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ANALYSIS OF SEDIMENT PARTICLE VELOCITY IN WAVE MOTION BASED ON WAVE FLUME EXPERIMENTS

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Abstract: The experiment described was one of the elements of research into sediment transport conducted by the Division of Geotechnics of West-Pomeranian University of Technology. The experimental analyses were performed within the framework of the project "Building a knowledge transfer network on the directions and perspectives of developing wave laboratory and in situ research using innovative research equipment" launched by the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk. The objective of the experiment was to determine relations between sediment transport and wave motion parameters and then use the obtained results to modify formulas defining sediment transport in rivers, like Ackers–White formula, by introducing basic parameters of wave motion as the force generating bed material transport.

The article presents selected results of the experiment concerning sediment velocity field analysis conducted for different parameters of wave motion. The velocity vectors of particles suspended in water were measured with a Particle Image Velocimetry (PIV) apparatus registering suspended particles in a measurement flume by producing a series of laser pulses and analysing their displacement with a high-sensitivity camera connected to a computer. The article presents velocity fields of suspended bed material particles measured in the longitudinal section of the wave flume and their comparison with water velocity profiles calculated for the definite wave parameters.

The results presented will be used in further research for relating parameters essential for the description of monochromatic wave motion to basic sediment transport parameters and „transforming" mean velocity and dynamic velocity in steady motion to mean wave front velocity and dynamic velocity in wave motion for a single wave.

1. INTRODUCTION

The present study is the continuation of research into sediment transport. The first studies of sediment transport conducted by the Division of Geotechnics of Szczecin University of Technology concerned a one-dimensional model of sediment transport in uniform motion conditions. These analyses were based on the methodology of determining total sediment load (suspended load and bed load) transport according to Ackers–White formula and on research into vertical velocity distributions in a flume, allowing for factors like wind stress or density stratification (Meyer 1981 and Buchholz 1989). In effect, they enabled developing a bed dynamics model for the area of the lower Odra river allowing for wind stress on the water surface (Coufal [2]). The analyses conducted for the needs of this model led to an observation that variations in the horizontal cross-section of a river channel are related to morphological changes in the river bed. Field studies have revealed that the river channel contains places particularly significant to water and sediment transport conditions. Waterway junctions of river bifurcations and confluences, as well as the problem of river flow close to hydrotechnical structures were identified as such places. Therefore, subsequent studies focused on such significant points, extending the model of sediment transport to river bifurcation conditions illustrated by the example of a river junction at Widuchowa or the confluence of the Odra and the Warta at Kostrzyń junction (Krupiński, 2001). Originally, a one-dimensional uniform motion model was built for the significant places mentioned above. It enabled determining relations between the position of the river bed and water and sediment balance equations based on iteration calculations and optimisation of equation parameters. In the next stage of the research, the water and sediment transport model was extended to allow for flow disturbances caused by bridge piers. It was based on two-dimensional model, again in relation to water and sediment transport balance equations. In this model, horizontal components of sediment flux described by diffusion equation were taken into consideration. All these studies employed one model of sediment transport based on Ackers–White method. During the long-term studies described above, this method was repeatedly compared to other sediment transport models, producing similar values in relation to sediment flux. At subsequent stages of the research, the method was recurrently verified by field examinations for the Lower Odra section. In contrast to other models, the method discussed provided a fairly simple way of analysing sediment composition used for calculations, adopting the composition of bed material, where division into traction and suspension is described with an equation parameter, as representative. The very structure of the formulas, presented in detail at the previous Polish National Conference of Hydrological Modelling, contains coefficients and parameters of water transport describing such complex phenomena as the influence of grain size and their mobility, division into suspended load and bed load determined by sediment composition and water transport parameters, the significance of motion initiation parameters for representative grains or, last but not least, the importance of bed roughness and the influence of bedform-induced flow disturbances. The study presented at the previous conference in the same cycle pointed to considerable differences between the values of channel roughness and water flow resistance determined in a traditional way and those resulting from sediment studies. These findings pointed to the necessity of devising a description of bed roughness dependent on parameters easily measurable in the field, such as channel shape and dimensions, bed load material size or the size and shape of bedforms known from literature. It is only such an extended definition of roughness that would enable correlating models describing water and sediment transport. These studies, and the preliminary conclusions mentioned above, have provided basis for even more thorough analysis of the structure of the most common formulas used for determining sediment flux, with particular attention to coefficients and parameters that quite often define all the above-mentioned processes with a constant value.

