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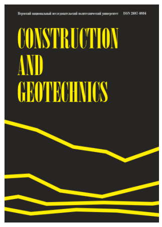

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LABORATORY STUDIES OF WAVE RUN-UP IN THE SHALLOW SEA ZONE ON SLOPES REINFORCED WITH FLEXIBLE CONCRETE SLABS

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ABSTRACT

The results of experimental laboratory studies of flexible concrete revetment of slopes aimed at protecting transport structures from the effects of sea waves have been presented in this article. The object of the study is the structures of protective wave-damping slopes – flexible concrete slabs (flexible concrete revetments) consisting of concrete blocks connected by flexible ties, manufactured in accordance with GOST R 58411-2019, constructed to protect bridge supports, roadbed and railways, etc., designed and operated under conditions of wave action on the seashores.

The purpose of the work is to obtain experimental data for the development of regulations for determining the height of run-up under wave action on flexible concrete revetments to protect the slopes of transport structures on the seashores.

The research was carried out using the method of physical modeling in a wave flume.

On a scale of 1:10, models of slope structures with a sand core reinforced with flexible concrete paving in accordance with GOST R 58411-2019 were built in the wave flume. In the process of research the interaction of the design wave of sea storms with protective slopes reinforced with flexible concrete slabs was assessed. Using a physical model the effect of storm waves on elements of flexible revetment on bank protection slopes with different slope angles (1:2, 1:3 и 1:5) was studied. It was made the assessment of the height of the wave run-up on coastal protection slopes under the influence of breaking waves, as well as in the shallow sea zone.

The research results are aimed at the development of the regulatory framework in the field of protection of the designed on the sea shores transport structures from washing out under the influence of a sea storm wave.

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ЛАБОРАТОРНЫЕ ИССЛЕДОВАНИЯ НАКАТА ВОЛН В МЕЛКОВОДНОЙ ЗОНЕ МОРЯ НА ОТКОСЫ, УКРЕПЛЕННЫЕ ГИБКИМИ БЕТОННЫМИ ПЛИТАМИ

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АННОТАЦИЯ

Представлены результаты экспериментальных лабораторных исследований гибких бетонных покрытий откосов для защиты транспортных сооружений от воздействия морских волн. Объектом исследования являются конструкции защитных волногасящих откосов – гибкие бетонные плиты (гибкие бетонные покрытия), состоящие из бетонных блоков, соединенных гибкими связями, изготавливаемые по ГОСТ Р 58411-2019, сооружаемые для защиты опор мостов, земляного полотна автомобильных и железных дорог и т.п., проектируемых и эксплуатируемых в условиях волнового воздействия на берегах морей.

Цель работы – получение экспериментальных данных для разработки нормативных положений по определению высоты наката при волновом воздействии на гибкие бетонные покрытия для защиты откосов транспортных сооружений на берегах морей.

Исследования выполнены методом физического моделирования в волновом лотке. В масштабе 1:10 в волновом лотке были построены модели откосных сооружений с песчаным ядром, укрепленным гибкими бетонными покрытиями по ГОСТ Р 58411-2019. В процессе исследований проводилась оценка взаимодействия расчетного волнения морских штормов с защитными откосами, укрепленными гибкими бетонными плитами. На физической модели исследовалось воздействие штормового волнения на элементы гибких покрытий на берегозащитных откосах с различными уклонами (1:2, 1:3 и 1:5). Выполнялась оценка высоты наката волн на берегозащитные откосы при воздействии обрушающихся волн, а также в мелководной зоне моря.

Результаты исследований предназначены для развития нормативной базы в области защиты транспортных сооружений, проектируемых на берегах морей, от размыва при воздействии морского штормового волнения.

Introduction

The object of the study is flexible concrete revetment – flexible concrete slabs consisting of concrete blocks connected by flexible connectors manufactured in accordance with GOST R 58411-2019 «Flexible concrete slabs. Specifications» (Fig. 1).

The current regulatory documents of the Russian Federation (SP 116.13330.2012 «Engineering protection of territories, buildings and structures from dangerous geological processes. Basic principles», SP 86.13330.2022 «Trunk pipelines «, SP 80.13330.2016 «River hydraulie engineering facilities») prescribe the use of flexible concrete revetment for the protection of transport structures, river banks, lakes and reservoirs.

Methodological and industry documents on calculation, design and construction of flexible concrete revetment for the protection of slopes of transport structures have also been developed [1–4]. Calculation methods and technologies for the construction of flexible concrete revetment are constantly being improved and this is confirmed by the ongoing research [5–9].

