Velocity measurements in and around a permeable breakwater

Tests executed in the Waterlab at TU Delft
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Traineeship title: Training on Physical Modelling in Turbulence Measurements in Submerged Permeable Rubble Mound Breakwaters under wave action

Description of the model set-up: TU DELFT Wave Flume

Main goal of the proposed experiments: Capture and obtain simultaneous laboratory measurements of the main hydrodynamic parameters generated by the response of small model scale submerged permeable rubble mound trapezoidal breakwaters (SPBs) under wave action, focusing on the turbulent wave flow characteristics in their interior, in order to investigate their eco-hydraulic properties (i.e. artificial habitat function efficiency in conjunction to shoreline protection level under the attack of wind waves).

Main byproduct: Address stability and economy issues related to the environmental applicability range of the SPBs.

Type of coastal structure: Submerged Permeable Breakwater (SPB) <4 models in total> (Table 1); tests for regular and irregular conditions (Table 2).

Measuring instruments to be used for the **parameters** of interest are:

- 1 Fiber optic laser Doppler anemometer of one component: orbital velocities (U in 3D: U_x, U_y components inside the structure and U_x, U_y, U_z components outside the structures.[*if available, modification of wave runs' schedule, pp 3-5*]
- 1 Acoustic Doppler Velocimeter (ADV): orbital velocities (U in 3D: U_x, U_y, and U_z components inside and outside the structure).
- 8 pressure sensors of small measuring surface positioned towards the wave flow/stream (capable of continuous monitoring and of high frequency response, 1 KHz minimum) for hydrodynamic pressures (P_s). [*1 of the set of 8 sensors is to be placed on the leeward slope of the model]*.
- 8 Resistant-type wave gauges for water surface elevation (ζ).

SBs: Height h_s=0.50 m, Crest width B=0.40 m, two different slopes, m of 1:1.5 & 1:2, Free Board (2 cases), FB= 0.10, 0.15 m, two different porosities, n=0.40, 0.50. Wave scenarios for each SPB model, 8 regular & 5 irregular <13 main wave scenarios per model, 52 per 4 models; 13 secondary wave scenarios per model, 52 per 4 models; 104 wave runs in total>. Total rock units' volume is roughly 1.5 m^3 of mean diameter D_{50}=0.07÷0.12 m.

<**U, P_s**>, 5 measurement sections (Fig. 1), per wave scenario; <**ζ**>, 8 measurement stations (3, upstream of the rubble mounds; 3 over the structure <sections 1, 2, 3 Fig.1>, 2, downstream).

Table 1. Rubble mounds' main features and codification (models, under scale roughly 1:10).

SPBs' description	SPB - Layout A		SPB - Layout B		SPBs' description
n=0.4	m=1:1.5	m=1:2	m=1:1.5	m=1:2	**n=0.5**
SBs: model code	**SPB 1**	**SPB 2**	**SPB 3**	**SPB 4**	**SBs: model code**

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Table 2. Wave characteristics: regular waves: H, wave height; T, wave period & irregular waves: H_s, significant wave height; T_p, peak period (spectra of Jonswap type).

Wave state	**Regular**		**Irregular**	
Wave characteristics	H (m)	T (s)	H_s (m)	T_p (s)
SPBs	0.05÷0.015	1.0÷2.5	0.05÷0.015	1.0÷2.5

Table 3. Experimental Schedule (4 weeks plan).

# week	**1**					**2**					**3**					**4**				
model code	SPB 1					SPB 2					SPB 3					SPB 4				
# working day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	119	20
task/activity	c^1	e	e	e	e	e^1	e	e	e	e	c^2	e	e	e	e	e^1	e	e	e	e^2

c^1: construction of Layout A; e: wave runs;e^1 wave runs including modification of the slopes to 1:2; c^2: decomposition of Layout A and construction of Layout B; e^2: wave runs including decomposition of Layout B.

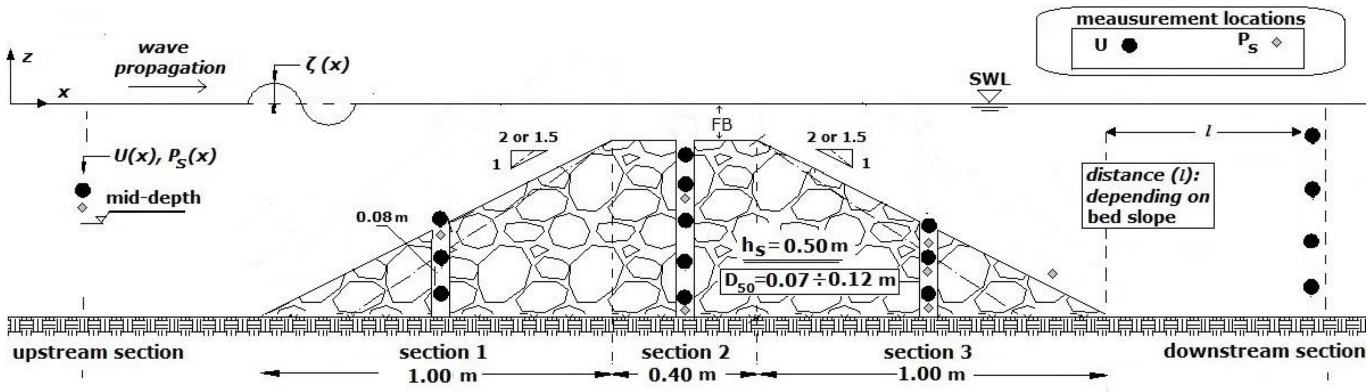

Fig. 1. Layout of the SPBs models, scale 1:10. Average 1.5 hours duration for each wave test (the wave tests are sorted in two main categories: basic of average duration of 2.0 hrs, and secondary of average duration of 0.25 hrs.

