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Wave run-up and overtopping reduction by block revetments with enhanced roughness

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ABSTRACT

Block revetments that are placed in special patterns, in a way that lower (standard) sets are surrounded by sets of higher (protruding) units, have been studied by means of physical model tests. This paper focuses on prediction formulae for the wave run-up and wave overtopping reduction by means of special pattern block revetments. This reduction is significant and leads to lower crest levels of dikes. Reducing or limiting crest levels without reducing safety is often a preferred solution in areas where dikes form an integral part of the existing area and where raising dikes will lead to social drawbacks or a negative impact on the landscape.

1. Introduction

Block revetments are used on dikes to protect the structure against wave action. Most of these block revetments are built up by a matrix of individual concrete blocks placed next to each other. In the past these block revetments were often constructed by natural stones. Nowadays prefabricated concrete units are used. Installation of these artificial blocks is done mechanically. Sets of about 16 to18 units forming approximately a 1 by 1 m panel are installed in one go. The required thickness of a set is usually between 0.2 m and 0.5 m. In general the revetments form a smooth slope by having each set levelled at the top. In order to have the same overtopping discharge, but with a lower crest level, the sets can be placed in special patterns: a rib pattern or a chessboard pattern (see Fig. 1). The special pattern increases the roughness of the block revetment, which leads to reduction of wave run-up and wave overtopping. This study focuses on the development of a prediction method to be able to quantify the effect (reduction factor) of special roughness patterns in placed-block revetments on wave overtopping and wave run-up. Physical model tests have been executed to assess the roughness of the relevant patterns.

The special patterns are constructed by varying the thickness of the sets of blocks that are placed. Higher sets will protrude above the adjacent sets. Rib patterns are formed by having a number of sets with a larger thickness next to each other. They rise above the surrounding sets. Within a rib pattern a standard set height can be used for easier runoff of the water. Chessboard patterns are formed by using the thicker and thinner sets alternatingly and staggered. Also here, an overlap between adjacent rows at one side creates a gap at the other side for easier runoff of the water during wave attack.

1.1. Literature

Wave run-up investigations in which artificial roughness elements have been applied in physical models have been studied over several decades already.

Wassing (1957) gives an overview of wave run-up model investigations performed in The Netherlands. An overview is given to roughness coefficients of different types of slopes, where roughness is formed by steps, ribs, cuboidal elements, shark teeth and more. In these studies regular waves were used.

In Führböter et al. (1989) a study is described where wave run-up reduction was measured by using cuboidal elements covering 1/25 of the total surface. Both regular as irregular waves were used in this study. The wave run-up levels were compared to tests on a smooth asphalt slope and wave run-up formulae.

In Wouters et al. (1994) a similar study is described, although the covering and the protrusion height of the cuboidal elements were varied during the test series. Wave run-up levels were however not directly compared with smooth slope physical model results, but were compared by using a wave run-up formula for smooth slopes, which introduces more scatter.

Schulz (1992) studied scale effects in physical modelling related to wave run-up for smooth and rough slopes. Two model scales are used,

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Fig. 1. Rib pattern Hydroblock® block revetment (left) and chessboard pattern Basalton® block revetment (right).

i.e. scale 1:1 and scale 1:10 and four different slope gradients, i.e. 1:6, 1:8, 1:10 and 1:12. Regular waves were used in this study. The study showed that the scale effects decreased for steeper slopes. By extrapolating the trend line in the graphs scale effects related to wave run-up will become relatively small for steep slopes 1:2–1:4.

In Szmytkiewicz et al. (1994) the effect of wave run-up reduction was studied for irregular waves. Physical model tests were performed with amongst others rough slopes build up out of either cuboidal elements or ribs. The run-up level of the rough slopes was compared with smooth slopes. It was concluded that positioning of the roughness above water provides a better reduction of run-up. Furthermore, the slope length, where roughness is applied should be larger than 50% of the wave run-up level of the smooth slope for getting the best reduction effect. It also shows that the effect of roughness increases, when the height of the protruding element increases.

In all these previous studies the roughness coefficient was determined by comparing the wave run-up between smooth and rough slopes. In the present study, this will be done by comparing wave overtopping discharges. Not only the position of the roughness elements on the roughness coefficient will be investigated but also the effect on the roughness coefficient over a range of overtopping discharges, including large overtopping discharges will be studied. Also next to rib patterns a dense roughness pattern i.e. a chess board pattern (equivalent to cuboidal elements with covering of 1/2 of the surface) will be used in this study. Table 1 gives an overview of results of the former investigations in comparison to this study.

2. Physical model tests

Physical model tests have been performed in one of the wave flumes at Deltares, the Scheldt Flume. The wave flume is 55 m long, 1 m wide and 1.2 m deep. The piston-type wave board is equipped with active reflection compensation, which means that the motion of the wave board compensates for reflected waves preventing them to re-reflect at the wave board towards the model. Also second order wave steering is available, meaning that the second order effects of the first higher and first lower harmonics of the wave field are taken into account in the wave board motion, which reduces the generation of unwanted spurious waves. Irregular waves based on the JONSWAP spectrum have been used in the physical model tests. Also double-peaked spectra have been used. Wave conditions were measured by arrays of four wave gauges at about two wave lengths from the wave board and at the toe of the structure. The analysis has been based on the measurements of incident waves at the toe. By using the method of Zelt and Skjelbreia (1992), time series of the waves were separated into incident and reflected waves. From the measured incident wave energy spectra, the spectral significant wave height H_{m0} and the mean energy wave period $T_{m-1,0}$ ($T_{m-1,0} = m_{-1}/m_0$ with $m_n = {}_0\int^{\infty} f^n\, S(f)\, df$ with $n = -1$ or 0) were obtained. In Van Gent (1999) and Van Gent (2001) the mean energy wave period was found to appropriately describe the influence of non-standard wave energy spectra on wave run-up and wave overtopping. This was verified by the double-peaked test runs, see also Fig. 22.

2.1. Model set-up

The basic configuration consisted of a 1:3 (Vert.:Horiz.) slope with a chessboard pattern above the waterline. The crest level was fixed per slope and the size of the chessboard pattern, from the top down to the water level, was changed. The water depth was varied, when the size of the chessboard was changed, i.e. the water depth increased when the size of the chessboard decreased. The standard and protruding (higher) sets were schematized by concrete cubes with ribs of 5 cm in

Table 1
Overview of results of former investigations and this study.

Reference	Type of waves	Roughness value rib pattern	Roughness value cuboidal pattern	Assessed by comparing	Model scale	Slope angle	Roughness density
Wassing (1957)	Regular	0.55 for most ideal pattern	0.85 for 1/9 cover	2% wave run-up levels	Small scale approx.1:20	1:3.5	Not available
Führböter et al. (1989)	Irregular	Not tested	0.88 ± 0.06 for 1/25 cover	2% wave run-up levels	Large scale	1:6	0.040-0.044
Wouters et al. (1994)	Irregular	Not tested	Depending on Iribarren number; on average 0.80 for both 1/9 as 1/25 cover	2% wave run-up levels	Large scale	1:4	0.015-0.051
Szmytkiewicz et al. (1994)	Irregular	Depending on Iribarren number or ratio protrusion vs. wave height; on average 0.86–0.90	Depending on Iribarren number and roughness position; varying between 0.65 and 0.80	2% wave run-up levels	Small scale approximately1:20	1:4	0.01–0.06 for rib patterns; cuboidal patterns not available
This study	Irregular	Depending on several parameters; on average 0.76	Depending on several parameters; on average 0.76	Mean overtopping discharges	Small scale approx.1:20	1:3 1:4	0.012–0.094