In 2009, following long-term collaboration with the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk, including studies of sediment transport, the Division of Geotechnics at West-Pomeranian University of Technology was invited to take part in a joint research programme within the framework of the project "Building a knowledge transfer network on the directions and perspectives of developing wave laboratory and in situ research using innovative research equipment" launched as part of Regional Operational Programme for the Pomeranian Voivodeship in 2007–2013. Thanks to the long experience of studying the issues described, the researchers were able to contribute their knowledge and expertise in sediment transport to this research project. Based on earlier studies of the problem of river bed material transport and on an analysis of commonly used models describing water movements in wave motion, an assumption was made that it was possible to modify the chosen model describing sediment transport in steady motion in an open flume in such a way that the basic relations characterising water flow in a flume could be replaced with basic elements characterising wave motion. In view of the experience of studying and modelling sediment transport by means of the well-known and repeatedly modified for the conditions of the Lower Odra Ackers–White method, the aim of the experiment was specified as modifying Ackers–White formulas for calculating sediment transport by introducing basic parameters of wave motion as the force generating bed material transport. The modifications obtained in this way will enable, after the termination of the research, defining more precisely a few specific elements of this model described at the start like parameter α appearing when Prandtl formula is incorporated into the model, defining broadly the influence of all additional factors such as bedforms, near-bed swirls or channel shape as one constant value.

This article presents elements of obtained sediment particle velocity and sediment flux measurements for measurement series characterised by different wave parameters.

It was assumed for the needs of the experiment discussed that while measuring a sediment flux displaced by monochromatic waves, it would be possible to correlate the basic parameters crucial for sediment transport calculations with wave motion parameters. The basic parameters commonly used for calculating sediment transport are grain diameters, channel dimensions and mean velocity or dynamic velocity defining near-bed stresses. The leading parameters for wave motion studies are usually wavefront velocity, wave amplitude and wavelength in various conditions of the system geometry defined, for instance, by the ratio of wave height to the mean depth. A preliminary analysis of the possibility of such a modification assumes that comparing measurements of sediment flux in wave motion with computational parameters, like those for steady motion generating the same sediment flux, will enable transforming mean velocity and dynamic velocity in steady motion to the mean velocity of wavefront and dynamic velocity in wave motion for a single wave.

2. RESEARCH POST DESCRIPTION

For the assumptions and theses described above, the experiment required fitting a wave flume with a platform enabling simulations of a movable bed with a sand trap that would enable measuring sediment mass displaced for a measurable number of cycles. Consultations and the literature analysed suggested that it would be most appropriate to produce a hundred wave cycles for every measurement session, each session being described with a different ratio of wave height and period to the mean depth. The preliminary assumptions proposed such a structure of the model that the platform could offset or enable defining the influence of counter-currents on bed material transport, which resulted from the fact that the wave flume was not adapted for obtaining uniform water flow, and counter-currents could have a key influence on near-bed stresses crucial for sediment transport. With this aim, building two independent bed traps was planned so that one could intercept sediment particles moving along wave direction, and the other one – the mass displaced in the opposite direction. The model structure is shown in Fig. 1.