* Byproduct of the combined use of the LDA & ADV systems: At least 4 of the basic wave runs (1 per model) are to be measured twice, once with the LDA and once with the ADV system in order to compare and correlate the orbital velocities' measurements response to the turbulent component for the two methods; provide thus accurate values for U_z inside the mound through ADV.

Macrofeatures of the water surface transformation around the structures' wave breaking zone (between the seaward slope and crest) through video camera recordings is also foreseen, making advantage of the flumes' windows.

Sampling duration (for U, P_s) should be about 3 minutes for each location. However, the exact selection of minimum measuring duration and sampling frequency of 50 or 100 Hz, should be tested through regression analysis during the experiments set up.

Table 4. Time schedule and wave runs' characteristics: regular waves: H, wave height; T, wave period & irregular waves: H_s, significant wave height; T_p, peak period (spectra of Jonswap type).

Coding of the experiments				**Regular waves - R**			**Irregular waves - I**	
Model code	# day	Wave scenario code	Free Board (m)	H (m) range = 0.05÷0.015	T (s) range = 1.0÷2.5		H_s (m) range = 0.05÷0.015	T_p (s) range = 1.0÷2.5
SPB1	2	1-R1$_a$*	0.10	0.05	2.5			
	2	1-R1$_b$	0.10	0.08	2.5			
	2	1-R2$_a$	0.10	0.10	2.0			
	2	1-R2$_b$	0.10	0.12	2.0			
	3	1-R3$_a$	0.10	0.12	1.75			
	3	1-R3$_b$	0.10	0.14	1.75			
	3	1-R4$_a$	0.10	0.14	1.00			
	3	1-R4$_b$	0.10	0.15	1.00			
	3	1-R5$_a$	0.15	0.08	2.5			
	3	1-R5$_b$	0.15	0.10	2.5			
	3	1-R6$_a$	0.15	0.10	2.0			
	3	1-R6$_b$	0.15	0.12	2.0			
	4	1-R7$_a$	0.15	0.08	1.75			
	4	1-R7$_b$	0.15	0.10	1.75			
	4	1-R8$_a$	0.15	0.12	1.00			
	4	1-R8$_b$	0.15	0.14	1.00			
	4	1-I9$_a$	0.10				0.10	2.0
	4	1-I9$_b$	0.10				0.12	2.0
	4	1-I10$_a$	0.10				0.12	1.75
	4	1-I10$_b$	0.10				0.14	1.75
	5	1-I11$_a$	0.15				0.14	2.00
	5	1-I11$_b$	0.15				0.15	2.00
	5	1-I12$_a$	0.15				0.08	1.75
	5	1-I12$_b$	0.15				0.10	1.75
	5	1-I13$_a$	0.15				0.12	1.00
	5	1-I13$_b$	0.15				0.14	1.00
SPB2	6	2-R1$_a$*	0.10	0.05	2.5			
	6	2-R1$_b$	0.10	0.08	2.5			
	6	2-R2$_a$	0.10	0.10	2.0			
	6	2-R2$_b$	0.10	0.12	2.0			
	7	2-R3$_a$	0.10	0.12	1.75			
	7	2-R3$_b$	0.10	0.14	1.75			
	7	2-R4$_a$	0.10	0.14	1.00			
	7	2-R4$_b$	0.10	0.15	1.00			
	7	2-R5$_a$	0.15	0.08	2.5			
	7	2-R5$_b$	0.15	0.10	2.5			
	7	2-R6$_a$	0.15	0.10	2.0			
	7	2-R6$_b$	0.15	0.12	2.0			
	8	2-R7$_a$	0.15	0.08	1.75			
	8	2-R7$_b$	0.15	0.10	1.75			
	8	2-R8$_a$	0.15	0.12	1.00			
	8	2-R8$_b$	0.15	0.14	1.00			
	8	2-I9$_a$	0.10				0.10	2.0
	8	2-I9$_b$	0.10				0.12	2.0
	8	2-I10$_a$	0.10				0.12	1.75
	8	2-I10$_b$	0.10				0.14	1.75
	9	2-I11$_a$	0.15				0.14	2.00
	9	2-I11$_b$	0.15				0.15	2.00
	9	2-I12$_a$	0.15				0.08	1.75
	9	2-I12$_b$	0.15				0.10	1.75
	9	2-I13$_a$	0.15				0.12	1.00
	9	2-I13$_b$	0.15				0.14	1.00
	Codification on p. 5							

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Table 4. (Cont'd)

