

NUMERICAL STUDY OF WAVE RUN-UP AT PERMEABLE FIXED REVETMENT SLOPE

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The numerical model of wave surface elevation and water filtration in the saturated-unsaturated porous medium is developed. The model uses to define the parameters of the wave run-up at the slope protected by the permeable fixed layer. The model shows the wave surface in the different times, including the wave run-up height at the slope and wave run-down. Also, the velocities in the upper protected layer as well in the soil body of the slope are defined. Model is verified with using of the published large-scale tests with the slopes protected by Elastocoast technology layers. The tests were carried out in the wave flume of Technical University Braunschweig. The numerical model may be applied to calculate the maximal waves run-up at the protected engineering and beach slopes in natural conditions.

Keywords revetment slope; permeable polyurethane cover; wave run-up; water filtration; numerical modelling; large-scale tests comparison

INTRODUCTION

Protective permeable revetment slopes are widely used as in port construction and coastal protection. The existing calculation methods for multi-layer protective revetments cannot count such constructions due to the complexity of the theoretical description of the task interaction of waves with a slope.

As one of the modern technological solutions the technology Elastocoast, developed by German chemical concern BASF can be named.

The main idea of coastal protection technology Elastocoast is the construction on the surface of the beach or the construction of permeable revetment slope with open-pore of gravel or crushed stone, stuck between them. An important feature-no glue fills the pores completely between rubble and glues his only contact the individual elements of the rubble with each other. This makes it possible to attain the permeability of protective revetment.

The most detailed interaction of waves with plinth, protected by Elastocoast, studied in large-scale experiments at the Technical University of Braunschweig, Germany.

For an innovative idea to use Elastocoast technology in marine coastal protection with respect to folded gravel shores could be further developed in the framework of the present work was carried out numerical study of running up waves on the coastal slope, protected with Elastocoast technology.

For this numerical model, has been developed in the zone of wave propagation on a slope with permeable revetment in wave run-up area. The model was tested by the results of the large-scale experiments performed at the Technical University of Braunschweig, Germany.

To simulate the wave's run-up the mathematical model consisting of two submodels linked together, describing the movement of surface waters and the movement of moisture in saturated-unsaturated porous medium is constructed.

The developed numerical model of movement of surface waters and the movement of moisture in saturated-unsaturated porous medium allows to define the characteristics of the flow on a slope, sheltered in the run-up area by the permeable pinned layer. When this model establishes regulations free wave surface at different points in time, including the height of the run-up of waves on slope and height of waves at the run-down of a slope. In addition, the calculated velocity field of a fluid in the upper protective layer of a slope and moisture distribution in the body of the outgoing ground slope may be defined. The model is verified using published results of large-scale experiments performed in the wave tray at the Technical University of Braunschweig.

RUN-UP OF WAVES ON THE IMPENETRABLE SLOPE

Laboratory studies

As the initial problem explores the run-up waves on an impermeable slope. As before, this case is a "control" for the task waves run-up on permeable protected slopes. Model of a coastal slope with the

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beach, was built at a scale of 1:25 in shallow pool of laboratory, across the entire width of the wave channel of 1.6 m (to exclude the effect of the impact basin walls) and along its axis (Fig. 1).



Figure 1. Experimental research of slope structures in wave basin

The width of the base of a coastal slope to the beach on a physical model was 5 m, height 0.6 m, slope angle 0.12 degrees. The width of the beach on the model, was 1.2 m and inclination 0.07. Behind the beach model of not-moving was a coastal slope, width of 0.5 m, and a height of 0, 1 m, at an angle to the horizon 0.2 degrees.

Waves generated by shield mobile wavemaker, installed on 3 m from the pool wall. Between the shallow pool wall and wavemaker the dissipater was placed. The width of the shield of wavemaker was 6 m, height-0.9 m. On both sides of the wavemaker at 6 m installed fencing panels from acrylic glass, forming a wave channel length 18 m, which ended for the model of a coastal slope. Model of a coastal slope began from 11 m from wavemaker.

Measurement of wave parameters in the process of experimental studies carried out instrumentally with the four capacitive sensors-wave measurers, whose signal cable system, over the surface of the water in the pool at special tripod mounted, acted on a personal computer, where carried out processing of measurement results according to a specially designed program. Wave measurers were located at 1.4 m, 2.9 m, 4.8 m and 7 m from water line (Fig. 1).

There have been three series of experiments, different parameters of the simulated storm and situation model. In the first series of experiments on model slope worked wave 13% exceedance, estimated the storm (1 times in 50 years), like a wave, equivalent to storms by the beach erosion.

The first series of experiments.

It was studied the effects of waves on coastal protection dam of construction project, located in front of the concrete slope the beach width 1.2 m. Waves parameters, reproduced by the wavemaker were: wave height - 0.23 m, length - 3.84 m, period - 1,6s.

Table 1 presents the measured values of the amplitudes of the waves on wave measurers, where d is the depth of the water, L_b is distance between water level and wave measurer, h is the height of the waves.

The second series of experiments.

In the second series of experiments model subjected to processing the waves close to the maximum of 5% of exceedance estimated in the system of storm 1 times in 50 years.

Because in the scale 1:25 the waves of 5% exceedance cannot be reproduced, experiments were conducted at a scale of 1:36 with the following parameters: wave height was 0.18 m, length was 3.4 m, period was 1.4 s. The width of the beach, which was a model of protected coastal slope was 0.83 m.

Table 2 presents the measured values of the amplitudes of the waves on wave measurers, where d is the depth of the water, L_b - distance between water level and the wave measurer, h -wave height.

No. of wave measurer	d, m	L_b, m	h, m
1	0.60	7.8	0.230±0.005
2	0.58	4.8	0.215±0.005
3	0.35	2.9	0.205±0.005
4	0.17	1.4	0.186±0.005

No. of wave measurer	d, m	L_b, m	h, m
1	0.60	7.8	0.183±0.01
2	0.58	4.8	0.184±0.01
3	0.35	2.9	0.173±0.01
4	0.17	1.4	0.197±0.01

The third series of experiments.

In the third series of experiments investigated effects of the waves 1 times per year on the no moving model of a coastal slope, located behind the beach model with width 1.2 m. The aim was to show the influence of the small waves that can move along the beach slope more carefully than large waves. Experiments were performed in the scale 1:25. Parameters of the waves, reproducible by wavemaker were: wave height is 0.11 m, length is 3.84 m, period is 1.63 s.

Table 3 presents the measured values of the amplitudes of the waves on wave measurers, where d is the depth of the water, L_b is the distance between water level and wave measurer, h is wave height.

