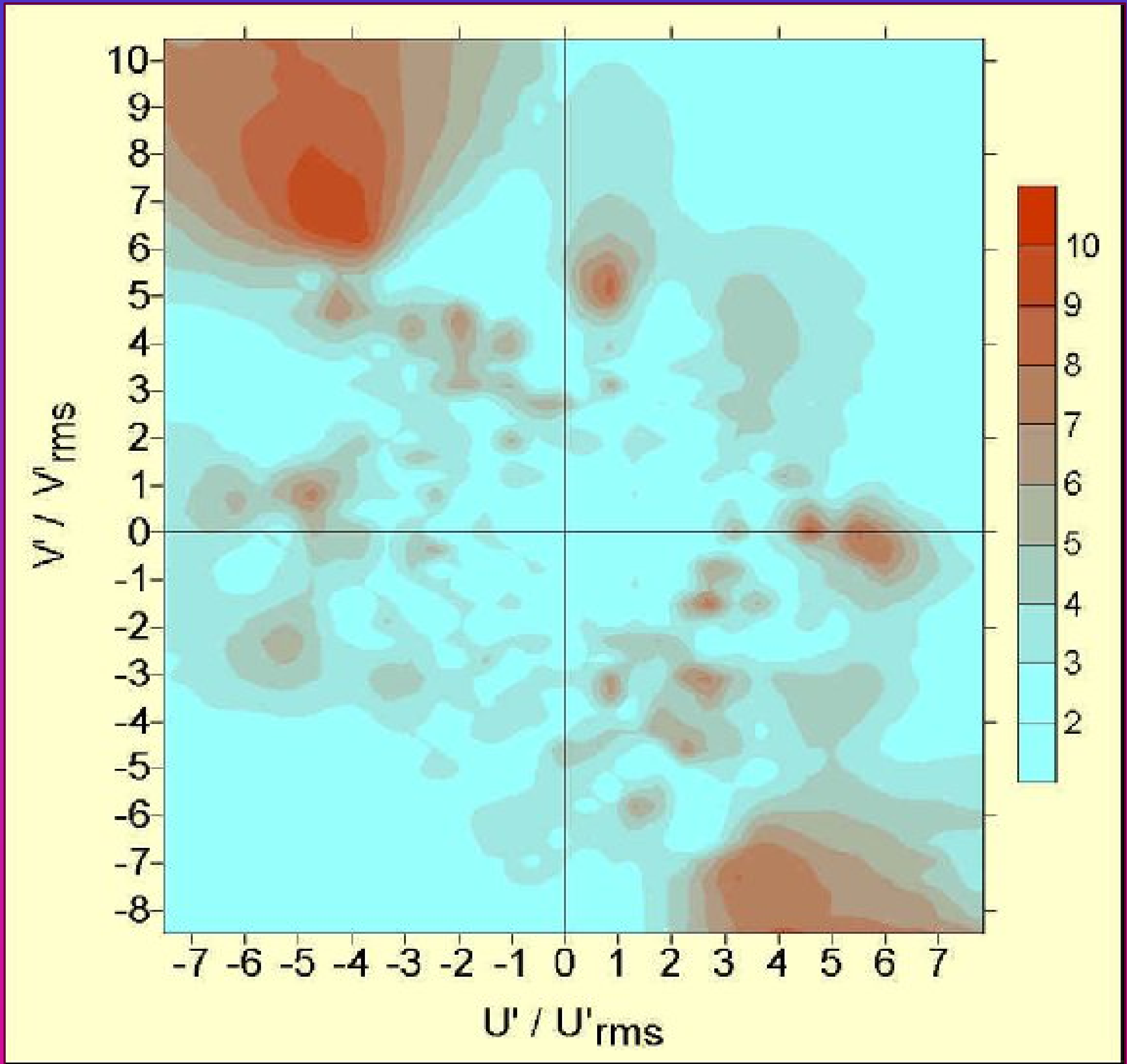

**The example of the suspension event in the middle part of surf zone.**




**The time series of the suspended sediment concentration (C) - a); the vertical turbulent velocity ($W_t$) - b); the vertical wave velocity (U) - c); the vertical component of suspended sand flux produced by turbulent velocity (C $W_t$) - d); the vertical component of suspended sand flux produced by the wave component of velocity (C $W_t$) - e).**