Coding of the experiments				Regular waves - R			Irregular waves - I	
Model code	# day	Wave scenario code	Free Board (m)	H (m) range = 0.05÷0.015	T (s) range = 1.0÷2.5		H_s (m) range = 0.05÷0.015	T_p (s) range = 1.0÷2.5
	12	3-R1$_a$*	0.10	0.05	2.5			
	12	3-R1$_b$	0.10	0.08	2.5			
	12	3-R2$_a$	0.10	0.10	2.0			
	12	3-R2$_b$	0.10	0.12	2.0			
	13	3-R3$_a$	0.10	0.12	1.75			
	13	3-R3$_b$	0.10	0.14	1.75			
	13	3-R4$_a$	0.10	0.14	1.00			
	13	3-R4$_b$	0.10	0.15	1.00			
	13	3-R5$_a$	0.15	0.08	2.5			
	13	3-R5$_b$	0.15	0.10	2.5			
	13	3-R6$_a$	0.15	0.10	2.0			
	13	3-R6$_b$	0.15	0.12	2.0			
SPB3	14	3-R7$_a$	0.15	0.08	1.75			
	14	3-R7$_b$	0.15	0.10	1.75			
	14	3-R8$_a$	0.15	0.12	1.00			
	14	3-R8$_b$	0.15	0.14	1.00			
	14	3-I9$_a$	0.10				0.10	2.0
	14	3-I9$_b$	0.10				0.12	2.0
	14	3-I10$_a$	0.10				0.12	1.75
	14	3-I10$_b$	0.10				0.14	1.75
	15	3-I11$_a$	0.15				0.14	2.00
	15	3-I11$_b$	0.15				0.15	2.00
	15	3-I12$_a$	0.15				0.08	1.75
	15	3-I12$_b$	0.15				0.10	1.75
	15	3-I13$_a$	0.15				0.12	1.00
	15	3-I13$_b$	0.15				0.14	1.00
	16	4-R1$_a$*	0.10	0.05	2.5			
	16	4-R1$_b$	0.10	0.08	2.5			
	16	4-R2$_a$	0.10	0.10	2.0			
	16	4-R2$_b$	0.10	0.12	2.0			
	17	4-R3$_a$	0.10	0.12	1.75			
	17	4-R3$_b$	0.10	0.14	1.75			
	17	4-R4$_a$	0.10	0.14	1.00			
	17	4-R4$_b$	0.10	0.15	1.00			
	17	4-R5$_a$	0.15	0.08	2.5			
	17	4-R5$_b$	0.15	0.10	2.5			
	17	4-R6$_a$	0.15	0.10	2.0			
	17	4-R6$_b$	0.15	0.12	2.0			
	18	4-R7$_a$	0.15	0.08	1.75			
SPB4	18	4-R7$_b$	0.15	0.10	1.75			
	18	4-R8$_a$	0.15	0.12	1.00			
	18	4-R8$_b$	0.15	0.14	1.00			
	18	4-I9$_a$	0.10				0.10	2.0
	18	4-I9$_b$	0.10				0.12	2.0
	18	4-I10$_a$	0.10				0.12	1.75
	18	4-I10$_b$	0.10				0.14	1.75
	19	4-I11$_a$	0.15				0.14	2.00
	19	4-I11$_b$	0.15				0.15	2.00
	19	4-I12$_a$	0.15				0.08	1.75
	19	4-I12$_b$	0.15				0.10	1.75
	19	4-I13$_a$	0.15				0.12	1.00
	19	4-I13$_b$	0.15				0.14	1.00

Codification on p. 5

Codification:
example: 1-R1$_a$
[1-] refers to SPB model code
[R] is for regular wave runs
[I] is for irregular wave runs
[1] is the wave run code
[$_a$] refers to the main wave runs
[$_b$] refers to the secondary wave runs

*** double run, LDA & ADV system**

Some slight modifications may be expected especially for the wave height of the tested wave runs, a task to provide its expected outcome early September.

PhD "basic lines" proposal by Elpidoforos G. Repousis

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SUSTAINABLE SUBMERGED BREAKWATERS

Summary

In the present research proposal, submerged rubble mound permeable breakwaters (SPBs) will be studied. For this type of structure, it has been observed that apart from defying beach erosion, it may enhance, under specific circumstances, marine life conditions in the nearshore. This function of SPBs is implemented by providing shelter and suitable conditions for attracting marine life in and around the porous structure. To decide on the suitability of the hydraulic conditions suitability for specific marine species data are needed on such parameters as velocities, turbulence levels, pressures. On the other hand, technical efficiency has to be evaluated through the percentage of wave energy abstraction induced by the SPBs, through water surface elevation analysis of the waves propagating over such rubble mounds. Despite research progress in low crested structures, when considering both shore protection and artificial habitat efficiency of SPBs, a simultaneous systematic experimental investigation on wave transmission and hydrodynamic field inside and around SPBs is still lacking.

Considering the turbulent nature of the hydrodynamic field developing due to wave action around and inside SPBs, and in order to obtain experimental data for parameterization in terms of SPBs' geometry and wave state, a series of laboratory experiments is needed, for both regular and irregular wave conditions.

1. Introduction

1.1. Scientific context

Nowadays, the need for protecting the shore from wave action is one of the most ordinary yet complex issues scientists, engineers, and managers have to deal with. In regard to coastal erosion, the necessity for sustainable protective measures increases constantly. In this direction, contemporary coastal zone management proposes, among other measures, multi-purpose and resilient protective infrastructures. A core component of such infrastructures is the shore-parallel breakwater. Considering past experience, conventional installations as emerged breakwaters have been widely applied in defying beach erosion, with knowledge obtained on their coastal behaviour covering a wide scope. Therefore their defensive efficiency has been studied and assessed extensively both empirically and experimentally. Despite the overall acceptability of integrating such structures in the coastal zone, it has been observed that they are usually followed by a significant environmental impact. In particular, they occupy large seabed areas, they affect drastically water circulation, sediment transport climate, and yet the aesthetic value of the landscape. As environmental awareness gradually increases, submerged breakwaters (SBs) have become a shore protection alternative aiming in confining side effects.

Beyond the basic goal in protecting the coast, it has been deduced that especially permeable rubble mound submerged breakwaters (SPBs) may function similarly to natural reefs as they tend to attract marine life. This dual function is most effective in micro-tidal environments (Mediterranean Sea, Baltic Sea and Caribbean) of up to average exposure. However, for the SPBs two main mechanisms in reducing notably wave energy are generated. Wave breaking and the fluid flow through the voids of the structure (Metallinos *et al*. 2016). Beyond basic considerations in technical efficiency, design of SPBs serving not only in just minimizing degradation of the marine ecosystem but rather in its enrichment has become a challenge. Summarizing, the investigation of SPBs design in order to serve as an artificial reef in shallow waters protecting at the same time the coastline forms the core of this research.