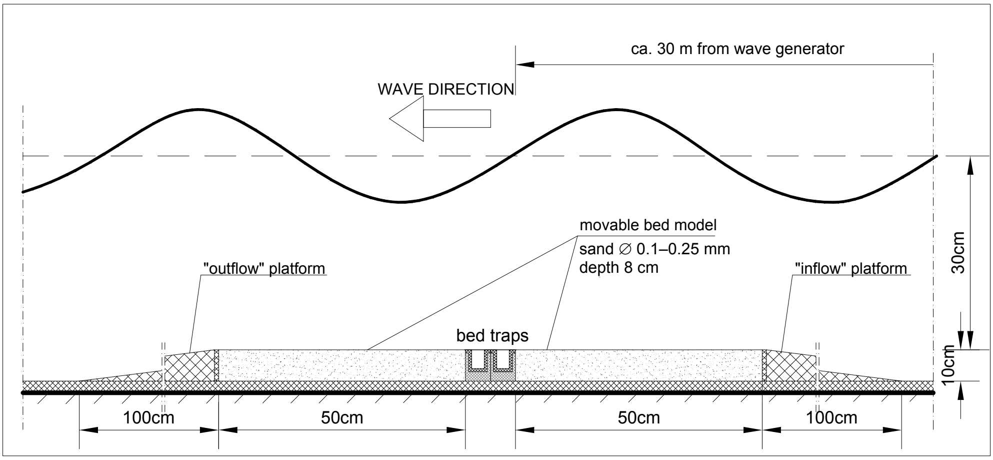

Fig. 1. Diagram of the model in a wave flume

The measurements were performed in a wave flume based at the Division of Wave Mechanics and Structural Dynamics of the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk. The laboratory was built between 1998 and 1999. The wave flume was constructed in the way ensuring a high precision of experiments being conducted. The wave flume dimensions were: length 64.1 m, width 0.6 m, depth 1.4 m (for the needs of the experiment the depth used was 0.4 m). The walls on both sides of the flume, along its whole length, are made of glass, which enables detailed observation of the experiments. Wave motion is generated by a computer-controlled piston mechanism. At both ends of the flume, there are wave absorbers made of plastic mats with the properties of a porous medium, installed with the aim of extinguishing wave energy. The amplitude of reflected waves defined in the previous experiments was 5–10% of the incident wave amplitude, which for the model installed in the centre of the flume, with fairly intensive waves adopted for the experiment, enabled ignoring this phenomenon in calculations. For the needs of the experiment, the wave pattern was adopted as a typical monochromatic wave pattern with the length of 100 cycles.

According to preliminary assumptions, the only expected objective was to measure the velocity vectors at selected points over the model and measure sediment mass dislocated during the whole wave cycle. Therefore, measurements of vertical water velocity by means of ADV (Acoustic Doppler Velocimeter) and measuring the weight of sediment held in traps were planned. However, thanks to the access to modern research equipment at the stage of model construction, a decision was made to measure the velocity by means of PIV (Particle Image Velocimetry) set produced by LaVision. The apparatus consists of a laser, a video camera and a computer unit defining the position of registered suspension particles. The measurement consists of determining the location of representative particles in a pre-defined measurement area of the flume by two successive series of laser pulses registered with the camera. Using this information, the computer system unit defines the distance and duration of displacement of representative particles. Such a character of the measurement enables simultaneous determination of velocity field all over the surface lighted by the laser. The PIV system was installed in the flume above the physical model with the velocity field measurement plane in the middle of the flume and along its axis. The PIV system, according to its author's premises, uses artificial suspension added to water before the measurement to determine a velocity field. This suspension should contain particles whose size and mass ensure movement consistent with water movement, without delays or accelerations caused by density difference and co-occurring inertias of suspended particles, and grains small enough not to affect the results of the experiment. Such assumptions for PIV measurements were incompatible with the basics of the experiment, which assumed that these were the quantity and concentration of the suspension formed of part of the suspended sediment that were to be the leading parameters in the measurements. At the stage of experiment preparation and while observing the installation start-up, a decision was made not to add system suspension to the water in the flume. Moreover, it was observed that the bed material, whose finest fractions were suspended from the first wave cycles and remained in the suspended form without contact with the bed for the whole wave action period, was interpreted by the PIV system apparatus as system suspension. Accordingly, with successive pulses, PIV system defined displacement vectors directly for particular sediment particles. For similar wave conditions, the results produced by the measurement system were verified in other experiments conducted during all the research project.

3. RESULTS

The experiment was conducted for three measurement series, each using a different wave pattern represented by: wave period (T), wavelength (L) and the ratio of wave length to the mean depth (L/h). The assumptions for each wave sequence were to reflect the most commonly described waves as short waves with high intensity and so-called long waves. Measurements were performed for the following wave parameters:

Measurement series No. 1, period 1.5 s, L/h = 8.8; L = 2.63 m.

Measurement series No. 2, period 2.0 s; L/h = 12.3; L = 3.68 m.

Measurement series No. 3, period 2.5 s; L/h = 15.8; L = 4.74 m.

During measurements, wave pattern was registered as the position of wave crest and trough and the amplitude, and the maximum and minimum levels of each measurement were defined for the entire 100-cycle series. The findings confirmed maintaining the pre-defined parameters for the whole cycle (apart from the first three-four warming-up waves) with the accuracy and repeatability at the level of +/–2 mm.