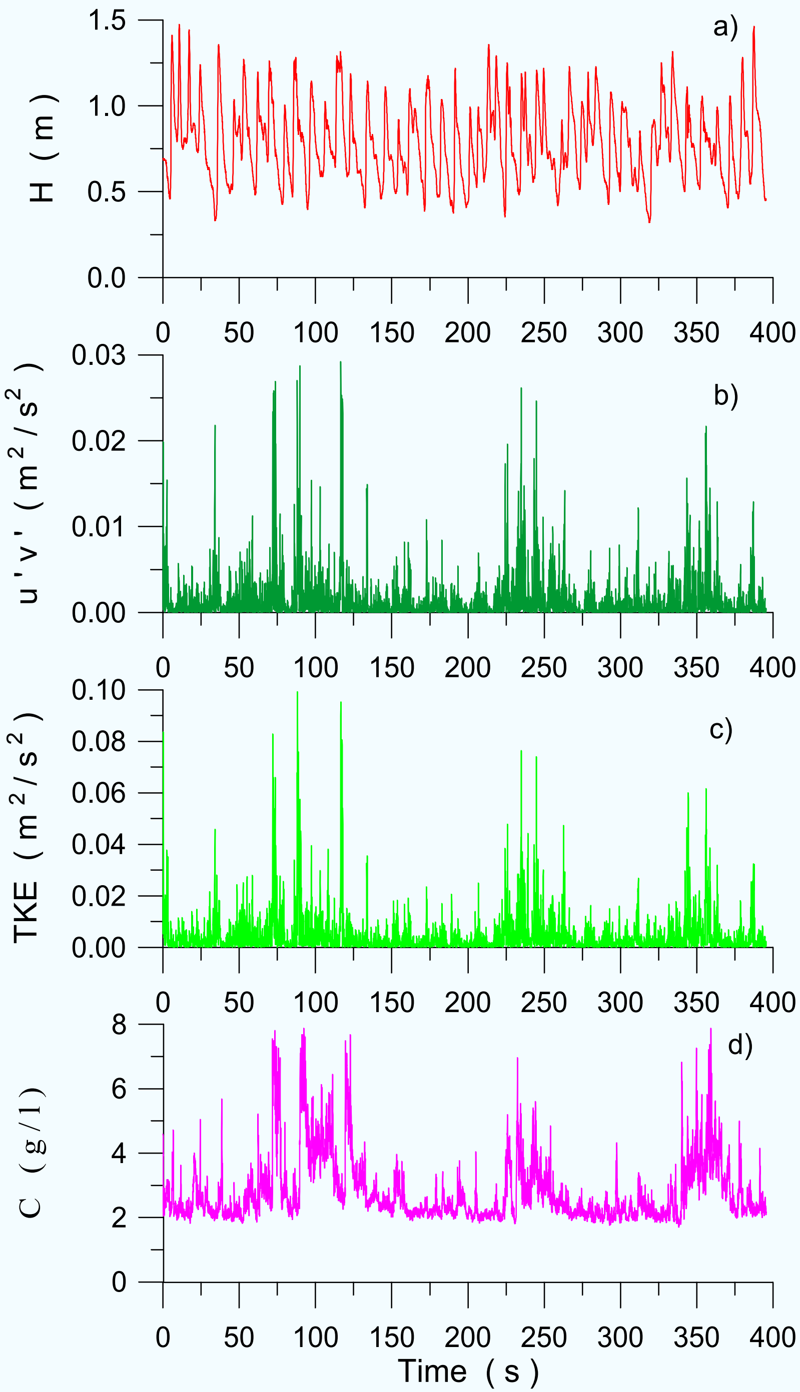



**The short fragment of the temporal variability of the sediment concentration (C), the 2D turbulent kinetic energy (TKE) and the position of turbulent velocity vector (upper part of the figure) for the time interval of the suspension event from the previous Figure**