As said, the main reason for examining this coastal structure is that it can offer both a certain level of coastline stabilization and a mild, if not positive, intervention to local marine life. Also, it is inherently resilient but further improvement in this area can be achieved. Coastline stabilization can be enhanced by abstracting energy from incoming wave trains. With marine biology issues in concern, the structure's interaction with its biotic environment is multifold:

- SPB's high porosity may support habitation for certain marine flaura and fauna.
- SPB's high permeability through and above the structure allows for better circulation and renewal of the coastal waters in the zone between the coastline and the structure, enhancing thus the nearshore water quality.
- The previous characteristics induce also a more efficient distribution of food for marine life.

In the above framework, where a SPB functions as an eco-hydraulic structure, a solid understanding of its interaction with water waves is vital, especially in rubble mounds with relatively steep slopes, addressed herein, that apparently are more friendly to the environment as occupying less seabed area. In particular the hydrodynamic field inside and around the structure as well as the wave transmission above it will be studied. Pressure and velocities (in three dimensions) will be measured, including turbulence levels, parameters that provide a solid background to marine scientists for their performing of relevant habitation studies. Additionally, the stability of SPBs will be investigated, as development of subpressures leading to dislodgement of rock units on the leeward slope of SPBs has been observed.

1.2. <u>Previous research on SB and positioning of the problem</u>

Several studies examining phenomena around submerged breakwaters (SB) can be found in the literature, including wave transmission, wave-induced set up in the protected area, wave breaking macrofeatures, circulation pattern, wave reflection and wave spectrum modifications. In contrast, the hydrodynamics inside a porous SB is a field of relatively recent research. The response of marine organisms to the presence of SPBs has not yet been in-depth investigated. Hydrodynamic parameters as pore pressures and orbital velocities, inside their permeable body, have been observed to be significant factors when addressing marine life attraction within and around these artificial bars, in terms of, for example, distribution-species biodiversity and abundance. It has been stressed so far that acquiring information on the hydrodynamic field (as maximum wave-induced forces), is important in order to assess such structures' ecological potential along with their technical efficiency (Kontaxi & Memos 2005, Moschella *et al.* 2005). Vital parameters in forming tolerable and proper living conditions for each species may be different but at this point in time it can be reasonably argued that water velocities and pressures are the key hydraulic factors governing marine habitation levels (e.g. Siddon & Witman 2003, Hammond & Griffiths 2004).

Due to the turbulent nature of the hydrodynamic field associated with wave propagation inside and around a SPB, significant deviations from mean values develop. However, most numerical models focus on mean quantities, due to the complexity of the phenomenon that makes numerical simulation a very difficult undertaking. A few models predicting the hydrodynamic field including averaged turbulence terms under wave propagation inside a porous SB have been developed, but their comparison with "un-averaged" experimental data is still limited (Losada *et al.* 1995, Garcia *et al.* 2004, Lara *et al.* 2006, Chan *et al.* 2007, Metallinos *et al.* 2014). However, when considering both shore protection and artificial habitat efficiency, a simultaneous systematic experimental investigation of wave transmission and hydrodynamic field inside and around SPBs seems a promising field of research in the above context.

Using experimental data of Metallinos *et al.* (2014), and recent laboratory experiments conducted by our team it was found that for both hydrodynamic pressure and hydrodynamic velocity measurements as described previously, preliminary analysis of this data showed that deviation of maximum values compared to average quantities is quite significant (Repousis 2016), not taken into account so far though. A typical section, of a model for measuring hydrodynamic velocities follows.

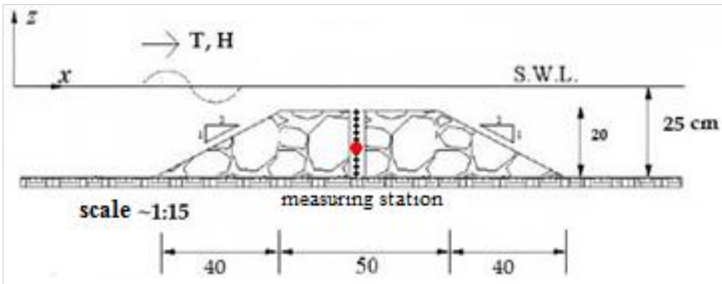

Fig. 1. Layout of a SPB model for measuring hydrodynamic velocities in three dimentions (u_x, u_y, u_z).

In the following figure an example of deviations of recently measured by our team local maxima from their average value is given, for a regular wave scenario, showing a 10 seconds horizontal hydrodynamic velocity timeseries.