During the whole cycle, in the middle of each measurement session (from the 50th wave), the velocity distribution of sediment particles was registered by the PIV system for about 50 seconds.

After the termination of each cycle, the accumulated material was removed from both sand traps. The results of sediment discharge measurements are shown in Table 1. Based on wave parameters and the number of wave cycles in each series, the unit sediment flux ω was determined in grams for each full wave cycle. The results of sediment flux measurements and basic wave motion parameters are shown in Table 1.

Table 1

Results of sediment flux measurements

Series	Sediment mass		Wave motion parameters						Calculated sediment flux	
	Sediment mass								ω [g/cycle]	
	Flume front	Flume back	L [m]	T [s]	L/h	H [m]	t [min]	No. of cycles	Flume front	Flume back
1.5 s	333.6	487.4	2.63	1.5	8.8	0.117	10	400	0.83	1.22
2.0 s	385	393.9	3.68	2	12.3	0.112	10	300	1.28	1.31
2.5 s	993	861.4	4.74	2.5	15.8	0.151	10	240	4.14	3.59

Based on PIV velocity measurements, a full profile of suspended sediment particle velocity vectors was registered for each cycle. Due to the large amount of the registered material, this article presents only selected characteristic velocity vector field distributions. To provide an example, velocity distribution has been presented for a wave from a measurement series with the period of 2 s in three consecutive characteristic phases, i.e., wave crest passage exactly over the model – Fig. 2; passage of wave trough over the model in Fig. 3, and the next slope with the approach of the next crest in Fig. 4.

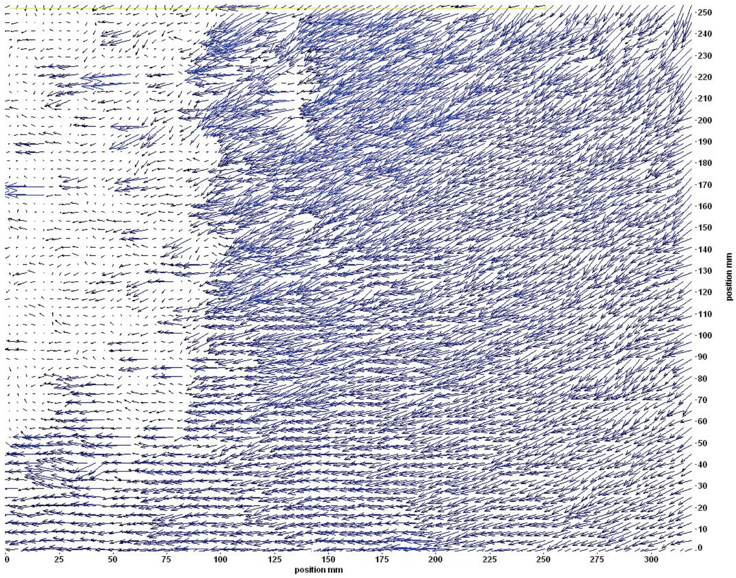

Fig. 2. Velocity field distribution for wave period of 2 s,
at the moment of wave peak passage over the model

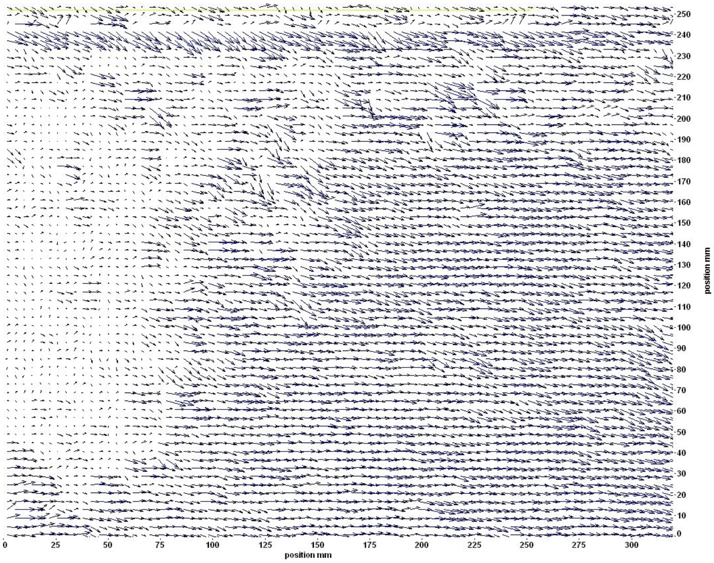

Fig. 3. Velocity field distribution for wave period of 2 s,
at the moment of inter-wave trough passage over the model