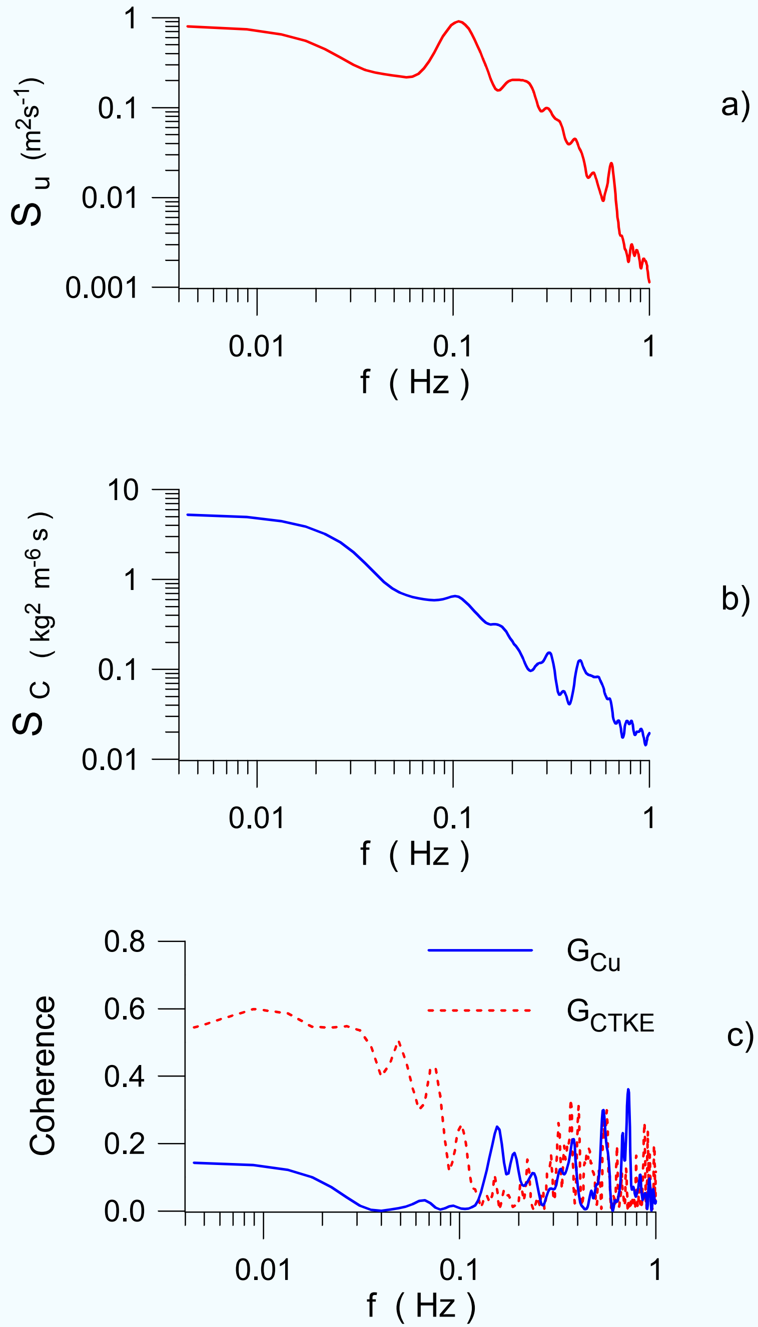



**The sediment concentration contours plotted in the velocity space.**

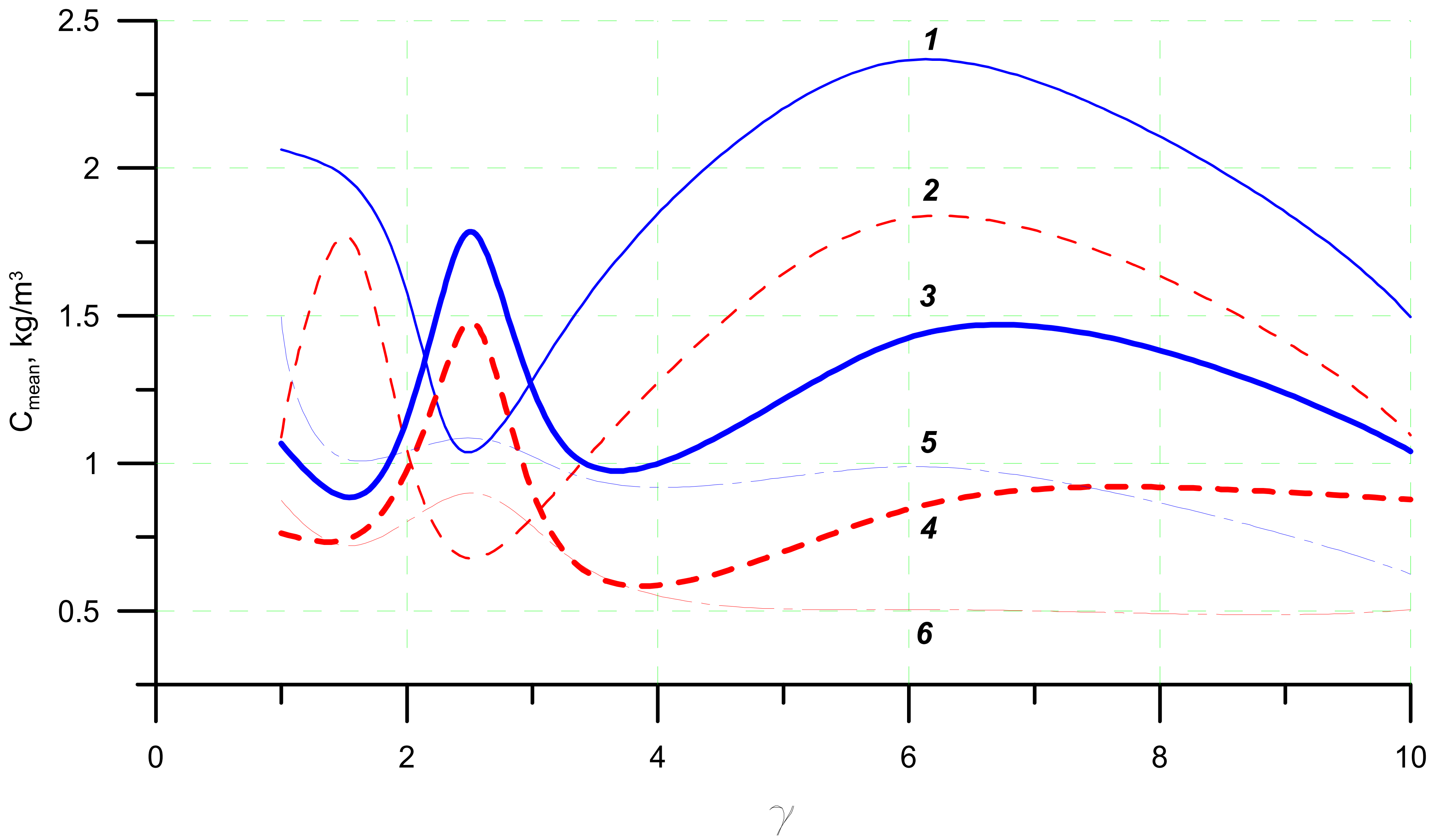
**U' and V' - cross-shore and longshore turbulent velocities respectively; $U'_{rms}$ and $V'_{rms}$ - root-mean-square values of u' and v', respectively**




**The short fragment of the temporal variability of the sediment concentration (C), the 2D turbulent kinetic energy (TKE) and the position of turbulent velocity vector (upper part of the figure) for the time interval of the suspension event from the previous Figure**




**Time series of 400 seconds:**
**a) spectra Su of the cross-shore velocity (u);**
**b) spectra Sc of the suspended sediment concentration (C);**
**c) spectra of the coherence between Sc and Su (Gcu) and between the spectra of the sediment concentration and of the turbulent kinetic energy ($G_{ctke}$). – ”Norderney’94” experiment.**




**1** hsign=0,9m, d=7cm
**2** hsign=0,9m, d=15cm
**3** hsign=1,1m, d=7cm
**4** hsign=1,1m, d=15cm
**5** hsign=1,0m, d=7cm
**6** hsign=1,0m, d=15cm

$$< C_T(t)u(t) > = < C_T(t) > < u(t) > + < C_T(t)u(t) >_L +$$
$$< C_T(t)u(t) >_W + < C_T(t)u(t) >$$

The turbulent cross-shore suspended flux is about one order less then the other terms of the equation; therefore it may be omitted.

The measured suspended sediment flux can be calculated in a comparable manner:

$$< C_T(t)u(t) > = < C(t) > < u(t) > + < C(t)u(t) >_L + < C(t)u(t) >_W$$

# CALCULATION OF THE VERTICAL PROFILES OF THE CONCENTRATION

**The analysis of the existing points of view to the modeling of the suspended sediment concentration has shown that today simple models with analytic final formulae are more preferable ones for the practical calculation than complex models where one or double-parameter equations of turbulence are used for the closing of the system of equations. It is bound with the fact that in the latter models due to the vagueness of the physical picture there is a number of coefficients, the determination of a numerical value of which for the wave flow is not sufficiently grounded from the physical aspect. And that gives a small gain in accuracy as compared with simple models, and expenditures of time and means for the calculation are essentially large ones.**

**The verification of simple models on the basis of the field measuring of the suspended sediment concentration has shown that the diffusion model by Kos'yan (1985), in which the parameters of significant waves are used, gives quite satisfactory coincidence of measured and calculated profiles of suspended sand concentration in the zone of nonbreaked waves.**

**The exponential distribution of the suspended sediment concentration with distance from the bottom is characteristic one for the breaking zone (1):**

$$\frac{C(z)}{C_b} = \exp\left\{-\int_b^z \frac{w_s}{k_b}\,dz\right\} \qquad (1)$$

**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.**

**Concrete calculation formula (2) and dependencies for $k_b$ are given by Kos'yan (1985).**

$$\frac{C(z)}{C_b} = \exp\left\{ -\int_b^z \frac{w_s \cdot dz}{\dfrac{a_1 \cdot H^2 \cdot \sinh(k \cdot z)}{T \cdot \sinh(k \cdot h)} + \dfrac{a_2 \cdot (U_m - w_s) \dfrac{z}{\delta_w}}{1 + a_3 \cdot \dfrac{z}{\delta_w} \cdot \exp(\dfrac{z}{\delta_w})}} \right\} \qquad (2)$$

**where** $a_1 = \frac{\pi}{2\sqrt{2}}$; $a_2 = 116 \cdot \frac{\rho}{\rho_s - \rho} \cdot \left(\frac{\nu^2}{g}\right)^{1/3}$; $a_3 = 0.06$; $k = \frac{2 \cdot \pi}{\lambda}$; $H, \lambda, T$ **are the height, length and wave period;** $h$ **is the depth of the sea;** $U_m$ **is the maximum value of the near bottom velocity;** $\rho_s, \rho$ **-are densities of solid particles and liquid, respectively;** $g$ **is acceleration of gravity;** $\delta_w$ **is a thickness of the nearbottom boundary layer, which can be defined by (3).**

$$\frac{30\delta_w}{K_s} \cdot \log\left(\frac{30\delta_w}{K_s}\right) = 1.2 \frac{a_m}{K_s} \qquad (3)$$

**where** $a_m = U_m / w_s$ **is an amplitude of a water particle motion near the bottom;** $K_s$ **is a linear size of bottom roughness elements;** $\nu$ **is the kinematic viscosity;** $\omega$ **is an angular frequency.**