No. of wave measurer	d, m	L_b, m	h, m
1	0.60	7.8	0.113±0.005
2	0.58	4.8	0.104±0.005
3	0.35	2.9	0.082±0.005
4	0.17	1.4	0.109±0.005

Numerical simulation

Modeling of transformation waves on slopes for the parameters of model studies by nonlinear numerical model based on equations of Boussinesq-Jeleznyak-Pelinovsky (Serres) with special additives. Basic equations of numerical model are listed below [Jeleznyak and Pelinovsky. 1985]:

$$\begin{aligned}
 & H_t + (Hu)_x + (Hv)_y = 0, \\
 & u_t + uu_x + vu_y + g\eta_x + \\
 & + (\alpha_2 - \alpha_1) h^2 [u_{txx} + v_{txy} + (uu_x)_{xx} + (vu_y)_{xx} + (uv_x)_{xy} + (vv_y)_{xy} + g\eta_{xxx} + g\eta_{xyy}] - \\
 & - \alpha_2 h [(hu_t)_{xx} + (hv_t)_{xy} + (huu_x)_{xx} + (hvu_y)_{xx} + (huv_x)_{xy} + (hvv_y)_{xy} + g(h\eta_x)_{xx} + g(h\eta_y)_{xy}] = \\
 & = \frac{1}{H} \left[\frac{H^3}{3} R + \frac{H^2}{2} Q \right]_x - h_x \left(\frac{H}{2} R + Q \right) \\
 & v_t + uv_x + vv_y + g\eta_y + \\
 & + (\alpha_2 - \alpha_1) h^2 [u_{txy} + v_{txy} + (uu_x)_{xy} + (vu_y)_{xy} + (uv_x)_{yy} + (vv_y)_{yy} + g\eta_{xxy} + g\eta_{yyy}] - \\
 & - \alpha_2 h [(hu_t)_{xy} + (hv_t)_{yy} + (huu_x)_{xy} + (hvu_y)_{xy} + (huv_x)_{yy} + (hvv_y)_{yy} + g(h\eta_x)_{xy} + g(h\eta_y)_{yy}] = \\
 & = \frac{1}{H} \left[\frac{H^3}{3} R + \frac{H^2}{2} Q \right]_y - h_y \left(\frac{H}{2} R + Q \right)
 \end{aligned} \tag{1}$$

where

$$R = u_{xt} + v_{yt} + uu_{xx} - u_x^2 + vv_{yy} - v_y^2 + vu_{xy} + uv_{xy} - 2u_x v_y ,$$

$$Q = h_x u_t + h_y v_t + h_x uu_x + h_y vv_y + h_{xx} u^2 + h_{yy} v^2 + h_y u v_x + h_x v u_y + 2h_{xy} uv$$

In shallow water theory, there is no dependence of the velocity of water depth, but when plotting equations the hypotheses used about the distribution of pressure in depth. In the classic (without dispersion) theory of shallow water pressure changes by the hydrostatic law with disregard for the influence of flow speeds on the pressure distribution. Obtained in this approach, the equations do not take into account the dispersion - dependence of the speed of waves from its length.

The equations of nonlinear dispersion theory (Boussinesq-type equations) are already taken into account the contribution of the vertical accelerations on the vertical wave pressure distribution the equations [Jelesnyak and Pelinovsky. 1985] take into account wave dispersion.

The equations of nonlinear dispersion models of shallow water apply to describe as long waves, for which the dispersion effects are weak (which follows from the dispersion relation of linear wave theory) and shorter waves than the nonlinear equations without dispersion ("classical") theory of shallow water. Similarly, the accepted model equation, taking into account the influence of wave velocity on the vertical pressure distribution, have a wider applicability than the "classic" equations of nonlinear shallow water theory.

Asked the following parameters: $\alpha_1 = 1/17.5$, $\alpha_2 = 1/10$. Introduced with the coefficient of Chézy bottom friction, equal to 60. H_{rms} was calculated - RMS wave height during the period:

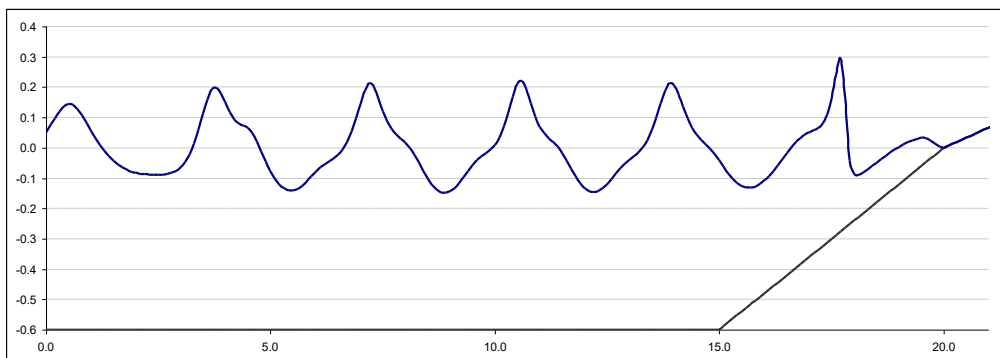
$$H_{rms} = \frac{2}{T} \sqrt{\int_{t_0}^{t_0+T} \eta^2 dt} ,$$

where η is the free surface elevation.

For the first series of experiments (waves, reproducible by wavemaker were: wave height 0.23 m, length-3.84 m, period-1.6 s) comparison of calculations and measurements shown in table 4, and the results of numerical simulation provides in Fig. 2.

1.

Table 4. The measured and calculated values of the heights of the waves, the first series.				
No. of wave measurer	d, m	L_b, m	Measured h, m	Numerical simulation $H_{rms} m$
1	0.60	7.8	0.230±0.005	0.231
2	0.58	4.8	0.215±0.005	0.218
3	0.35	2.9	0.205±0.005	0.200
4	0.17	1.4	0.186±0.005	0.179



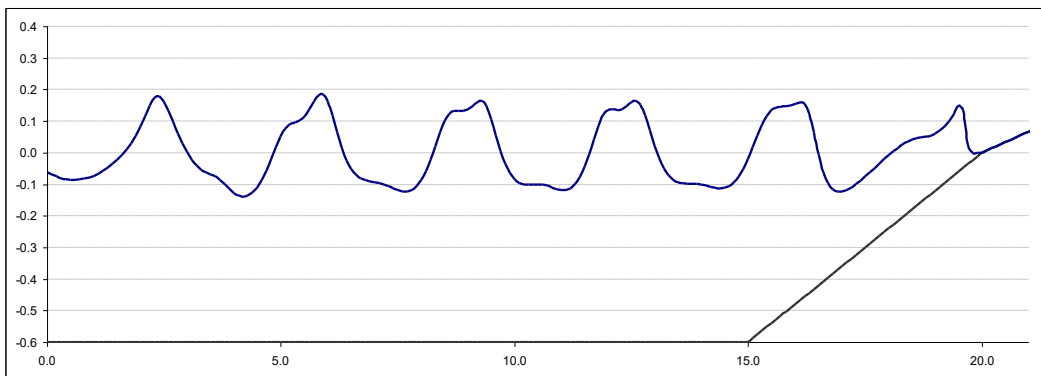
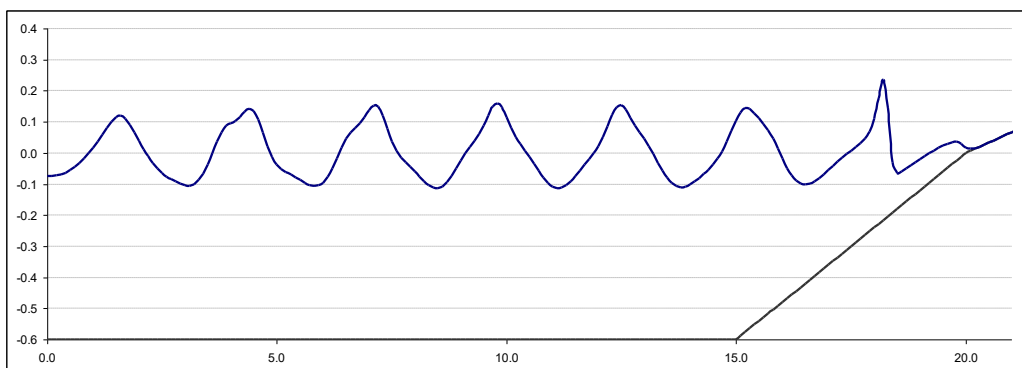