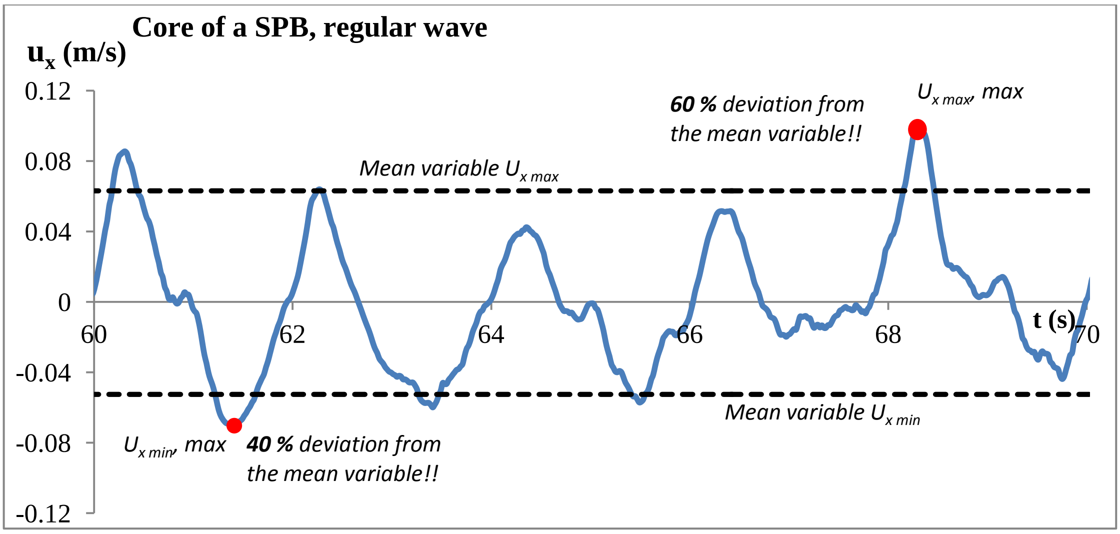

Fig. 2. Timeseries of hydrodynamic horizontal velocity measurement in the core-central section of permeable SB 3D natural model, z=0.10 m from sea bottom, regular wave of T=2.0 s and H=0.03 m (ongoing research). An ADV instrument was used.

2. Research plan–A study of SPBs based on laboratory experiments

2.1. Scientific need for requesting access in the TU Delft's wave flume installations

It has been observed that marine organisms are rather sensitive in deviations from the mean hydrodynamic field. These organisms, especially benthic ones, colonize not only the exposed outer surface of a porous medium but tend to occupy also its interior making advantage of the voids and hollows, if the latter is roomy enough, serving as shelter for their living needs. Therefore, measuring accurately the core hydrodynamic parameters including their turbulent part not only around but and in the insides of a defensive porous medium is of great importance in improving the design of a SPB in order to efficiently attract marine life. Since current numerical models cannot cope with the above requirements, it is evident that the experimental work has to be as accurate as possible and, more importantly, involving scale effects to a minimum level. Working scales 1:10 or larger are thus envisaged. Flumes equipped with random wave generator are desired to represent closer real-life conditions. Systematic laboratory experiments on such scale layouts, considering both technical sufficiency and marine life enhancement, are needed to provide valuable information in determining reliably the applicability range of the experimental results for SPBs, including the potential of supplementing existing impermeable SBs or emerged detached breakwaters, along with their design improvement.

2.2. Scientific need for requesting to the TU Delft's wave flume installations

Experiments on large scale natural models (scale 1:2 to 1:5) that should be performed in an appropriate wave flume will be proposed to be included in the Transnational Access projects of HYDRALAB+. Specifically the CIEM large wave flume (UPC) or the special purpose Scheldt wave flume (Deltares) will be proposed. As, at this point, most of relevant laboratory studies on SPBs are limited in model scales of 1:10–1:20, scale effects investigation should be also included in this research. Considering, that gathering data for more than one experimental layout will apparently amplify the amount and quality of the expected findings, additional experiments for models' scale of 1:10, are foreseen. Access in a appropriate wave flume in the facilities of the Delft University of Technology will be pursued through the Erasmus Programme of the EU, for the academic year 2016-17*.

*for the Erasmus Programme, the deadline for applying for the next academic year 2016-17, is expected to be February, 10 of 2016.

2.3. Methodology

As already mentioned, experiments providing accurate measurements are needed. Recording of the hydrodynamic field including wave transmission in physical models of rubble mound SPBs with steep slopes as well as studying aspects of their stability are the main features to be addressed experimentally. The parameters to be measured are: orbital velocities (in three dimensions), pressures, turbulence levels inside and around the rubble mounds and free surface excursion for a range of wave conditions, slopes and porosities of the model. Laser Doppler anemometry is the optimum technique for measuring velocities, providing adequate accuracy in capturing turbulence fluctuations in a turbulent water flow (Papanikolaou & List 1988), but if not available an acoustic Doppler velocimeter could serve for this purpose satisfactorily. Pressures will be measured through sensors of small measuring surface and water surface elevation with resistant-type wave gauges.

In order to evaluate the SPB's efficiency on both aspects, i.e. coastal protection and marine life support, as well as to understand better the turbulence component's contribution, a comparative study with impermeable counterpart submerged breakwaters will be executed.

Apart from the preliminary measurements with no model over a mildly sloping flume bed, two basic experimental set-ups for the same incoming wave train are foreseen, as summarized in the following steps.

1. Waves over impermeable SB, 2 models of different seaward slope (2 models).

2. Waves over SPB, 2 models of different seaward slope per 2 porosity scenarios (4 models).

A detailed description of the rubble mound models, wave state, measuring equipment and locations can be found in the section "description of the model set-up".

2.4. <u>Proposed analysis of the results - Objectives</u>

Results will be sought considering:

1. Verification of the technical efficiency of SPBs in terms of wave energy abstraction.
2. Provision of quantitative information useful to marine biologists for their ecological assessment of the SPBs in relation to the particular environment they are placed in.
3. Answers to stability issues of SPBs associated with recursive flow in the insides of the structure.
4. Investigation of scale effects, in order to improve the design of real life applications.

Specifically, the main objectives of the analysis are:

i. Calculation of the transmission coefficient (K_t). The two main wave energy dissipation mechanisms, i.e. wave breaking and water flow through the permeable core of the SPB (Metallinos *et al.* 2016) will be considered for parameterizing K_t in conjunction to wave breaker type conditions and sea level, structure's geometry and porosity. Spectral analysis will be applied for measuring wave heights. Scale effects will be considered.

ii. Measurement of the orbital velocities' and pressures' mean ($\bar{u}$, $\bar{p}$) and turbulent (Δu, Δp) components, as well as their height-wise profiles for different sections inside and around the SPB. Based on statistical and turbulence extraction methods, derivation of probability distribution functions describing the turbulent and mean part of these parameters will be achieved. Parameterized predictor semi-empirical formulation on the development of the hydrodynamic dimensions inside and around the SPB will be produced, i.e. $\bar{u}+\Delta u$, $\bar{p}+\Delta p$, preferably in conjunction to variation coefficient. Spectral analysis will be also used for analysing the above quantities. Scale effects will be considered.

iii. Considering that the leeward slope of a SPB may exhibit instability around mid-height due to back flow, as shown in previous studies, damage evaluation methods will be included. Scale effects will be considered.

iv. The proposed experiments will generate a considerable amount of hydrodynamic velocity (3D), pressure (un-averaged), and free surface elevation timeseries inside and around the rubble mounds addressed herein. A data repository for such data in suitable digital form will be identified (along with a relevant annex giving the experimental context and listing the cases tested), accessible for research and education purposes (e.g. by marine biologists and for numerical modeling verification) throughout the scientific community. Commercial exploitation of this data repository may be implemented in the future through development of relevant simulation packages.