However, the calculation methods given in the current regulatory and methodological documents [3, 4] are applicable to the banks of rivers or reservoirs, but the problems of interaction of sea waves with flexible concrete slabs are not considered in them.

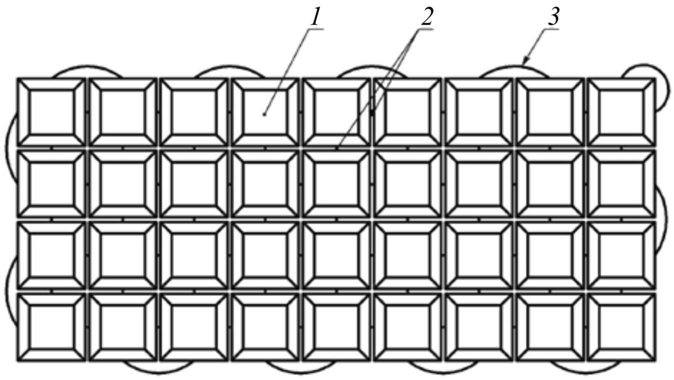


Fig. 1. Flexible concrete slab according to GOST R 58411-2019 [1]:
1 – concrete block; *2* – connecting rope; *3* – mounting loop
Рис. 1. Гибкая бетонная плита по ГОСТ Р 58411-2019 [1]:
1 – бетонный блок; *2* – соединительный канат; *3* – монтажная петля

One of the main calculated characteristics in the design of slopes which protect transport structures from washout by sea waves is the height of the wave run up (exceeding the mark of the highest point of the calculated wave on the slope above the level of calm water).

In general, the height of wave run up on slopes is determined in accordance with Appendix D SP 38.13330.2018 «Loads and impacts on hydraulic structures»:

$$h_{run} = k_r k_p k_{sp} k_{run} k_i k_a h_{1\,\%}, \tag{1}$$

where k_r and k_p – coefficients of roughness and permeability of the slope, taken depending on the design of the slope protection; k_{sp} – coefficient considering the angle of inclination to the horizon and speed of the wind; k_{run} – coefficient depending on the depth of the water and the gentleness of the wave; k_i – run up probability factor; k_a – coefficient taken depending on the angle of approach of the wave to the slope; $h_{1\,\%}$ – wave height with 1 % probability in the system.

In this calculation formula, various options for slope fixation are taken into account by empirical coefficients k_r and k_p through relative roughness of the material grains $r/h_{1\,\%}$ (or blocks) of the slope fastening for the following structures: smooth concrete (reinforced concrete) slabs, gravel-pebble or stone revetment, concrete (reinforced concrete) blocks. Since flexible concrete slabs cannot be attributed to any of the types of slope reinforcement listed in Appendix D of SR 38.13330.2018 by the nature of interaction with waves, additional studies are required to assess the applicability (or the possibility of clarifying) the regulatory methodology for calculating the wave run up on the slope.

In this paper the results of laboratory studies of the interaction of sea waves with slopes fixed with flexible concrete revetment have been presented. The purpose of the research is to obtain experimental data to assess the applicability of regulatory formulas for calculating the waves run up on the slope for flexible concrete surfacing aimed at the protection of slopes of transport structures (bridge supports, roadbed of roads and railways, etc.).

Methods of Research

The research was carried out by the method of physical modeling in the ‘Sea Shores’ research centre, Sochi (nowadays JSC TsNIITS ‘SRC “Sea Shores”). The method of physical modeling is widely used in solving various kinds of problems in geotechnics, hydraulic engineering [10–13], etc. Also the author refers this method to the basic one when substantiating the requirements of normative documents in the field of transport structures protection from hydrodynamic impact of natural water environment [14–16].