Figure 2. The transformation of waves for experiments of 1st series according to the results of numerical simulation. Horizontally-wave ray distance (m), vertically- wave surface elevation (m)

The results of numerical experiments quite satisfactorily consistent with measured wave heights (Table 4). Waves run-up in numerical experiments barely protected at the foot of the slope, as with physical modeling. Increasing of waves when approaching the breaking, as well as on the model.

On the second series of experiments (wave marker: wave height-0.18 m, length-3.4 m, period - 1.4s) comparison of calculated and measured wave heights are shown in Table 5, and instant surface wave profiles in Fig.3.

Table 5. The measured and calculated values of the heights of the waves. Second series				
No. of wave measurer	<i>H</i> , m	<i>L_b</i> , m	Measured <i>h</i> , m	Numerical simulation <i>H_{rms}</i> , m
1	0.60	7.8	0.183±0.01	0.201
2	0.58	4.8	0.184±0.01	0.184
3	0.35	2.9	0.173±0.01	0.186
4	0.17	1.4	0.197±0.01	0.187



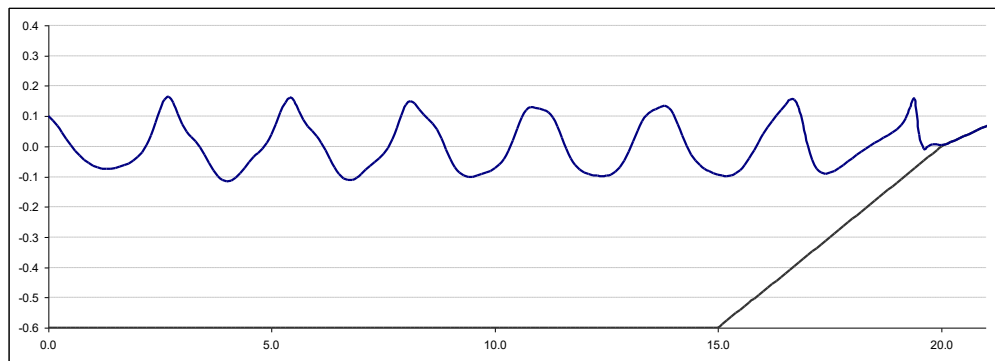
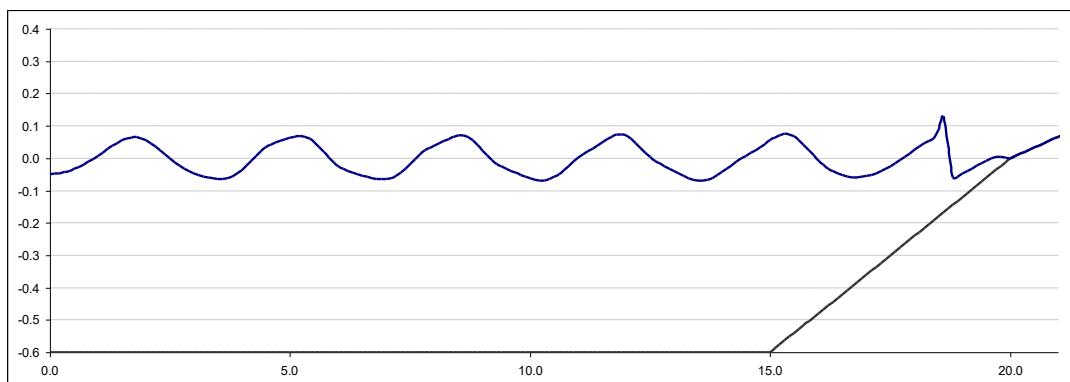


Figure 3. Transformation of waves for 2nd series, result of numerical simulation. Horizontally-wave ray distance (m), vertically- wave surface elevation (m)

Settlement agreement with measurements of wave heights again is quite satisfactory. In this case (high wave) run-up reaches the protected part of the berm. Waves significantly transformed when driving on a slope.

On the third series of experiments (wave height-0.11 m, length-3.84 m, period-1.63 s) comparison is shown in Table 6, and instant surface wave profiles in Fig. 4.

Table 6. The measured and calculated values of the heights of the waves, third series				
No. of wave measurer	H, m	L_b, m	measured h_e, m	Numerical simulation H_{ms}, m
1	0.60	7.8	0.113±0.005	0.107
2	0.58	4.8	0.104±0.005	0.104
3	0.35	2.9	0.082±0.005	0.094
4	0.17	1.4	0.109±0.005	0.109



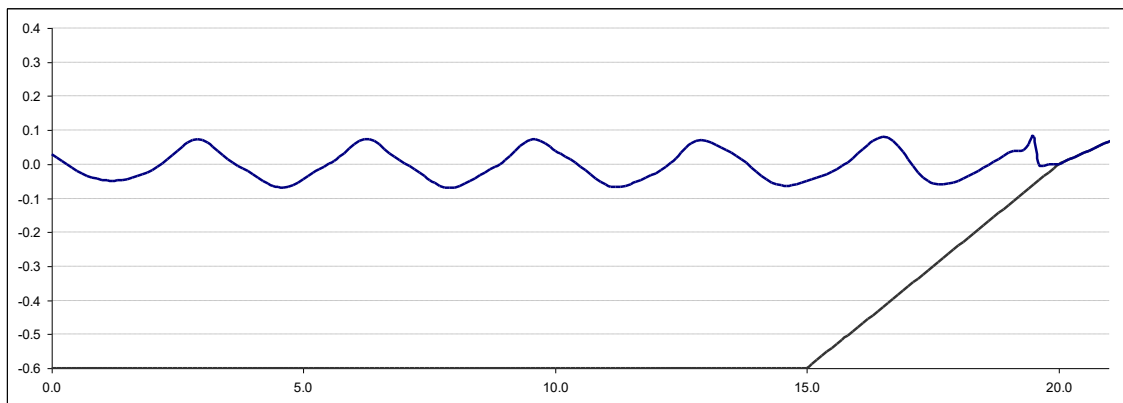


Figure 4. Transformation of waves for experiments of 3rd series based on the results of numerical simulation. Horizontally-wave ray distance (m), vertically- wave surface elevation (m)

Because of this series of experiments: the consent of calculations and measurements of the waves is satisfactory, run-up of waves does not reach a concrete slope, waves weakly transformed to form when driving on a slope.