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

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

# Model of suspended sediment concentration fluctuations

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

**C(z,t) - suspended sediment concentration,**

$\varepsilon_s$ **- coefficient of turbulent diffusion of suspended particles,**

$w_s$ **- sand settling velocity,**

**t - time**

**z - vertical coordinate.**

# Diffusion coefficient

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

***contribution of the orbital motion***

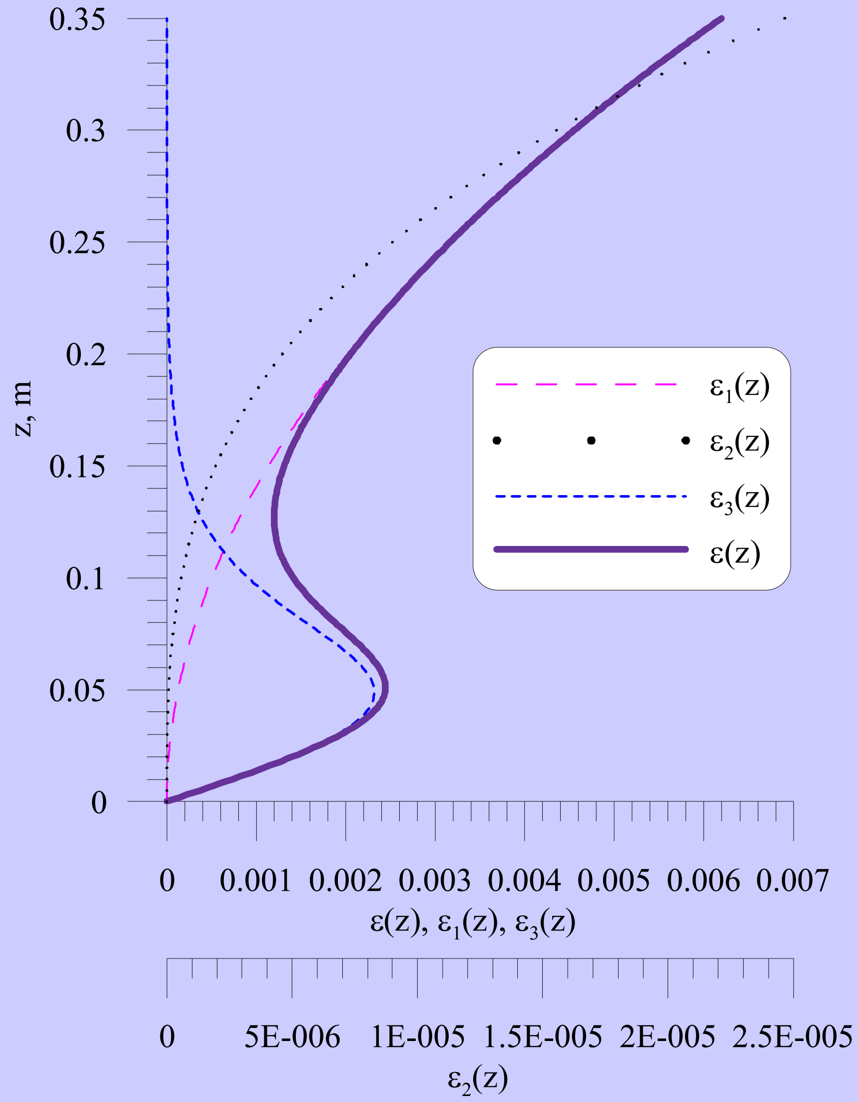
$$\varepsilon_1(z) = \frac{\pi H^2 \sinh^2 kz}{2\sqrt{2}T \sinh^2 kh}$$

***contribution of the wave flow***

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

***contribution of diffusion in near bottom layer***

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




**Vertical profile of the diffusion coefficient**

## Boundary conditions

**free water surface**

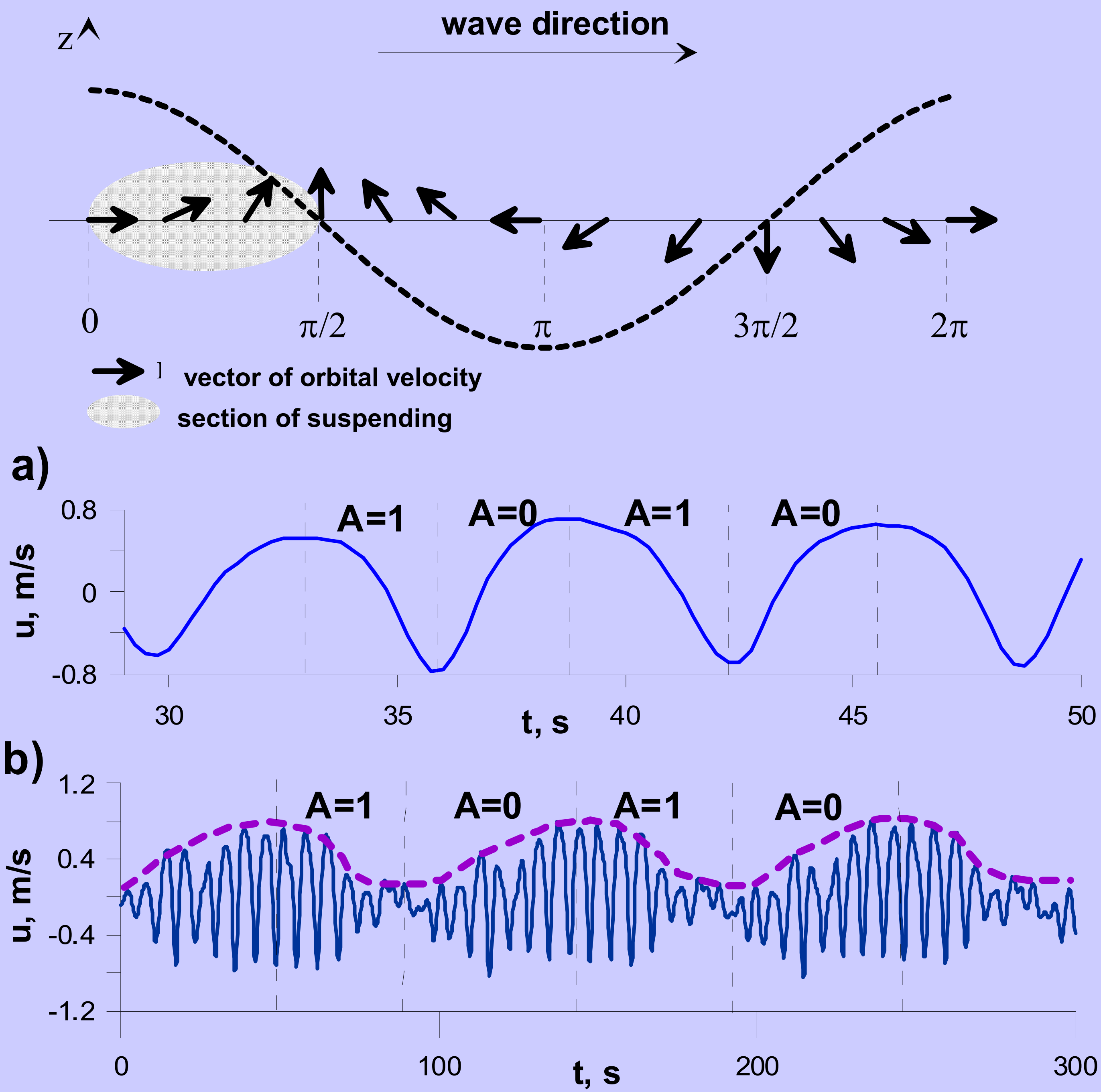
$$\varepsilon_s \cdot \frac{\partial C}{\partial z} + w_s \cdot C = 0$$