Experimental studies were carried out in a wave flume with a length of 20 m, a width of 0.6 m, and a wall height of 1.0 m. Waves in the wave flume were generated by a shield wave-producer installed in a pit at one of the end walls. The wave generator performs reciprocating movements with the help of a DC electric motor, which can be used for regulating the frequency and amplitude of the shield oscillations. The scheme of the wave flume is shown in Fig. 2

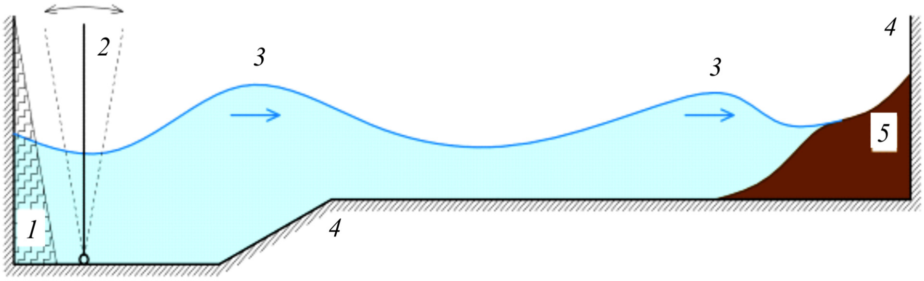
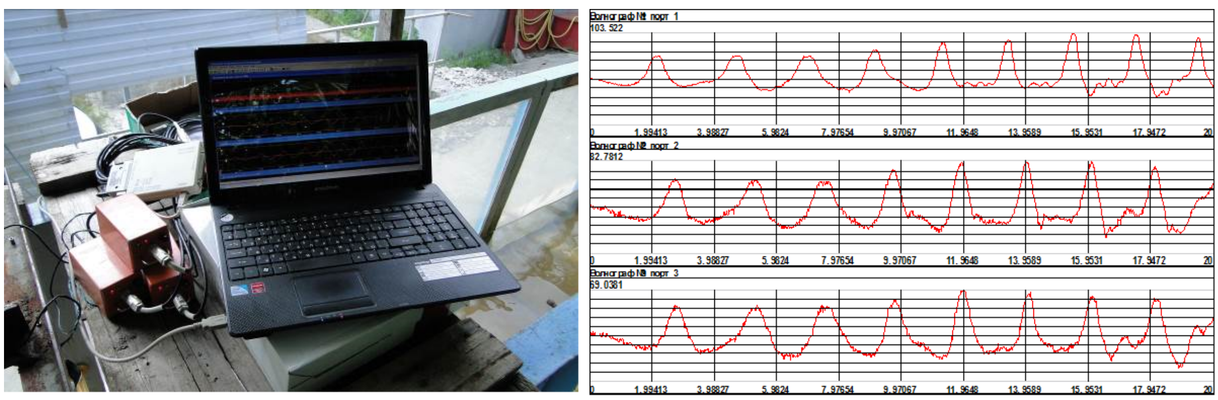


Fig. 2. Scheme of the wave tray: *1* – wave absorber; *2* – wave producer; *3* – wave; *4* – flume wall; *5* – model
Рис. 2. Схема волнового лотка: *1* – волногаситель; *2* – волнопродуктор; *3* – волна; *4* – стенка лотка; *5* – модель

Models of slope structures with a sand core reinforced with flexible concrete surfacing were built in the wave flume at a scale of 1:10 according to GOST R 58411-2019. Linear dimensions (geometric dimensions of structures and their elements, depths, heights and wavelengths) on the model were taken in linear scale.

Measurements of wave parameters were performed by a measuring system (Fig. 3), consisting of capacitive wave recorder DUE-1 and a portable PC connected to an analogue-to-digital converter (ADC) via USB channel, whose inputs received measurement data signals from wave recorders, fixtures to measuring instruments and auxiliary equipment after the necessary transformations.



a *b*

Fig. 3. System of transforming the measured wave parameters: PC connected to the ADC (*a*) and an example of wavegraph recording (*b*)
Рис. 3. Система преобразования измеренных параметров волн: ПК, соединенный с АЦП (*a*) и пример записи показаний волнографов (*b*)

Systematic errors of measurements of periods, wavelengths and heights were practically excluded by independent control with a stopwatch and by digital photography and video recording.

The sensors were calibrated before and after measurements. The measurement errors did not exceed 5 %.

The absolute error of the results of measurements of the average wave height did not exceed ± 2 mm, and of the periods ± 0.1 s.

For the purity of the experiments the initial wave mode in the flume was selected without structures. In order to avoid wave reflection a wave-absorbing berm was poured in the end part of the flume. Each experiment was repeated at least three times.

In the modelling, the wave parameters corresponding to the waves of the design storm, possible once in 25 years of 5 % probability were taken.

Physical modeling was carried out according to the methodology described in [16–18]. In this case, the Froude number should be used as the main similarity criterion, i.e. it is necessary to ensure the equality of the Froude numbers of the object and the model [19, 20]:

$$\mathrm{Fr} = \frac{V^2}{gL} = \mathrm{idem}, \tag{2}$$

where Fr – Froude number; V – characteristic velocity (e.g. wave propagation velocity); g – free-fall acceleration; L – characteristic linear dimension.