The aggregate of all data carried out measurements and calculations, built regression dependence of the measured and calculated heights waves in tables 4, 5, and 6 above. The results are shown in Table 7 and Fig. 5. The correlation coefficient of the measured and calculated heights of waves: $R = 0.985$, indicating good acceptance of the results of physical and numerical modeling.

Table 7. Measured and calculated the height of the waves for all experiments, m		
	experiment	model
Series 1	0.230	0.231
	0.215	0.218
	0.205	0.2
	0.186	0.179
Series 2	0.183	0.201
	0.184	0.184
	0.173	0.186
	0.197	0.187
Series 3	0.113	0.107
	0.104	0.104
	0.082	0.094
	0.109	0.109

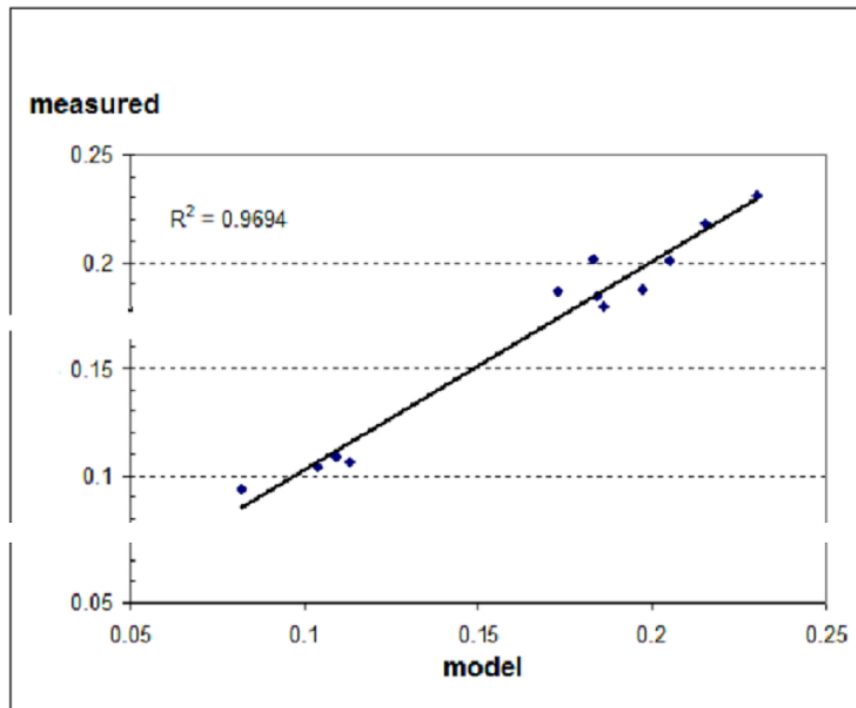


Figure 5. Wave height received physical and numerical modelling. Comparison

Thus, it is shown that the nonlinear dispersive long-wave model satisfactorily describes the run-up of waves on impermeable slopes. And it can be expected that such models can be used for numerical simulation of run-up of waves on permeable slopes.

Using of cover Elastocoast

Permeable constructions of slope profile with rubble mound protective coatings are widely used both in port construction and coastal protection. In view of the complexity of the theoretical description of the task interaction of waves with external coverings bank structures, there are certain difficulties in their design [Lappo, Strelakov, Zavalov. 1990; Alcerreca and Oumeraci. 2012; Didier and Neves. 2009; Hughes. 2004]. As an alternative to the existing design solutions, as well as further development of calculation methods of wave loads, it may be considered one of modern technological solutions. It is based on the application of technology Elastocoast [The Elastocoast System. 2008]), which is developed by the German chemical concern BASF.

Elastocoast system represents a new type of protective coating that can be applied in the zone of action of waves and splash zone or on the inner slopes of dams. This coverage consists of mound material and polyurethane. Each stone is covered with a thin film of polyurethane. Having hardened, the film brings the stones put together only at contact points. When the spaces between the stones remain to be filled, that ensures openness and permeability of the coating structure. This technology has been successfully applied in Western Europe, in many objects [Experimental Projects with Elastocoast System in Holland in Storm Period 2007/2008. 2008; The Elastocoast System. 2008] (Fig.6).

It should be noted that studies on wave impact on such sloping protective coating utilized only with waves up to 1.5 m. Study of wave loads on protective coating for the sea coast with pebbly beaches, where waves can be calculated in 4 ÷ 5 times more was not carried out. Therefore, the method of calculation for such conditions to be further developed. Therefore, it seems necessary to conduct research with the development of a mathematical model of the interaction of waves with slope covered with Elastocoast system. For verification of calculation methods and numerical models, it is advisable to use the results of existing experimental studies on the effects of waves on the protective covering of slopes, executed with application of Elastocoast technologies [Hydraulic Performance, Wave Loading and Response of Elastocoast and their Foundation. A Large-Scale Model Study (Final Report). 2010;

Compilation of the Technical Design Guidelines for Elastocoast. 2010].



Figure 6. Coastal protection slope using Elastocoast technology on Amrum inland in the North Sea

Thus, the objective of these studies is to develop numerical models of waves run-up on permeable protected slope and proof of its applicability for slopes, covered with Elastocoast system by comparing with the data of the experiments. In the future, with binding method at any time to the phase of a wave, it will be possible to obtain a new method of calculating wave loads on high permeable structure with coating. The results of this research will be applied in the development of new effective constructions of the slope profile, capable of resisting the effects of stormy excitement.

Setting characteristics of protective coating, using a numerical model can be measured the height of waves on slope and roll wave loads, which will be subject to coverage in storm periods. This will set the design characteristics that define its coverage strength and endurance, as well as reasonably assign top stamp (above-water part) constructions. In addition, the acquired data, will provide the opportunity to calculate the distributions of wave pressure and counter pressure on the permeable cover bank structures.

The closest research in this area are the experiences of experts on the interaction of waves with protective structures rubble mound type [Liebisch et al. 2012; Muttray et al.1998; Muttray and Oumeraci. 2005]. Known modelling techniques of waves run-up on an impermeable slope [Jeleznyak et al. 2011] and methods of calculation of running waves on the ground and mound slopes [Kantardgi, Kivva, and Shunko. 2014]. All these activities indicator height running waves on slope was the main criterion for research. However, such studies need improvement and development in accordance with the specific goal of the present work tasks. First, this relates to the accounting of the pore water movement that occurs in a relatively thin surface protective layer.