The proposed research in TU Delft, is to be scientifically documented through publication, in a relevant peer reviewed journal and a subject related conference. A technical report will be produced and will eventually be incorporated in the doctoral thesis proposed herein.

3. Description of the model set-up in regard to wave flumes in TU Delft facilities

The experimental set-up is adjusted to comply with the irregular wave flume at the Delft University of Technology.

In relevance to the type and number of natural models, i.e. 4 permeable submerged breakwaters (SPB) (2 different seaward slope per 2 porosity scenarios), and 2 impermeable submerged breakwaters (SB) of different seaward slope, 6 models in total (Table 1), made of irregular-angular rock and considering real life applications' geometry and sea state, adjustments for a scale of 1:10 have been applied herein, giving general information for the experimental needs. The proposed experiments are planned so that their overall duration does not exceed 4 weeks (Table 2).

Specifically:

The SBs height (h_s) is set to 0.50 m, crest width (B) to 0.4 m, two different slopes (m) of 1:2 and 1:1.5, 2 porosity (n) scenarios for permeable conditions, i.e. 0.5, 0.42 with mean diameter (D_{50}) of the structure's material varying from 0.12 to 0.07 m. One porosity for the two impermeable SBs, i.e. 0.22 obtained by filling with sand and gravel two of the above SPBs, i.e. the SPB of n=0.5 and m=1:2, and the SPB of n=0.42 and m=1:1.5. As for the sea state, various free board (FB) scenarios are considered, e.g. 0.05, 0.10, 0.15 m. Regular waves with periods (T) ranging from 1.0 to 2.5 s and heights (H) ranging from 0.05 to 0.15 m will be tested. As for irregular waves, spectra (of Jonswap type if possible) with peak periods (T_p) ranging from 1 to 2.5 s and significant wave heights (H_s) ranging from 0.05 to 0.15 m will be used. The SBs' layout and specific measuring locations (5 main sections/stations) are shown in Fig. 3. For each wave scenario, and for SPBs, measurements of orbital velocities (u_x,u_y,u_z) and hydrodynamic pressures ($P_{s)}$ will be taken over sections 1, 2 and 3, in their interior, at least at 12 points (0.05 to 0.08 m intervals along the vertical), whilst for the upstream and downstream sections one point for each one in sea/water level mid-height will be added. For the impermeable SBs the above parameters will be measured around of these structures at least on 7 points at the above 5 sections (red dots in Fig. 3). In relevance to these sections, measurement of water surface elevation (ζ) will be included. Total volume of rock units needed for the SPBs is 1.5 m^3 with additional 0.2 m^3 of sand and gravel for the impermeable SBs.

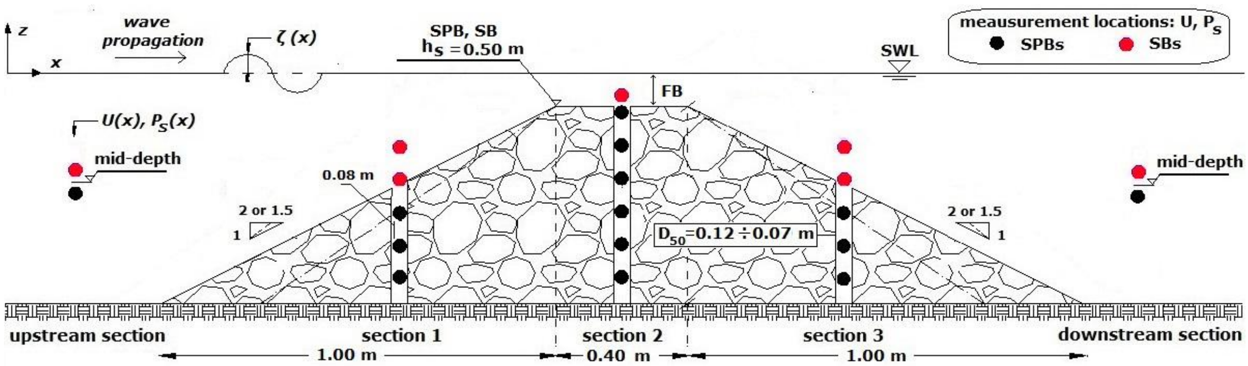

Fig. 3. Layout of the SPBs and impermeable SBs proposed for testing in Delft Technical University facilities, scale 1:5.

Measuring equipment/instruments to be used for the parameters of interest are:

- 1 fiber optic laser Doppler anemometer (fiber optic LDA) for u_x,u_y,u_z. If such instrument is not available, an acoustic Doppler velocimeter (ADV) could be used instead.
- 5 sensors of small measuring surface positioned in the main direction towards the wave flow/stream (capable of continuous monitoring and of high frequency response) for P_s
- 5 Resistant-type wave gauges for ζ.

Macrofeatures of the water surface transformation through video camera recordings is also included. Investigation on damages is to be carried out as well, especially at the lee slope, a feature not yet studied thoroughly.