It was also ensured on the model the fulfillment of the condition

$$\mathrm{Re} \geq 1000 \tag{3}$$

where Re – Reynolds number, determined by the formula

$$\mathrm{Re} = \frac{VL}{\nu} \tag{4}$$

where V – characteristic velocity (e.g. wave propagation velocity); L – characteristic linear dimension; ν – fluid kinematic viscosity.

In this paper, taking into account the dimensions of the wave flume and the modeled structure, the geometric scale of the model is assumed to be equal to:

$$\alpha_\ell = 1{:}10. \tag{5}$$

In order to ensure the equality of Froude numbers (2) on the model and in the field conditions the scale of the wave period was as follows:

$$\alpha_t = \sqrt{\alpha_\ell} = 1{:}3{,}16, \tag{6}$$

and mass scale of protective slope protection fastening elements:

$$\alpha_G = \alpha_\ell^{\,3} = 1{:}1000. \tag{7}$$

Models of flexible concrete revetment were made in 1:10 scale taking into account the unified dimensions of FCS-240 (GOST R 58411-2019). The size of one concrete block of flexible revetment was equal to 30 × 30 × 24 mm (30 × 30 × 24 cm)[1]. The mass of one concrete block of flexible

[1] Hereinafter in the text and in the figures in brackets are the values corresponding to the in-situ values.

revetment was about 34 g (34 kg), which satisfactorily corresponds to GOST R 58411-2019 and the expression (7).

The bottom of the physical model was made rigid [17, 18] by surface concreting of the backfill material along characteristic profiles.

The core of the slope was made as an impermeable sand structure with an impermeable geotextile cover.

A physical model was used to investigate the impact of storm waves in a shallow sea zone on elements of flexible revetment of coastal protection slopes with different grades (1:2, 1:3 and 1:5).

Different wave regimes with mean period from 1.54 to 1.66 s (4.87 to 5.25 s) were considered. The waves in the flume were selected in such a way that they did not collapse on the investigated shore protection slope, but gently rolled on the slope during the experiments. The view of the model during the experiments is shown in Fig. 4.

Fig. 4. View of the model during experiments in a wave flume
Рис. 4. Вид модели во время экспериментов в волновом лотке

Further, the results obtained experimentally for flexible concrete revetment were compared with the results of calculations for concrete slabs and concrete blocks in accordance with the appendix D SR 38.13330.2018.

Results

Series No1. Slope with the 1:2 slope angle. The parameters of the model and waves in the experiments of the first series are presented in Table 1.

The results of experiments of the first series aimed at determining the wave run up on the slope with 1:2 slope angle and reinforced with flexible plates according to GOST R 58411-2019 are presented in Table 2 and Figure 5. Also, the results of calculations of wave slope in accordance with Appendix D of SR 38.13330.2018 for concrete slabs and concrete blocks are presented in Table 2 and Fig. 5.

Table 1

Parameters of the model and waves in the experiments of the No 1 Series

Таблица 1

Параметры модели и волнения в опытах серии № 1

Number of the experiment	Slope angle *i*	Scale	Parameters of waves	
			average wave period *T*, s	waves height *h*, mm
1	1:2	1:10	1.66 (5.25)	63 (630)
2			1.62 (5.12)	65 (650)
3			1.58 (5.00)	66 (660)
4			1.56 (4.93)	72 (720)
5			1.54 (4.87)	80 (800)

Table 2

Height of the waves run up on the slope with the angle equal to 1:2

Таблица 2

Высота наката волн на откос с уклоном 1:2

Number of the experiment	Slope angle *i*	Scale	Parameters of waves		Height of the waves run up on the slope, m		
			average wave period *T*, s	waves height *h*, m	flexible concrete slabs (Model)	concrete slabs (calculation according to [15])	concrete blocks (calculation according to [15])
1	1:2	1:10	1.66	0.63	0.111	0.159	0.056
2			1.62	0.65	0.106	0.159	0.056
3			1.58	0.66	0.108	0.158	0.055
4			1.56	0.72	0.114	0.164	0.057
5			1.54	0.80	0.126	0.172	0.060