Experiences with Elastocoast protection in a large wave flume

The most detailed interaction of waves with slope, protected coating Elastocoast, studied in large-scale experiments, [Hydraulic Performance, Wave Loading and Response of Elastocoast and their Foundation. A Large-Scale Model Study (Final Report). 2010; Oumeraci. 2012] as described below. These experiments will be used to verify further developed numerical models.

Experiments were conducted in a large wave flume in Hannover, Germany. Installation length approx. 300 m and width of about 5 m, height of the walls to 7 m allows you to have up to 5 m water depth, that allows you to generate a regular wave height up to 2 m and wave spectrum with a significant wave height of up to 1.3 m. Facility also allows you to receive single waves with a height of about 1 m and wave-killer (focusable) waves of up to 2.5 m. Wave generator has a good absorbing control to ensure permanent wave parameters experience for a long time.

The large size of the wave flume allows the study of the protective coating of slope in the field scale. This is fundamentally important to the problem since the strength properties of the coating in the flume did not simulate under scaling.

The model schema in a large wave flume with slope, protected coating Elastocoast, is shown in Figure 7.

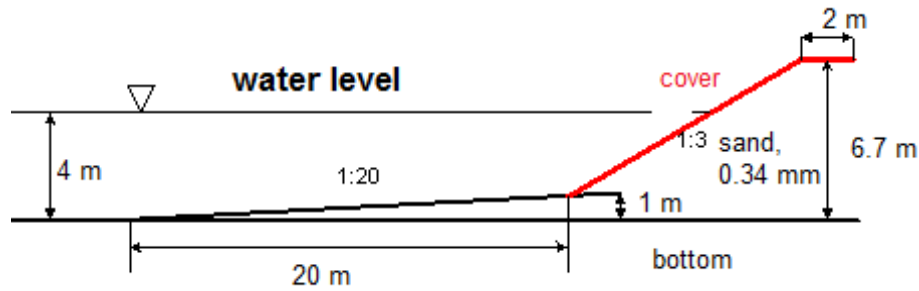


Figure 8. A schematic of the experimental setup in a large wave flume of Technical University Braunschweig

In experiments [Hydraulic Performance, Wave Loading and Response of Elastocoast and their Foundation. A Large-Scale Model Study (Final Report), 2010] three different cover slope investigated outlined as model A, model B and model C.

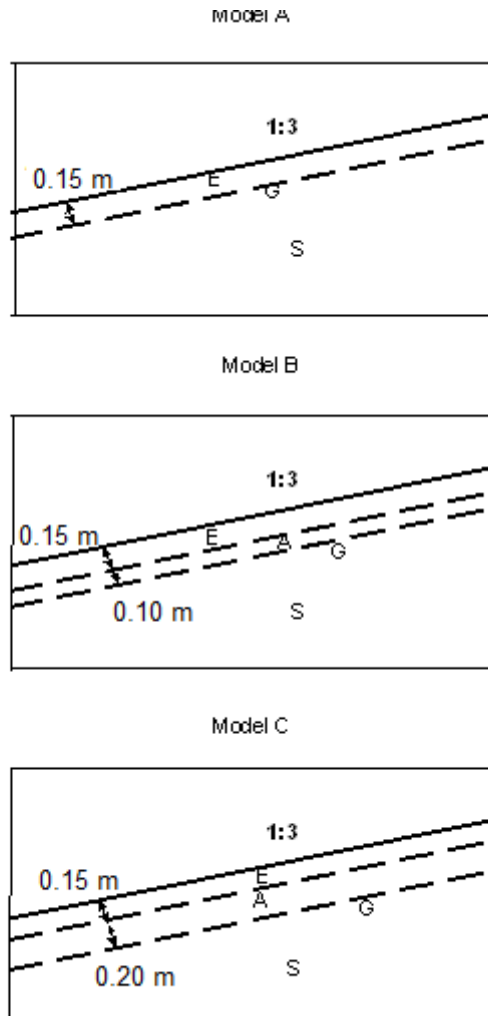


Figure 8. Cover slopes in the flume experiments:

E-coating system Elastocoast, thickness of 0.15 m, filler-lime crushed stone, size 20-40 mm, for model with granite was used, size 16-36 mm (porosity 0.388);

A-filter layer, thickness of 0.10 m, consisting of calcareous gravel size 20-40 mm, for model C with a filter layer amounted to 0.20 m, with a filling of granite macadam, size 16-36 mm;

G-stamps geotextiles layer "Terrafix 609" hydraulic permeability $4.7 \cdot 10^{-3}$ m/s;

S-sandy basis, $D_{50} = 0.34$ mm, $D_{60}/D_{10} = 2.11$, hydraulic permeability $4.7 \cdot 10^{-4}$ m/s.

About the destruction of the cover while increasing wave height in experiments, experiments on this cover was carried out only partially. Wave modes in experiments with regular waves are presented in Table 8.

Table 8. Parameters of regular waves in the wave flume, Technical University Braunschweig

No. of test	H_{nom} , m	T_{nom} , s	h , m	H_m , m	T_m , s	C_r	ξ_m
1	2	3	4	5	6	7	8
09051301	0.2	3	3.4	0.22	3.00	0.339	2.67
09051302	0.2	4	3.4	0.19	4.00	0.621	3.77
09051303	0.2	5	3.4	0.21	5.00	0.682	4.59
09051401	0.2	6	3.4	0.18	5.93	0.734	5.78
09051402	0.2	7	3.4	0.22	7.00	0.782	6.24
09051403	0.2	8	3.4	0.17	7.90	0.860	7.94
09051404	0.6	3	3.4	0.65	3.00	0.127	1.55
09051405	0.6	4	3.6	0.68	4.01	0.292	2.02
09051406	1.0	3	3.6	1.04	3.00	0.183	1.22
09051501	0.6	5	3.7	0.64	4.95	0.487	2.57
09051502	1.0	4	3.7	1.14	3.92	0.161	1.53
09051503	1.3	4	3.7	1.40	3.92	0.143	1.38
09051504	0.6	6	3.9	0.65	6.00	0.581	3.10
09051505	0.6	7	3.9	0.54	6.93	0.665	3.91
090511801	0.6	8	3.9	0.55	7.98	0.695	4.49
090511802	1.3	5	3.9	1.37	4.90	0.155	1.75
09060501	0.2	3	3.4	0.22	2.99	0.332	2.65
09060502	0.2	5	3.4	0.20	5.00	0.678	4.66
09060503	0.2	8	3.4	0.17	8.00	0.863	8.05
09060504	0.6	3	3.4	0.66	3.00	0.091	1.54
09060505	0.6	4	3.6	0.69	4.00	0.289	2.00
09061803	0.6	5	3.8	0.58	4.99	0.521	2.72
09061804	0.6	6	3.9	0.72	6.00	0.567	2.95
09061805	0.6	7	3.9	0.52	6.99	0.633	4.02
09062301	0.5	7	3.8	0.44	7.00	0.731	4.39
09062302	0.4	8	3.7	0.50	7.99	0.731	4.72
09062303	0.7	3	3.5	0.67	3.00	0.102	1.53
09062304	0.8	3	3.5	0.75	3.00	0.119	1.44
09062305	0.9	3	3.5	0.84	3.00	0.152	1.36
09062306	1.0	3	3.5	0.92	3.01	0.105	1.31
09062307	0.4	3	3.4	0.39	3.00	0.241	1.99
09062308	0.5	3	3.4	0.49	3.00	0.228	1.79
09062912	1.0	5	3.9	1.01	5.01	0.358	2.08
09062913	1.0	6	4.1	0.92	6.02	0.496	2.61
09062914	1.3	6	4.2	1.24	6.03	0.406	2.25
09062915	1.0	7	4.2	1.17	7.02	0.541	2.70
09062916	1.0	8	4.2	0.91	8.05	0.689	3.52