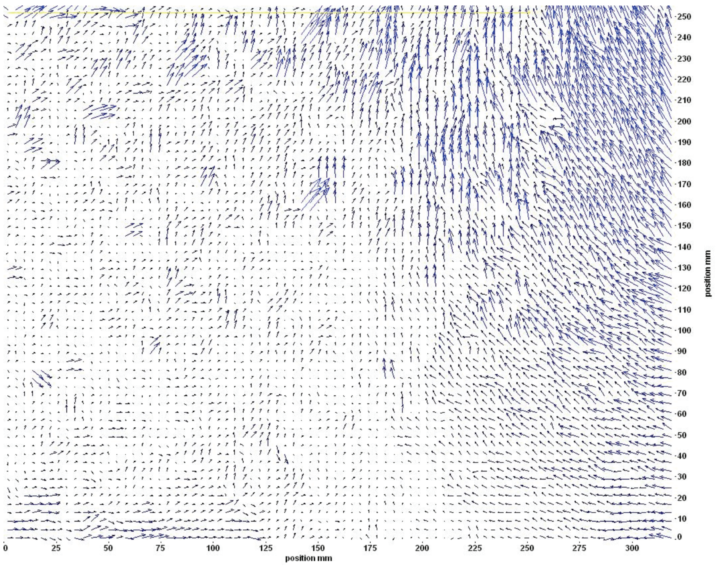

Fig. 4. Velocity field distribution for wave period of 2 s,
after trough passage before the approach of the next crest

For the measurement session presented, the results based on recorded velocity vectors have been compiled in the form of vertical profiles of horizontal velocities *u* of moving suspended sediment particles. The graph in Fig. 5 presents vertical velocity distributions.

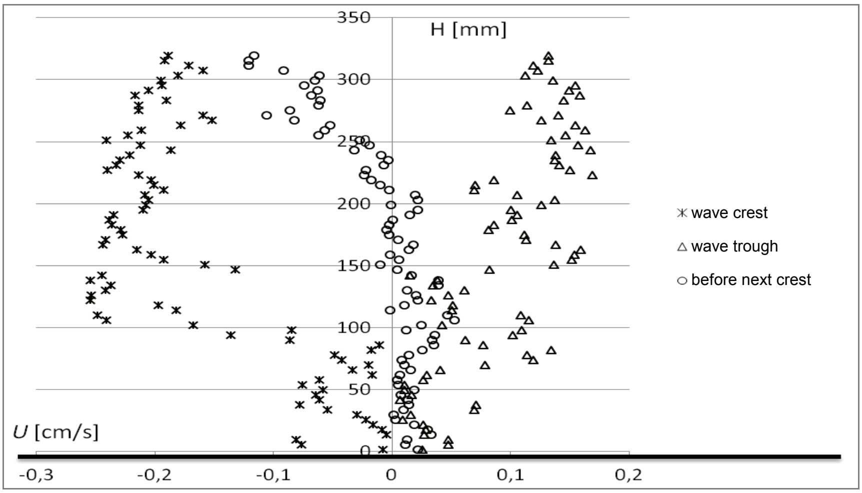

Fig. 5. Velocity profiles for wave period of 2 s, at the moment of wave crest,
trough and the rise to the next crest passing over the model