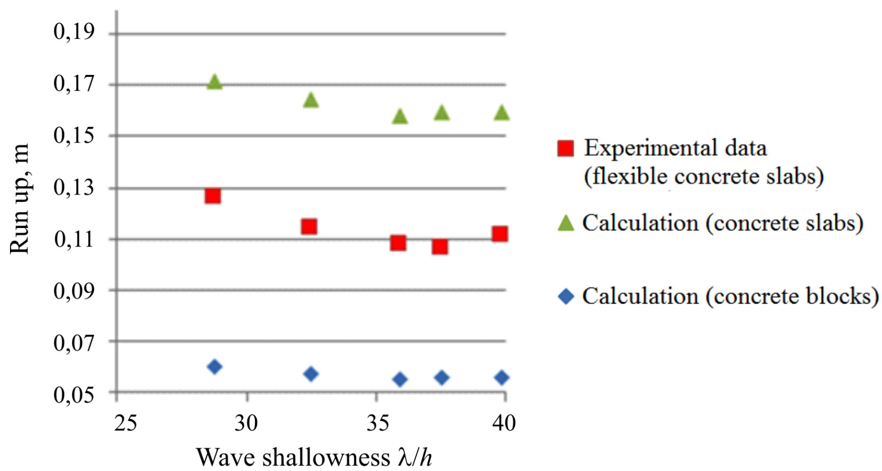


Fig. 5. Height of the waves run up on the slope with the angle equal to 1:2
Рис. 5. Высота наката волн на откос с уклоном 1:2

<u>Series No 2</u>. Slope with 1:3 slope angle. The parameters of the model and waves in the experiment of the second series are given in Table 3.

The results of experiments of the second series aimed at determining the wave run up on the slope with 1:2 slope angle and reinforced with flexible plates according to GOST R 58411-2019 are presented in Table 4 and Fig. 6. Also, the results of calculations of wave slope in accordance with Appendix D of SR 38.13330.2018 for concrete slabs and concrete blocks are presented in Table 4 and Fig. 6.

Table 3

Parameters of the model and waves in the experiments of the No 2 Series

Таблица 3

Параметры модели и волнения в опытах серии № 2

Number of the experiment	Slope angle *i*	Scale	Parameters of waves	
			average wave period *T*, c	waves height *h*, mm
6	1:3	1:10	1.66 (5.25)	70 (700)
7			1.62 (5.12)	75 (750)
8			1.58 (5.00)	83 (830)
9			1.56 (4.93)	87 (870)
10			1.54 (4.87)	90 (900)

Table 4

Height of the Waves Run up on the Slope with the Angle equal to 1:3

Таблица 4

Высота наката волн на откос с уклоном 1:3

Number of the experiment	Slope angle *i*	Scale	Parameters of waves		Height of the waves run up on the slope, m		
			average wave period *T*, c	waves height *h*, m	flexible concrete slabs (Model)	concrete slabs (calculation according to [15])	concrete blocks (calculation according to [15])
6	1:3	1:10	1.66	0.70	0.125	0.169	0.059
7			1.62	0.75	0.119	0.173	0.060
8			1.58	0.83	0.114	0.178	0.062
9			1.56	0.87	0.125	0.182	0.064
10			1.54	0.90	0.132	0.184	0.064

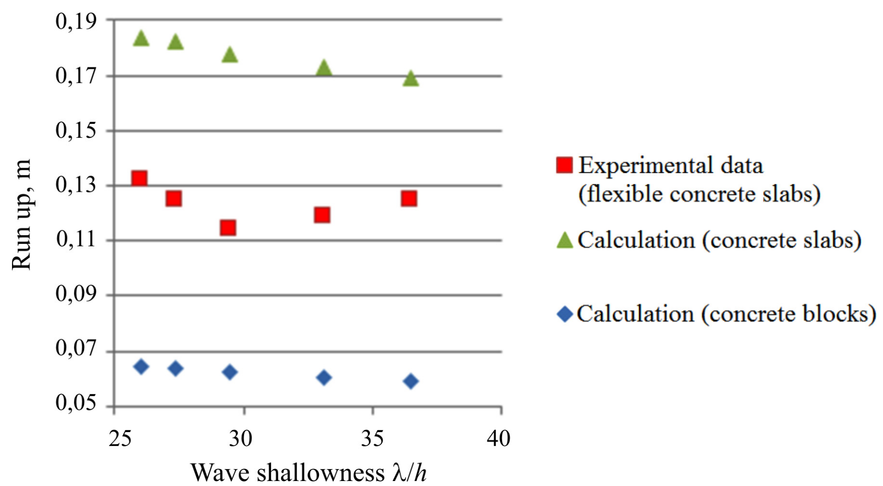


Fig. 6. Height of the waves run up on the slope with the angle equal to 1:3
Рис. 6. Высота наката волн на откос с уклоном 1:3

Series No 3. Slope with 1:5 slope angle. The parameters of the model and waves in the experiment of the third series are given in Table 5.