Legend: H_{nom} -set wave height, wave period set- T_{nom} , h is the water depth, H_m -height of the waves at the foot of the slope, T_m -period waves at the foot of the slope, C_r -wave reflection coefficient, $\xi_m = \frac{tg\alpha}{\sqrt{H_m/L_0}}$ parameter similarity of surf zone, $L_0 = \frac{gT^2}{2\pi}$ - length of waves on deep water.

Characteristics definition schema of wave run-up on slope is shown in Fig. 9.

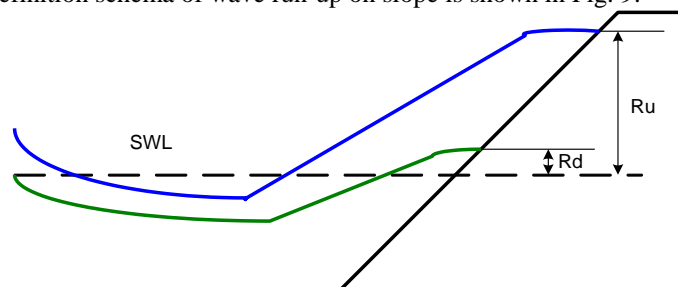


Figure 9. Run-up/run-down definition schema on slope, R_u -height of run-up, R_d is the height of the run-down, SWL-water surface level

To approximate the results of experiments in [Hughes S.A. 2004] were used the following dependencies:

Model B

$$\frac{R_u}{H_m} = 0,54 [1,65\xi], \xi < 2,7$$

$$\frac{R_u}{H_m} = 0,78 \left[4,0 - \frac{1,5}{\sqrt{\xi}} \right], \xi \geq 2,7 \quad (2)$$

Модель C

$$\frac{R_u}{H_m} = 0,52 [1,65\xi], \xi < 2,7$$

$$\frac{R_u}{H_m} = 0,76 \left[4,0 - \frac{1,5}{\sqrt{\xi}} \right], \xi \geq 2,7 \quad (3)$$

Experimentally it has been found that experienced values of wave run-up on slope coated by B cover in is not significantly different from the values of the wave run-up on the slope with cover C. Experiments indicated the same substantial lowering of the wave run-up on slope with permeable coating, if compared to the wave run-up on the smooth impermeable slope. The difference in the data depended on setting ξ and was for relative surge R_u/H_m from 25%, for large values of up to 50% for smaller values of ξ .

Mathematical model of waves run-up on slope protected by permeable fixed coating.

Within the framework of solving the problem of the applicability of the Elastocoast system for marine shores with pebbly beaches, numerical study was conducted of the coastal waves running the slope. The developed model was tested for the results of the large-scale experiments performed at the Technical University of Braunschweig, Germany. The mathematical model consists of two submodels linked together, describing the movement of surface waters and the movement of moisture in saturated-unsaturated porous (the water level under the cover). The model scheme is presented in Fig.10.

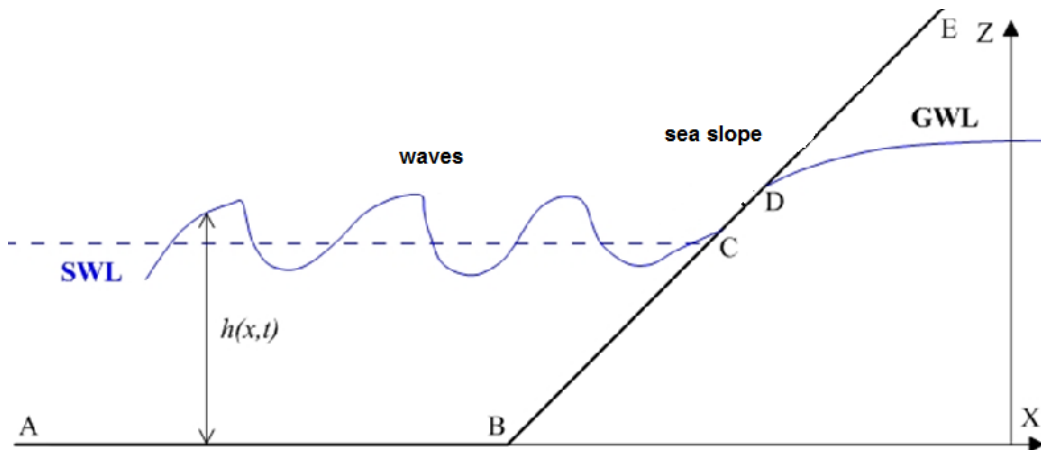


Figure 10. Schematic of waves run-up on slope in numerical model

The equations of motion of the water with a free surface were obtained by integrating the Navier-Stokes equations for the flow depth using kinematic boundary conditions. These equations include the equation of continuity and momentum equations. They can be written in the following format:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x_i} (u_i h) = I, \quad (4)$$

$$\frac{\partial}{\partial t}(u_i h) + \frac{\partial}{\partial x_j}(u_j u_i h) + gh \frac{\partial \xi}{\partial x_i} + g \frac{n^2}{h^{4/3}} u_i |u| = 0, \quad (5)$$

where t is the time; x_i are the spatial coordinates; $h = \xi - \eta$ is the depth of flow; u_i is the flow velocity in the direction x_i ; $\xi(x, t)$ is the equation of free surface; $\eta(x, t)$ is the bottom equation; g is the gravitational acceleration; n is the Manning roughness coefficient; I is infiltration.

It is assumed that water movement in saturated-unsaturated porous media occurs under the influence of the force of gravity is proportional to the gradient of pressure per the generalized Darcy's law. Porous media seen as deformable and liquid as no compressed.

The term "saturated-unsaturated porous media" is the accepted term for more than 40 years. This term refers to porous media, one of which part is not saturated with moisture, and the other is full. Border section of these parts is unknown in advance and must be defined. Unsaturated soil moisture movement describes by a generalized law of Darcy, which in this case is non-linear, in contrast to an eventful occasion where it is linear.