Adequate sampling duration especially for orbital velocities and pressures should not be less than 5 minutes for each location. Sampling frequency of 50 or 100 Hz is to be set.

Table 1. Rubble mounds' main features (models, under scale 1:5).

SBs: Type	**SPB**				**SB**	
Porosity (n)	0.50		0.42		0.22	
D_{50} (m)	0.12÷0.07		0.12÷0.07		0.12÷0.07 (sand & gravel fill)	
slope	1:1.5	1:2	1:1.5	1:2	1:1.5	1:2
SBs: model code	**SPB 1**	**SPB 2**	**SPB 3**	**SPB 4**	**SB 1**	**SB 2**

Table 2. Experimental Schedule (4 weeks plan).

# week	1	2	2	3	4	4
model code	**SPB 2**	**SPB 1**	**SB 1**	**SPB 3**	**SPB 4**	**SB 2**

Human recourses, during: construction, 2 people; calibration, 2 people; wave testing, 2 or 3 people.

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Abbreviations

SPB: Submerged Permeable Breakwater

FB15: Free Board above the crest of the breakwater 15cm

FB20: Free Board above the crest of the breakwater 20cm

1-R3: 1: refers to the first breakwater model (SPB1). R: refers to regular waves. 3 refers to the 3rd wave scenario (see table below).

1-I2: 1: refers to the first breakwater model (SPB1). I: refers to irregular waves (Jonwap Spectra). 2 refers to the 2nd wave scenario (see table below).

Wave Scenario

- **SPB1**

Model code	Free board (m)	Total water depth (m)	Wave scenario	Wave height H (m)	Wave period T (s)	Significant wave height (m) H_s(m)	Peak period T_p (s)
SPB1	0.15	0.65	1-R1	0.06	1.0		
			1-R2	0.11	1.5		
			1-R3	0.17	2.0		
			1-R4	0.23	2.5		
			1-I1			0.06	1.0
			1-I2			0.11	1.5
			1-I3			0.17	2.0

Model code	Free board (m)	Total water depth (m)	Wave scenario	Wave height H (m)	Wave period T (s)	Significant wave height (m) H_s(m)	Peak period T_p (s)
SPB1	0.20	0.70	1-R5	0.06	1.0		
			1-R6	0.11	1.5		
			1-R7	0.17	2.0		
			1-R8	0.23	2.5		
			1-I4			0.06	1.0
			1-I5			0.11	1.5
			1-I6			0.17	2.0

- **SPB2**

Model code	Free board (m)	Total water depth (m)	Wave scenario	Wave height H (m)	Wave period T (s)	Significant wave height (m) H_s(m)	Peak period T_p (s)
SPB2	0.15	0.65	2-R1	0.06	1.0		
			2-R2	0.11	1.5		
			2-R3	0.17	2.0		
			2-R4	0.23	2.5		
			2-I1			0.06	1.0
			2-I2			0.11	1.5
			2-I3			0.17	2.0

Model code	Free board (m)	Total water depth (m)	Wave scenario	Wave height H (m)	Wave period T (s)	Significant wave height (m) H_s(m)	Peak period T_p (s)
SPB2	0.20	0.70	2-R5	0.06	1.0		
			2-R6	0.11	1.5		
			2-R7	0.17	2.0		
			2-R8	0.23	2.5		
			1-I4			0.06	1.0
			1-I5			0.11	1.5
			1-I6			0.17	2.0

<u>Files and folders included in each wave scenario.</u>

Folders

1. **ADV measurements**
   a. **bottom_14cm_front.dat** : measurements of the velocities in the front hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 14cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (m/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

b. **bottom_22cm_front.dat** : measurements of the velocities in the front hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 22cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (n/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

c. **bottom_30cm_front.dat** : measurements of the velocities in the front hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 14cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (n/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

d. **bottom_14cm_lee.dat** : measurements of the velocities in the lee hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 14cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (n/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

e. **bottom_22cm_front.dat** : measurements of the velocities in the lee hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 22cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (n/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

f. **bottom_30cm_lee.dat** : measurements of the velocities in the lee hole (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf) at 30cm distance from the bottom. The first column is the time (sec), the fourth column is the horizontal velocity (m/s) along the length of the flume, the fifth column is the horizontal velocity (n/s) along the width of the flume, the sixth and the seventh column are the vertical velocities (generally the same, choose the one with higher correlation). Sixteenth, seventeenth, eighteenth and nineteenth are the correlations of the aforementioned velocities respectively.

2. **Calibration**

a. **Calibration WG.xlsx** : calibration of the wave gauges (x axis: volts, y axis: elevation (cm))

b. **EMS Calibration.xlsx** : calibration of the two EMS instruments.

c. **pressure sensors calibration.txt** : calibration of the pressure sensors.

3. **EMS measurements**

a. **EMS Veloc.ASC** : Horizontal velocities collected by two EMS instruments, one on front (see E8 in files SPB1 Layout of experimental setup.pdf and

SPB2 Layout of experimental setup.pdf) of the breakwater and at lee (see E13 in files SPB1 Layout of experimental setup.pdf and SPB2 Layout of experimental setup.pdf) of the breakwater. The first column is the time (sec), the second column is the horizontal velocity (m/s) in the front of the structure and the third column is the horizontal velocity (m/s) at the lee of the breakwater.

b. **EMS Volts.ASC** : Volts measurements referring to horizontal velocities from the two EMS instruments. The first column is the time (sec), the second column are the volts in the front of the structure and the third column are the volts at the lee of the structure.