**bottom boundary** C(0,t)=Ap(t),

**p(t) – function of local ejection of suspended sediment (pick-up function)**

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

$s = \dfrac{\rho_s}{\rho}$ **relative density of sediments**



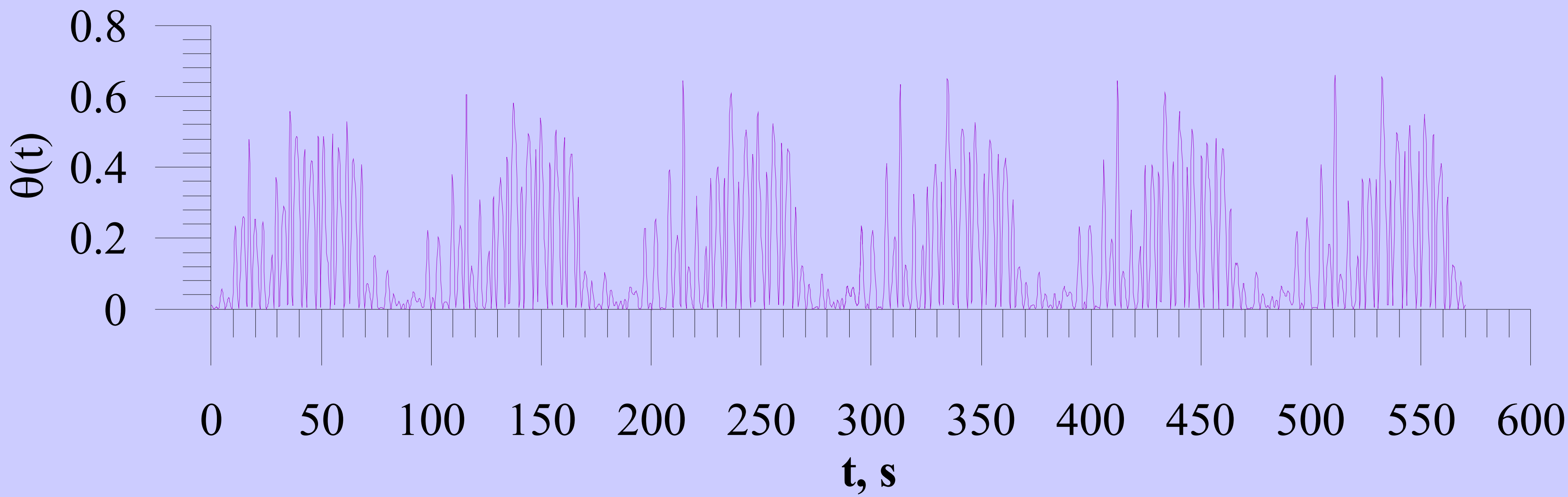
wave direction
z
0
π/2
π
3π/2
2π
vector of orbital velocity
section of suspending
a)
0.8
0
-0.8
u, m/s
A=1
A=0
A=1
A=0
30
35
40
45
50
t, s
b)
1.2
0.4
-0.4
-1.2
u, m/s
A=1
A=0
A=1
A=0
0
100
200
300
t, s