Table 5

Parameters of the model and waves in the experiments of the No 3 Series

Таблица 5

Параметры модели и волнения в опытах серии № 3

Number of the experiment	Slope angle *i*	Scale	Parameters of waves	
			average wave period *T*, c	waves height *h*, mm
11	1:5	1:10	1.66 (5.25)	77 (770)
12			1.62 (5.12)	96 (960)
13			1.58 (5.00)	112 (1120)
14			1.56 (4.93)	109 (1090)
15			1.54 (4.87)	105 (1050)

The results of experiments of the second series aimed at determining the wave run up on the slope with 1:5 slope angle and reinforced with flexible plates according to GOST R 58411-2019 are presented in Table 6 and Fig.7. Also, the results of calculations of wave slope in accordance with Appendix D of SR 38.13330.2018 for concrete slabs and concrete blocks are presented in Table 6 and Fig. 7.

Table 6

Height of the waves run up on the slope with the angle equal to 1:5

Таблица 6

Высота наката волн на откос с уклоном 1:5

Number of the experiment	Slope angle *i*	Scale	Parameters of waves		Height of the waves run up on the slope, m		
			average wave period *T*, c	waves height *h*, m	flexible concrete slabs (Model)	concrete slabs (calculation according to [15])	concrete blocks (calculation according to [15])
11	1:5	1:10	1.66	0.77	0.076	0.106	0.037
12			1.62	0.96	0.082	0.116	0.041
13			1.58	1.12	0.083	0.124	0.043
14			1.56	1.09	0.085	0.121	0.042
15			1.54	1.05	0.081	0.118	0.041

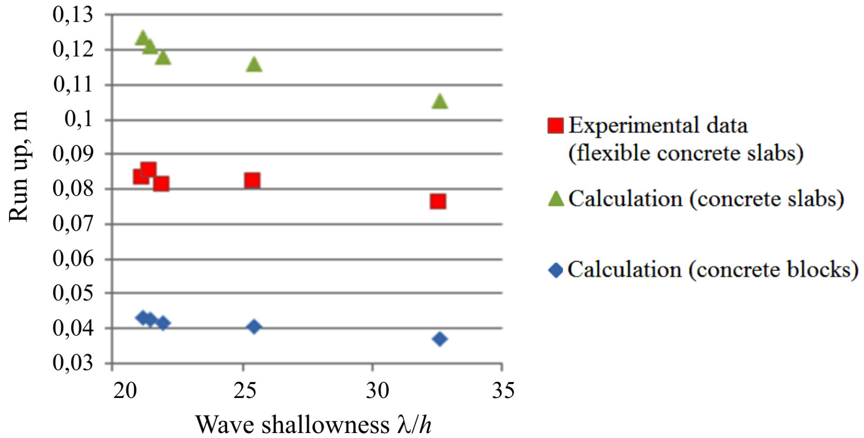


Fig. 7. Height of the waves run up on the slope with the angle equal 1:5
Рис. 7. Высота наката волн на откос с уклоном 1:5

Conclusion

Based on the results of laboratory studies of the waves run up in the shallow zone of the sea on slopes reinforced with flexible concrete slabs, the following conclusions can be drawn:

1. In the current regulatory documents there are no methods for calculating the run upl of sea wind waves on the slope reinforced with flexible concrete slabs. The calculation according to the method set out in Appendix D of SR 38.13330.2018, specific to concrete slabs and concrete blocks, is not fully suitable for flexible concrete slabs (the discrepancy is approximately ± 35 %).
2. To calculate the height of the run-up of sea wind waves on a slope reinforced with flexiblwe concrete slabs it is necessary to introduce additions to the methodology set out in the Appendix D SR 38.13330.2018, taking into account the design features of such paving.
3. Considering the widespread use of flexible concrete slabs to protect the slopes of transport structures, including on the seashores it is also recommended to reflect the above mentioned additions in SR 277.1325800.2016 «Costal protection constructions. Design rules».

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Конфликт интересов. *Автор заявляет об отсутствии конфликта интересов.*
Вклад 100 %.

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