Observation results for the examples presented confirm literature data describing the behaviour of water in consecutive wave cycles. Comparing the recorded visible image with the registered velocity fields from the PIV apparatus, one can observe a high agreement of the measured particle velocities. It is noteworthy that the apparatus has quite high sensitivity to changing concentrations of the suspended material (visible on the right side of the calculated velocity vector fields). Due to the lack of water velocity measurements in each series, a decision was made to compare the velocity of sediment particles with water velocities determined theoretically, e.g. from Airy formulas (Chybicki [3]). Comparing the velocity of sediment particles (measured values between 0.25 cm/s and –0.2 cm/s) with water velocity profile for the wave action parameters defined (calculated values between 0.4 and –0.3 cm/s) confirms the character of this distribution, although with a certain delay in sediment transport caused, among other factors, by particle inertia. The observation of particle velocity fields and observations and recordings of the visible image conducted during the experiment point to a possibility of distinguishing three independent cycles of suspended sediment displacement. Starting from the stage of wave crest passage, this is increased transport caused by relatively high water velocities. Due to the downward sense of velocity vectors, this is also the phase of increased bed erosion. After the passage of a wave crest, larger particles displaced in the previous phase are deposited on the bed and the flow direction of suspended particles is gradually reversed. The rise towards the next wave crest tends to lift the suspended particles and to reduce particle concentration near the bed with negligible particle displacement along the flume. This is followed by another cycle of wave crest passage, which starts the process anew. In literature, this process is usually simplified to a description of horizontal displacements leaving out vertical vectors, which are significant to sediment transport, and ignoring changes in characteristics of near-bed stresses caused by the vertical components of the very velocity vectors. The recorded character of the flow and the sense of sediment particle velocity vectors do not confirm the zero balances of sediment transport in wave motion adopted in literature. In the experiment conducted, it is noteworthy that outside the measurement range in the movable bed model with the total length of 1 m, in the whole cycle of 100 wave sequences a large part of the material was transported over the distance of up to 4 m away from the model along wave propagation direction, while such a displacement was not observed in the opposite direction. For technical reasons, however, it was impossible to measure the mass of the material taken from the whole model and displaced outside its area.

4. CONCLUSIONS

During the research, the amount of sediment material intercepted by traps was measured for the adopted wave parameters. For the adopted solution of trap location, no significant differences in the amount of sediment accumulated in both chambers of the trap were recorded. Consequently, it was not possible to separate the amount of the sediment carried along the wave and in the opposite direction. However, observations of the whole model demonstrate significant disturbances in the equilibrium between sediment transport along and against wave direction, which is often assumed in literature. After the end of every measurement session, a large amount of bed material was displaced outside the measurement area along wave direction over the distance between one and two wavelengths.

PIV measurement was performed without adding the suspension recommended by the system manufacturer and measurements of velocity vectors were registered for the bed material lifted and suspended in water along with the wave motion. Observations of the measurements and comparison of system suspension parameters with those of natural sediment demonstrated that measurement by the apparatus indicated directly the velocities of sediment particle transport .

Observations and analyses of recorded sediment velocity vector fields have enabled distinguishing at least two phases of bed material displacement. The greatest influence on sediment transport has been attributed to the phase of wave crest passage, which, due to its part in the whole wave cycle, determines the direction of sediment transport as corresponding to the direction of wave propagation.

Further detailed results of sediment velocity vector field measurements and their conformity with analytically determined water velocity profiles are being analysed. For selected measurement series, an approximated vertical velocity distribution profile has been presented. The velocity distribution of suspended load particles has a similar character to that of water velocity distribution, but its values are clearly lower.

In the next stage of the research, there are plans for basic modifications of Ackers–White formulas, defining sediment flux as dependent on such factors as near-bed stresses, mean velocities in vertical cross-section or depth, and replacing these elements with basic parameters describing wave motion.

REFERENCES

[1] ACKERS P., WHITE W.R., *Sediment transport, new approach and analysis*, Journal of the Hydraulic Division ASCE, 1973, Vol. 99, No. HY11.

[2] COUFAL R., *Zmiany położenia dna w ujściowym odcinku rzeki wywołane ruchem rumowiska*, Prace naukowe Politechniki Szczecińskiej, Katedra Geotechniki, Nr 515, Szczecin 1995.

[3] CHYBICKI W., *Teoria fal powierzchniowych w strefie zmiennej głębokości wody*, Wydawnictwo IBW, PAN, Gdańsk 2006.

[4] Prezentacje i materiały reklamowe dotyczące koryta falowego Zakładu Mechaniki Falowania i Dynamiki Budowli, IBW, PAN, Gdańsk.

[5] OSTROWSKI R., *Morphodynamics of a MultiBar Coastal Zone*, Wydawnictwo IBW, PAN, Gdańsk, 2004.

[6] KRUPIŃSKI A., *Pomiary ruchu rumowiska w ruchu falowym na podstawie badań na kanale falowym*, XIX Seminarium naukowe z cyklu *Regionalne Problemy Ochrony Środowiska*, Szczecin 2011.