4. LDV measurements

a. **ldv_volts_1.ASC** : Volts measured from the two outputs of the LDV instrument. The point of measurement is inside the top hole at the middle of the width of the breakwater. The first column is the time (sec), the second column are the volts measured by the **photo cell B** and the third column are the volts measured by the **photo cell A**. (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf)

b. **ldv_unfiltered_1.ASC** : Unfiltered horizontal and vertical velocities for a point inside the top hole at the middle of the width of the breakwater. The first column is the time (sec), the second column is the horizontal velocity (m/s) and the third column is the vertical velocity (m/s). The relationships that transforms the volts to velocities are given in equations (1) and (2).

c. **ldv_filtered_1.ASC** **:** Filtered horizontal and vertical velocities for a point inside the top hole at the middle of the width of the breakwater. The filter that has been applied is a second order low pass Butterworth filter. The first column is the time (sec), the second column is the horizontal velocity (m/s) and the third column is the vertical velocity (m/s). The relationships that transforms the volts to velocities are given in equations (1) and (2).

d. **ldv_volts_out.ASC** : Volts measured from the two outputs of the LDV instrument. The point of measurement is just above the crest, at the middle of the width of the breakwater. The first column is the time (sec), the second column are the volts measured by the **photo cell B** and the third column are the volts measured by the **photo cell A**. . (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf)

e. **ldv_unfiltered_out.ASC** : Unfiltered horizontal and vertical velocities for a point just above the crest, at the middle of the width of the breakwater. The first column is the time (sec), the second column is the horizontal velocity (m/s) and the third column is the vertical velocity (m/s). The relationships that transform the volts to velocities are given in equations (1) and (2).

f. **ldv_filtered_out.ASC** **:** Filtered horizontal and vertical velocities for a point just above the crest, at the middle of the width of the breakwater. The filter that has been applied is a second order low pass Butterworth filter. The first column is the time (sec), the second column is the horizontal velocity (m/s) and the third column is the vertical velocity (m/s). The relationships that transforms the volts to velocities are given in equations (1) and (2).

5. Pressure sensors measurements (SPB1 only)

a. **Volts PS.ASC** : Volts measured from the three pressure sensors that have been placed at the submerged breakwater model. The first column is the time (sec), the second column are the volts measured from the pressure sensor which is placed at the bottom of the front hole of the breakwater, the third column are the volts measured from the pressure sensor which is placed at the bottom of the lee hole of the breakwater and the fourth column are the volts measured from the pressure sensor which is placed at the lee slope of the breakwater and has a distance from the bottom 14cm. These volts in combination with their respective calibration give the dynamic pressure at these three locations . (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf).

b. **PS.ASC** **:** Dynamic pressure measured at three different locations of the submerged breakwater. The first column is the time (sec), the second column is the dynamic pressure (cm) measured from the pressure sensor which is placed at the bottom of the front hole of the breakwater, the third column is the dynamic pressure (cm) measured from the pressure sensor which is placed at the bottom of the lee hole of the breakwater and the fourth column is the dynamic pressure (cm) measured from the pressure sensor which is placed at the lee slope of the breakwater and has a distance from the bottom 14cm. (Figure).

6. **Pressure sensors measurements (SPB2 only)**

   a. **Volts PS.ASC** : Volts measured from the two pressure sensors that have been placed at the submerged breakwater model. The first column is the time (sec), the second column are the volts measured from the pressure sensor which is placed at the bottom of the front hole of the breakwater, the third column are the volts measured from the pressure sensor which is placed at the bottom of the lee hole of the breakwater. These volts in combination with their respective calibration give the dynamic pressure at these two locations . (see SPB1 model & measuring locations.pdf and SPB2 model & measuring locations.pdf).

   b. **PS.ASC** **:** Dynamic pressure measured at two different locations of the submerged breakwater. The first column is the time (sec), the second column is the dynamic pressure (cm) measured from the pressure sensor which is placed at the bottom of the front hole of the breakwater, the third column is the dynamic pressure (cm) measured from the pressure sensor which is placed at the bottom of the lee hole of the breakwater. (Figure).

   c. **Volts PS_slope.ASC** **:** Volts measured from the pressure sensor which is placed at the lee slope of the breakwater and has a distance from the bottom 14cm. The first column is the time (sec), the second column are the volts measured. These volts in combination with their respective calibration give the dynamic pressure at that location (figure).

   d. **PS_slope.ASC** **:** Dynamic pressure measured from the pressure sensor which is placed at the lee slope of the breakwater and has a distance from the bottom 14cm. The first column is the time (sec), the second column is the dynamic pressure (cm) (figure).

7. **Wave gauges measurements**

   a. **WG Volts.ASC** **:** This file contains the volts collected by the 8 (or 9) wave gauges that were placed in the wave flume to measure the elevation of the free surface. For the exact number of wave gauges in each experiment see the file **Schedule of Experiments.xlsx** and for their exact location in the flume the corresponding figure. These measurements in combination with their respective calibration give the elevation of the free surface (cm). The first column represents the time (sec) and the other columns represent the volts measured. The second column corresponds to the wave gauge closest to the wave maker and the last column corresponds to the wave gauge which is further away from the wave maker. (see SPB1 Layout of experimental setup.pdf and SPB2 Layout of experimental setup.pdf)

b. **WG.ASC** **:** This file contains the elevation (cm) of the free surface in different location in front and behind the submerged breakwater. The first column represents the time (sec) and the other columns represent the elevation (cm) measured. The second column corresponds to the wave gauge closest to the wave maker and the last column corresponds to the wave gauge which is further away from the wave maker.

Equations for transforming the LDV volts output to horizontal and vertical velocities

$$\mathrm{U}_{x} = 0.096 * \mathrm{B} - 0.096 * \mathrm{A} \# (\mathbf{1})$$

$$\mathrm{U}_{\mathrm{z}} = 0.096 * \mathrm{B} + 0.096 * \mathrm{A} \# (\mathbf{2})$$

A	:	Volts measured from photocell A
B	:	Volts measured from photocell B