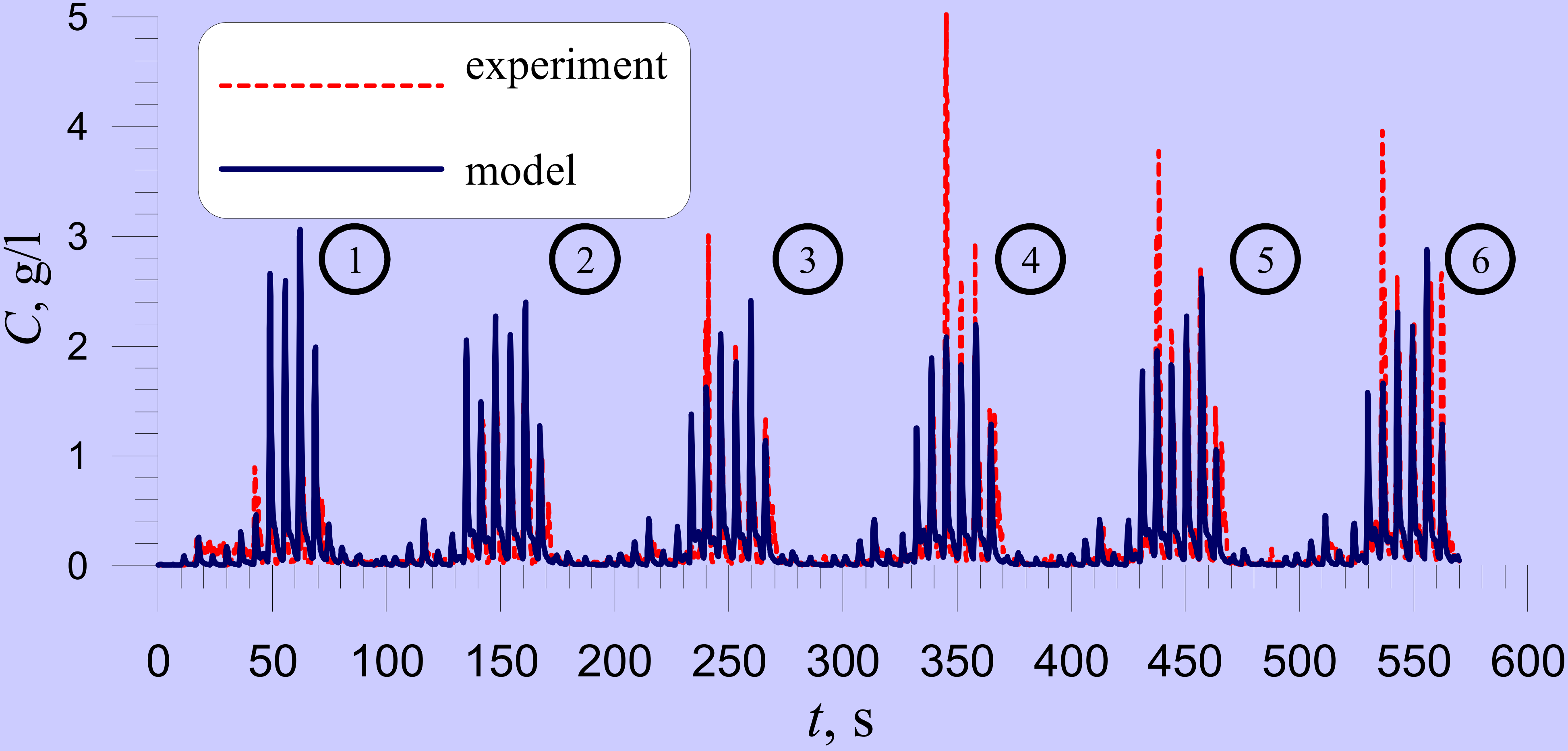
## Shields parameter

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

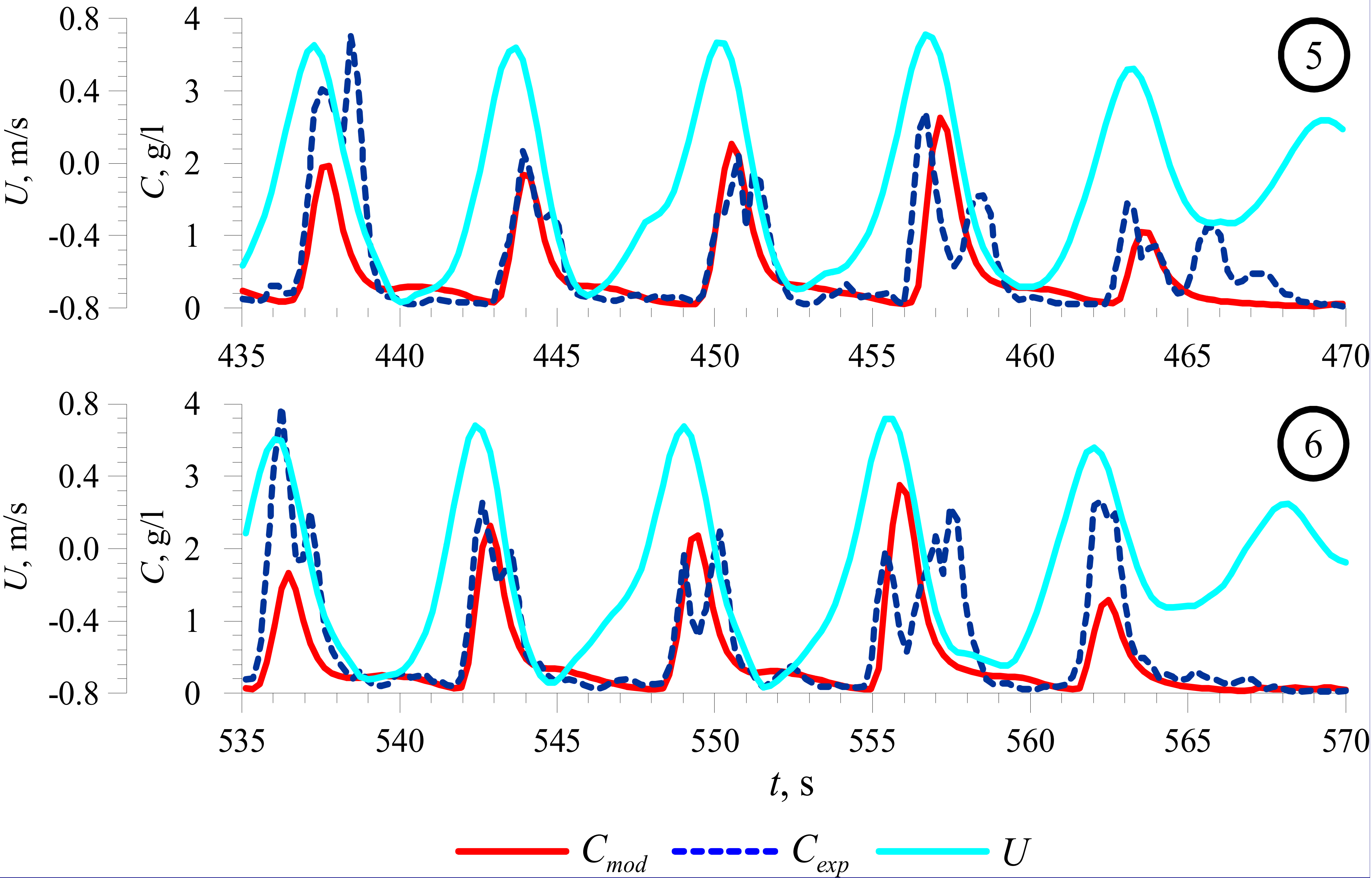
**$d_{50}$ - median diameter of sediments**