It is considered that the movement of water in gaseous form can be neglected. Then, ignoring the hysteresis and temperature gradients, water movement in unsaturated-saturated porous media can be described by the equation:

$$\frac{\partial}{\partial t}(\phi S) = \frac{\partial}{\partial x_i} \left[\frac{k_r k_{ij}}{\mu} \left(\frac{\partial p}{\partial x_j} + g \rho \frac{\partial z}{\partial x_j} \right) \right], \quad (6)$$

where t is the time, x_i are the Cartesian spatial coordinates, ϕ is the volumetric porosity, ρ is the density of porous moisture, k_{ij} are the coefficient of permeability tensor components, k_r is the coefficient of relative conductivity ($0 \leq k_r \leq 1$), μ is the dynamic coefficient of viscosity, p is the pressure of soil moisture, g is the gravitational acceleration, z is the height of the considered point fluid flow relative to the plane of the compare and S is the volume saturation.

The speed of movement of water obeys the generalized Darcy's law and is calculated by the formula:

$$v_i = -k_r k_{ij}^f \left[\frac{\partial}{\partial x_j} \left(\frac{p}{\rho g} \right) + \frac{\partial z}{\partial x_j} \right],$$

where k_{ij}^f are the components of the coefficient filtration tensor, which are determined from the ratio:

$$k_{ij}^f = \frac{k_{ij} \rho g}{\mu}.$$

To uniquely solving equations (4) - (6) were assigned initial and boundary conditions. Typically, the initial conditions specify the distribution of depths and velocities for surface water and pressure distribution of moisture in the soil in the initial time:

$$h(x, 0) = \varphi_h(x), \quad u(x, 0) = \varphi_u(x) \quad \text{и} \quad p(x, 0) = \varphi(x),$$

where x is the vector of spatial coordinates, and $\varphi_h, \varphi_u, \varphi$ are the defined functions.

For the waves rolled forward to shore as boundary conditions for the shallow water equations, select the corresponding Riemann invariants. Boundary conditions for the storage equation (6) can be the first kind (Dirichletian conditions):

$$p(x, t) = g_1(x, t) \quad \text{at} \quad \Gamma_1,$$

or the second type (Neumann):

$$\left[k_r \frac{k_{ij}}{\mu} \left(\frac{\partial p}{\partial x_j} + \rho g \frac{\partial z}{\partial x_j} \right) \right] n_i = g_2(x, t) \quad \text{on} \quad \Gamma_2,$$

where g_1 is the specified pressure on border Γ_1 ; n_i – is i -th vector component of external normal to border Γ_2 ; and g_2 is the known flow along the external normal to border Γ_2 ; Γ_1 и Γ_2 form a full border of modelling area (Fig.10).

In the zone of running waves to the shore is quite a complex interaction of waves with groundwater. To describe this interaction, it is used a system of three equations. The first two is a shallow water equations (equations or Saint-Venan) simulated the movement of waves on a slope. The third equation is the equation of moisture transport (or, as it is often called, Richards ' equation) describe the unloading of groundwater to reservoir.

For the numerical solution, the equations of shallow water were approximated by the apparent conservative differential scheme of Godunov's type.

The transport equation approximated by implicit conservative differential scheme. Because of this was the system of nonlinear equations, Newton method was applied.

Usually Γ_1 border is a common border of underground stream with surface water bodies and boundary Γ_2 is characterized by ongoing value through it flow (for example, impenetrable borders, infiltration and evapotranspiration, field and constant injection of fluids).

When unloading groundwater water to the reservoir near water level it is usually formed intervals of slow flowing (everyone could watch them on the banks of water bodies. These dark strips of soil near the water line). These intervals are characterized by the fact that the pressure of moisture in the pores on the surface of the soil, equal to atmospheric one. Value of these gaps in advance is unknown, and it can change over time, so it too is determined from the solution of the problem. And boundary conditions in the form of a water line near the inequities and enable you to find those intervals.

In the instant case, the boundary conditions for the transport equation on the bottom surface are of the form (as shown in Figure 10):

$$p + \rho g z = P_a + \rho g h + \rho u^2 / 2, \text{ on AB и BC;}$$

$$-\frac{\mathbf{k}k_r}{\mu} \frac{\partial}{\partial n} (p + \rho g z) = 0, \quad p < P_a \text{ on DE;}$$

$$-\frac{\mathbf{k}k_r}{\mu} \frac{\partial}{\partial n} (p + \rho g z) > 0, \quad p = P_a, \text{ on CD,}$$

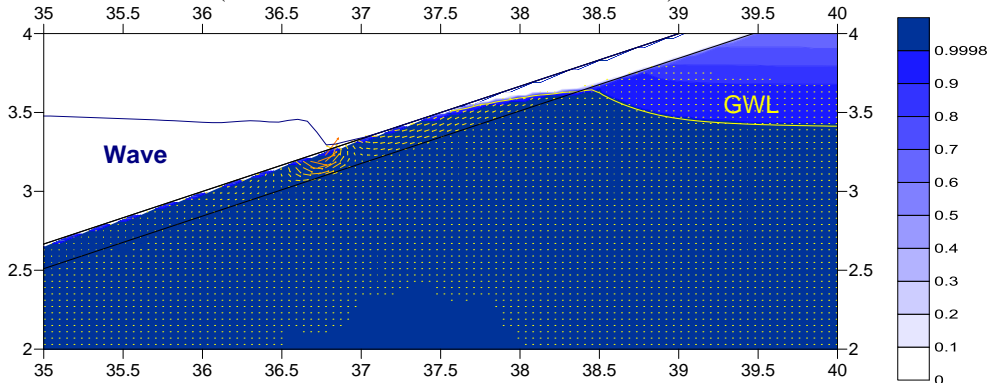
where n is external unit vector normal to the surface of the Earth, η ; P_a is the atmospheric pressure.

Note that the segment CD is not known in advance and must be determined from the solution. For the numerical solution of equations of Saint-Venan used a clear conservative second-order type Godunov's scheme, and for modelling the movement of water in a porous media - implicit conservative scheme of second order on spatial variables, and first for the time. Calculated values of run-up of waves on slope were obtained with the following filtration characteristics (run-up of waves on the shore is related depending on filtration characteristics of coverage):

Layer	E	A
Filtration coefficient, cm/s	30	20
Porosity (bulk)	0.48	0.42

Manning roughness coefficient taken equal to 0.02. The results of calculations on a slope waves run-up for the conditions of the experiments in the flume are presented in Table 9.

Fig. 11 shows an example of numerical calculation waves run-up on slope for the conditions of the experiment and coated A (blue marked shows the level of saturation).