**u*(t) - maximum shear velocity calculated from the flow velocity.**

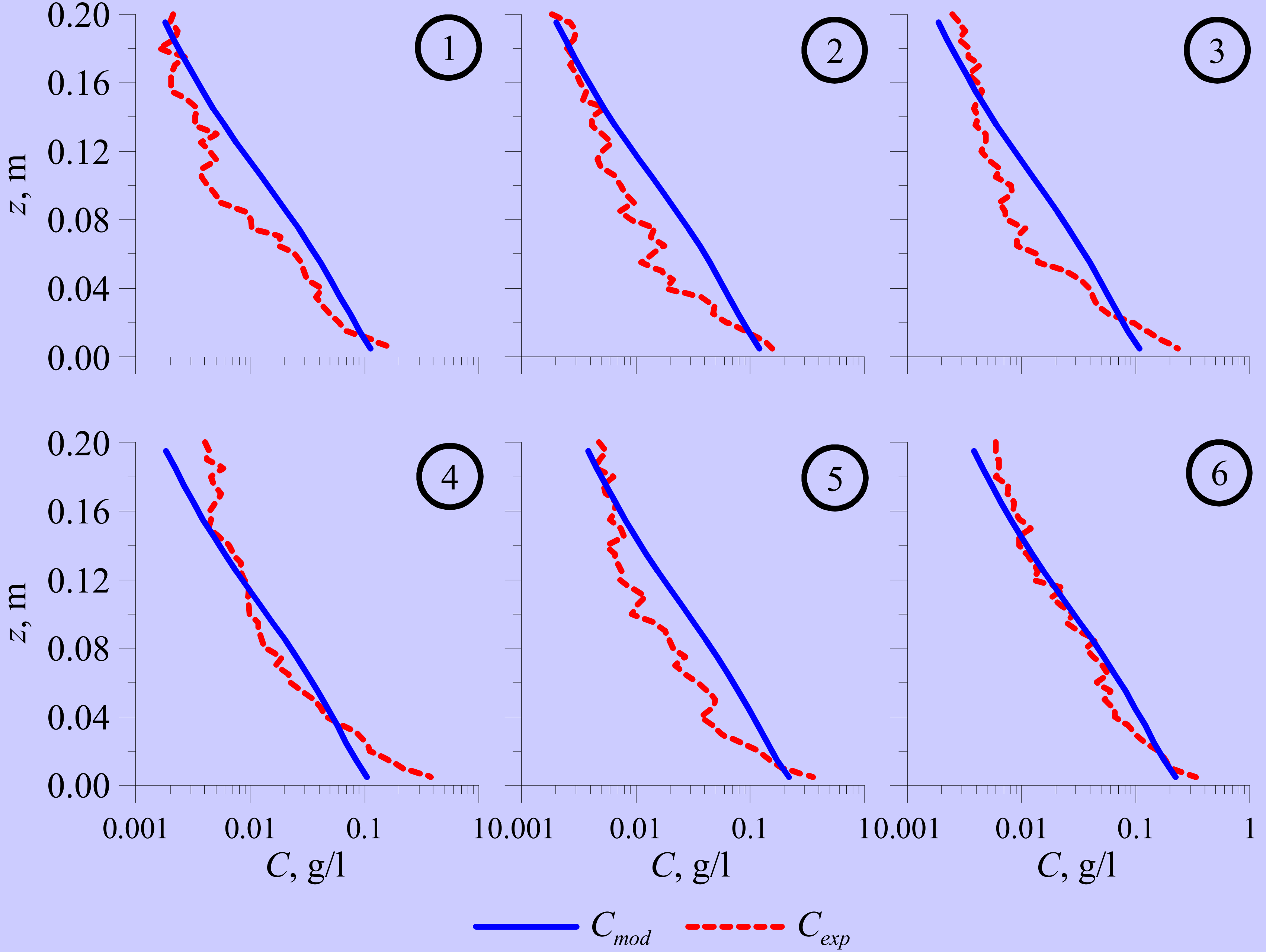




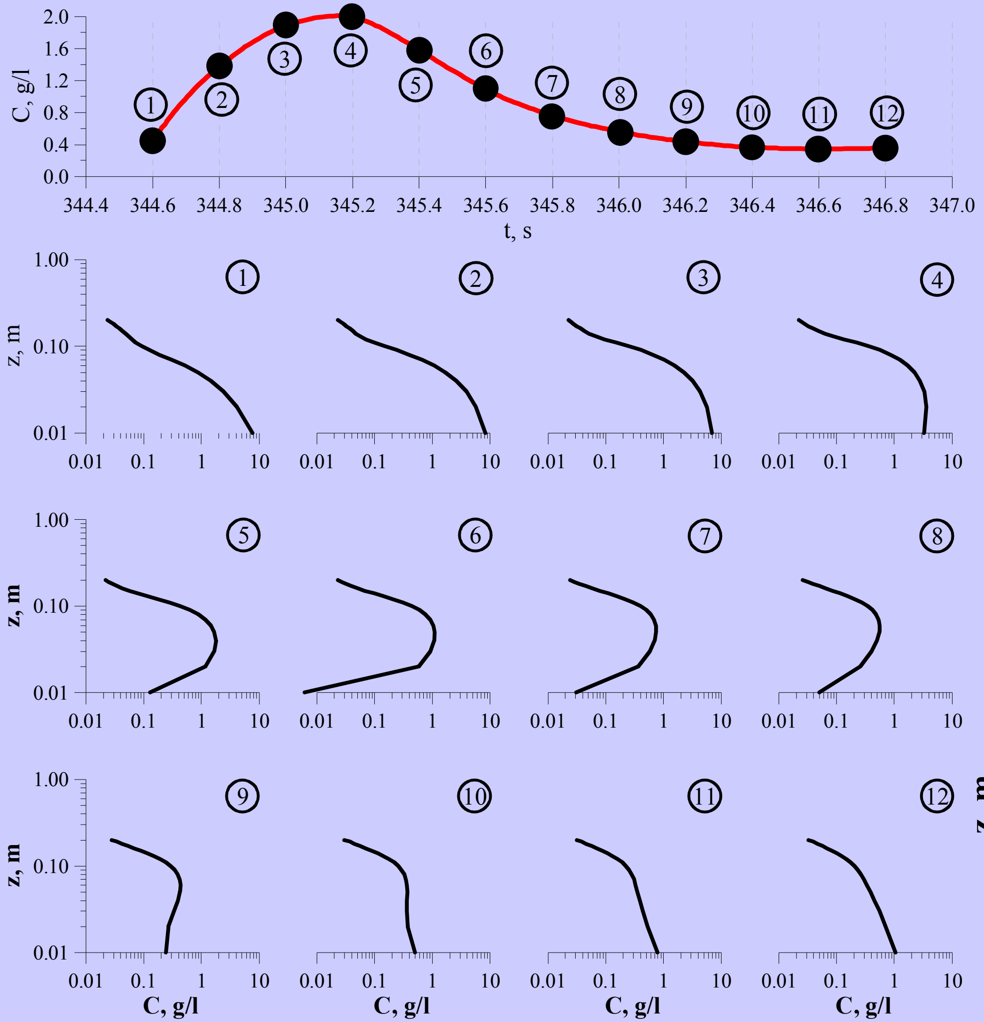

**Suspended sediment concentration**



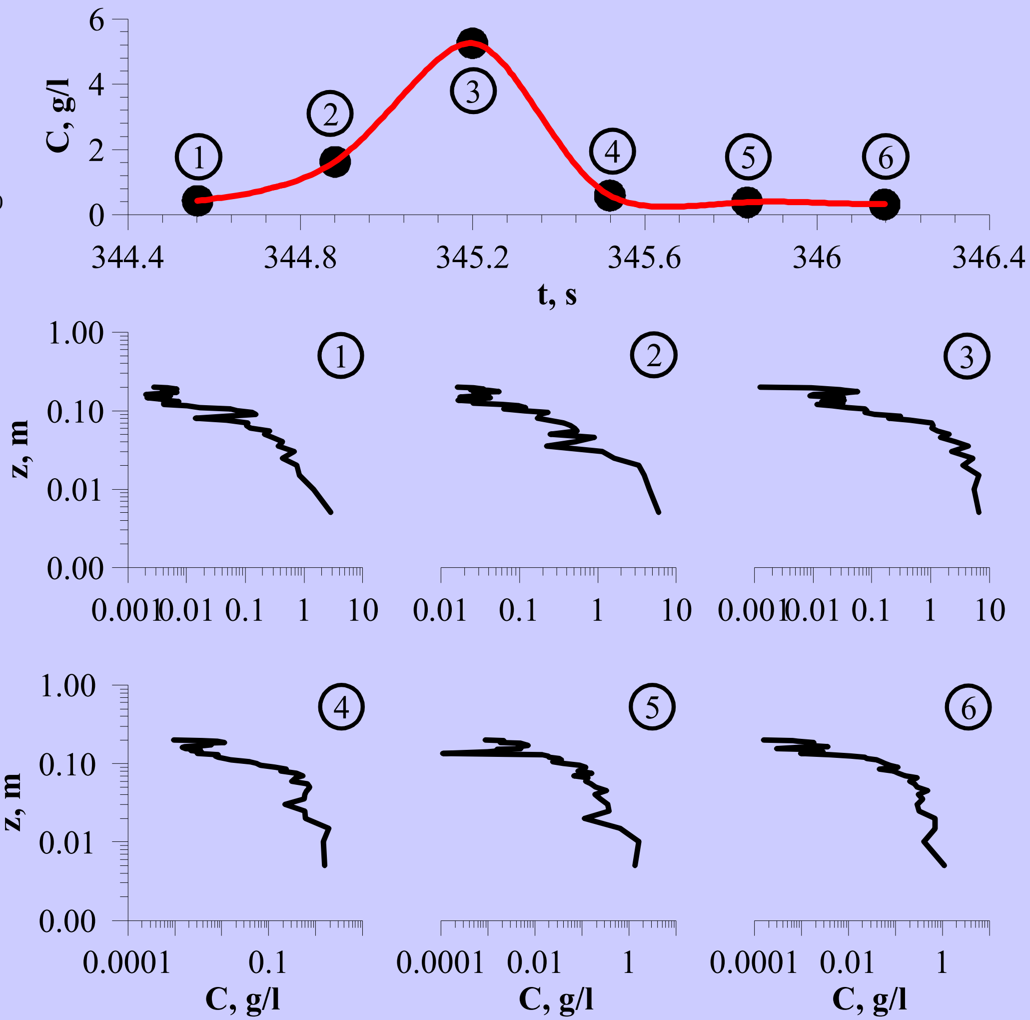

**Chronograms of horizontal velocity (U), experimental ($C_{exp}$) and model ($C_{mod}$) concentrations under wave groups**



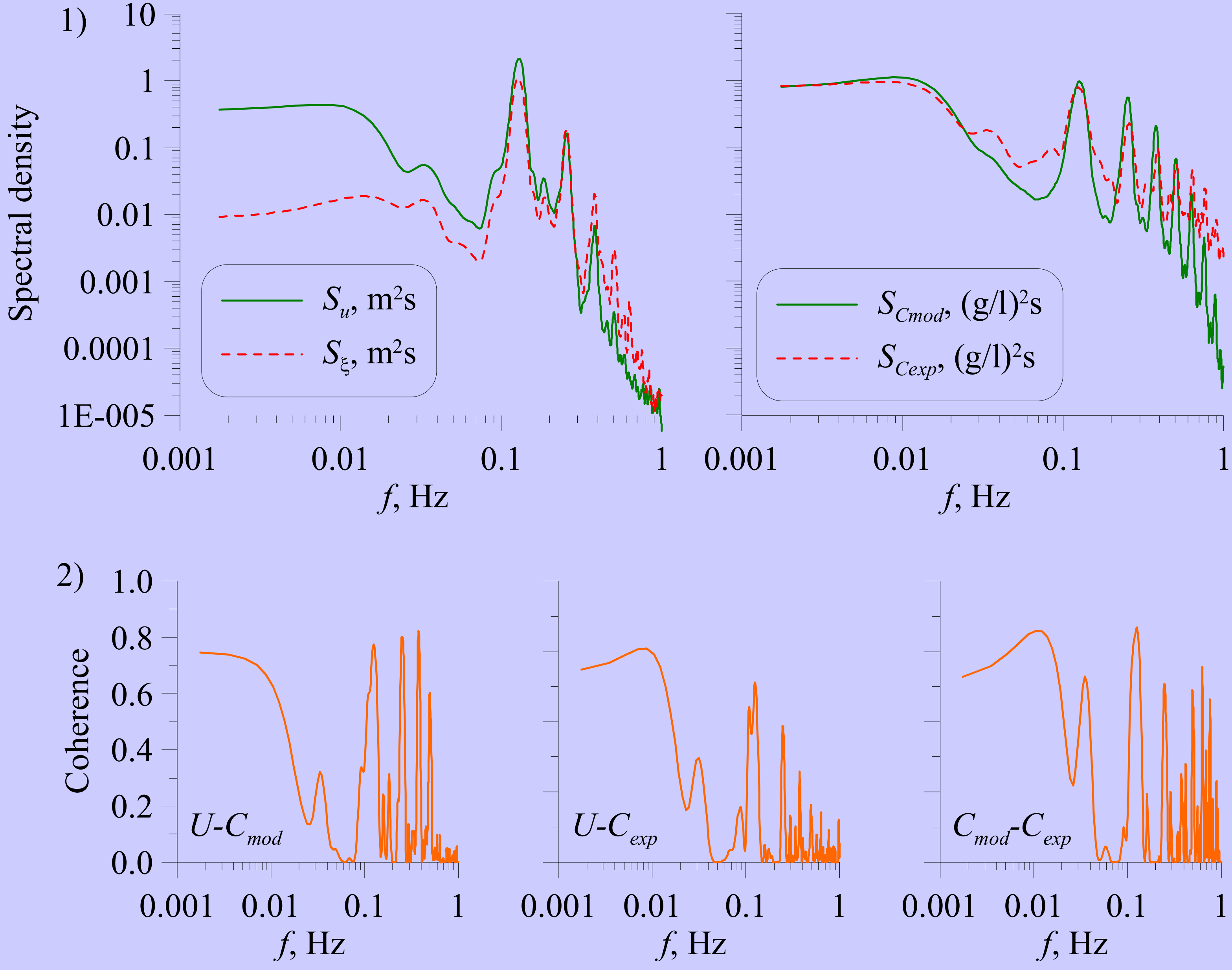

**Averaged vertical profiles of the experimental ($C_{exp}$) and model ($C_{mod}$) suspended sediment concentration under wave groups**




High-frequency fluctuations of vertical profile of model suspended sediment concentration




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




**Result of the spectrum analysis (Cexp – experimental and Cmod - model suspended sediment concentration)**


Thanks a lot
For your attention