T= 12 s

Figure 11. The results of numerical calculation of roll waves on permeable anchored slope. For the data of the experiment in a large wave flume in Hannover

Table 9. Characteristics of waves, height of run-up and run-down for the conditions of the experiments (measured, received numerical simulations, and calculated)

No. of test	h , m	H_m m	T_m s	ζ_m	$\frac{R_u^{(2)}}{H_m}$	$\frac{R_u^{simu}}{H_m}$	$\frac{R_d^{simu}}{H_m}$	$\frac{R_u^A}{H_m}$	$\frac{R_u^A}{H_m}$	$\frac{R_d^A}{H_m}$	$\frac{R_u^B}{H_m}$	$\frac{R_u^B}{H_m}$	$\frac{R_d^B}{H_m}$	$\frac{R_u^B}{H_m}$	$\frac{R_d^B}{H_m}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
09051301	3.4	0.22	3.00	2.67	2.33	2.23	-1.12	1.39	1.41	-0.82	-0.23	1.12	1.33	-0.71	-0.24
09051302	3.4	0.19	4.00	3.77	2.87	2.44	-2.03	1.85	1.63	-1.37	-1.55	1.77	1.56	-1.29	-1.33
09051303	3.4	0.21	5.00	4.59	3.11	2.49	-2.19	1.83	1.79	-1.59	-1.73	1.67	1.72	-1.52	-1.62
09051401	3.4	0.18	5.93	5.78	3.67	2.56	-2.24	2.06	1.72	-1.82	-1.92	1.79	1.67	-1.77	-1.84
09051402	3.4	0.22	7.00	6.24	3.64	2.37	-2.01	2.16	2.31	-1.67	-1.80	2.00	2.12	-1.61	-1.75
09051403	3.4	0.17	7.90	7.94	4.46	2.12	-1.84	1.83	1.75	-1.86	-1.85	1.70	1.83	-1.81	-1.86
09051404	3.4	0.65	3.00	1.55	1.76	1.30	-0.01	1.23	1.33	0.03	-0.05	1.24	1.34	-0.04	-0.03
09051405	3.6	0.68	4.01	2.02	1.93	1.81	-0.19	1.68	1.85	-0.03	-0.08	1.70	1.76	-0.20	-0.14
09051406	3.6	1.04	3.00	1.22	1.61	1.24	0.34	0.89	1.12	0.24	0.29	0.92	1.04	0.26	0.31
09051501	3.7	0.64	4.95	2.57	2.11	2.00	-1.08	1.79	1.85	-0.36	-0.72	2.00	1.79	-0.53	-0.60
09051502	3.7	1.14	3.92	1.53	1.71	1.51	0.31	1.39	1.52	0.28	0.33	1.45	1.60	0.35	0.33
09051503	3.7	1.40	3.92	1.38	1.65	1.43	0.36	1.22	1.24	0.29	0.36	1.28	1.19	0.41	0.39
09051504	3.9	0.65	6.00	3.10	2.27	2.31	-1.97	2.07	2.20	-0.50	-0.72	2.13	2.13	-0.72	-0.75
09051505	3.9	0.54	6.93	3.91	2.55	2.38	-2.10	2.15	2.22	-0.90	-1.01	2.17	2.31	-1.14	-1.12
090511801	3.9	0.55	7.98	4.49	2.67	2.19	-1.93	2.18	2.12	-1.13	-1.42	2.22	2.17	-1.28	-1.37
090511802	3.9	1.37	4.90	1.75	1.76	1.68	0.15			0.32		1.81		0.36	

Note: the ratio $\frac{R_u^{(2)}}{H_m}$ calculated under formulas (2), (3), "simu" indicates the result of the numerical simulation, the coating type specified: "A" or "B", the absence of such marking relates the result to the conditions of the smooth impermeable slope

Comparison of results of numerical and laboratory studies

To check the results of the simulation, height values compared with the waves run-up available experimental data. Figs 12 and 13 compares the results measured and received by numerical simulation of run-up heights and run-down of waves on a fixed permeable slope. Fig. 12 comparison refers to the height of run-up, as in Fig. 13- the height of run-down the waves, respectively. The same figures are the regression lines, indicating the degree of agreement measured in the laboratory and obtained numerical data experiences. The figures show the horizontal axis measurement data in accordance with table 9, and the vertical axis numerical simulation data are also presented in table 9.

Analysis of these results indicates that the numerical model satisfactorily consistent with data used in large-scale experiments in the wave flume.

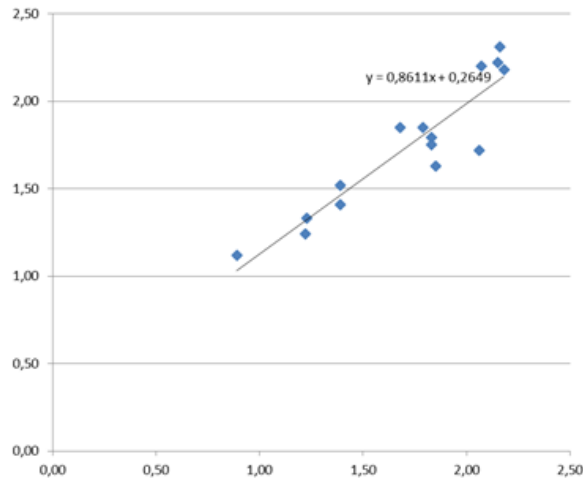


Figure 12. Comparing data on height of run-up of waves on permeable fixed slope obtained by measurements in the wave flume and numerical simulation

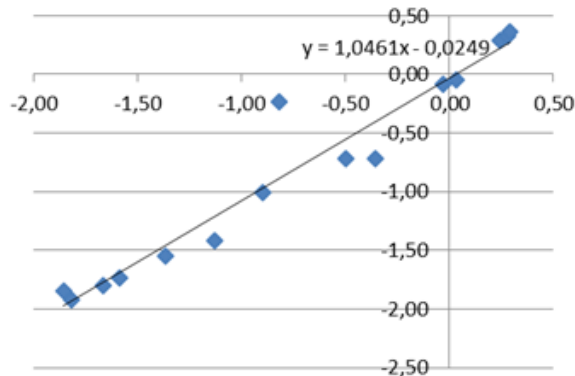


Figure 13. Comparison of height data run-down of waves on permeable fixed slope obtained measurements in the wave flume and numerical simulation

CONCLUSION

For permeable fixed protective coating, the top protective layer can be considered as porous media. That allowed the development of a numerical model of run-up of waves on slope, considering the interaction flow of run-up on the surface slope and filtration flow in porous protective layer. The developed numerical model of run-up of waves on slope, allows you to receive necessary for designing structures slope structures with permeable top layer, run-up and run-down of waves. It is possible to determine the position of the free wave surface (value of run-up of waves on slope and elevation waves with a run-down from a slope) at different points in time, necessary to calculate the top mark of slope construction with permeable top layer.

The developed numerical model verified by comparison with data published full-scale experiments performed in the wave flume at the Technical University of Braunschweig, Hannover, Germany. Satisfactory results of the comparison are obtained.

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