Damage to rubble mound breakwaters – Extracting design guidance from 'old' test data

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Abstract

The aim of this project has been to expand the concept of the CLASH overtopping database to include information on armour damage to rubble mound breakwaters and seawalls using a similar format. Response data have been entered under different armour types, and further distinction is made between different parts of the structure. To date, 2000 tests have been entered and proved the capacity of the database to summarize different rubble mound structures. This database can describe damage progression, thus improving analysis of lifetime risks for armoured rubble mound structures. Initial trials demonstrate the potential utility as a tool for validation and pre-design analysis.

Background

Rubble mounds are the most frequently used type of breakwater; protecting ports, beaches and shorelines. Despite the number of structures around the world, and the experience gained, rubble mound breakwaters and sea walls still suffer damage. The most effective tool to design / analyse / optimise these structures is the hydraulic physical model. Most model test data are, however, only used for the original site specific purpose, when the data could be used to develop new design guidance. This project explores the development of a tool to re-use those data.

One of the main purposes of the CLASH research project (De Rouck *et al.*, 2002) was the collection of data on overtopping discharges, structures and sea-states into the CLASH database (Van der Meer, 2008). This was done primarily to train the CLASH Neural Network generic overtopping prediction tool (Gent et al, 2004), as well as providing a searchable database on overtopping. These tools have become industry standard methods for those analysing the overtopping performance of coastal structures.

Objectives

The target of this new project has been to expand the concept of the CLASH database to include information on armour damage to rubble mound breakwaters and seawalls. It uses a generally similar format as the full CLASH overtopping database, but is extended to include the damage to, and description of, different parts of rubble mounds structures.

The main objectives of the new database development were to schematise each test structure and test condition using a limited number of new parameters. The project then explored how the database could be used on its own to answer typical design questions. By using simple filtering techniques, test data were selected where previously tested structures were similar to the structure under investigation. This can be used for the assessment of existing structures, or for the preliminary design of new ones.

Scope

This research project has taken anonymous rubble mound damage measurements from wave flume and wave basin models, used the 31 parameters of the existing CLASH database and introduced 29 new ones, to describe additional structural features and responses of the armour. To date, response data have been entered under different armour unit types, including rock (38%); double layer concrete armour (55%); and single layer armour (8%).

The database distinguishes between different parts of the structure. including: toe; principal armour; crest and rear armour. So far 2000 tests have been collected and have described more than 4000 responses. Among these are damage to the principal armour, toe damage, overtopping discharges, damage on the rear slope and displacement of the crown wall. In devising the database it was anticipated that many model tests only recorded a single response, or would not include some of the structural components considered in the database. The design of the database therefore allowed tests to be entered with partial, or zero, responses, thus increasing the total volume of data available for analysis.

Literature

The EurOtop Manual (Pullen *et al.*, 2007) discusses most of the published literature on overtopping up until 2007. For damage / response characteristics of rubble mound structures, research has been investigated and published my many contributers. Hudson (1953, 1959) and Van der Meer (1988b) have presented the main design advice for rock armour layers. Brorsen, Burcharth and Larsen (1975), and Van der Meer (1988a) carried out studies for cubes and Tetrapods. Burcharth and Liu (1993) analyzed Dolos, Accropodes (Van der Meer, 1988a; Burcharth, 1998), Core-locs (Melby and Turk, 1997; Turk and Melby, 1997). Additionally, Jensen (1984), Burcharth (1993) and others studied damage to the breakwater roundheads, whilst Van der Meer (1993, 1995) developed a generic approach for the toe analysis with rock armour. The stability of the crown wall is analysed for sliding and overturning by Jensen (1983) and Bradbury (1988) to give an empirical formulae for horizontal wave load.

Existing CLASH Parameters

The 31 CLASH parameters include the deep water and toe wave conditions, the geometry of the section, the overtopping responses and information about the reliability of the test and complexity of the structure schematization. The Reliability Factor is determined by several influence factors: the precision of the measurements of the overtopping test; the capabilities of the test facility used to perform the tests; or the estimations that had to be made because values were missing. The Complexity Factor gives an indication of the complexity of the tested structure. With the chosen structural parameters, it is possible to represent most structures generically with some specific approximations required. The Reliability and Complexity Factors range from 1, for the simple data, to 4, for the complex cases. The hydraulic and geometric parameters are summarised in Box 1 and Figure 1.

Box 1 CLASH parameters

- Generic (3): Test identification number, Reliability Factor (RF), Complexity Factor (CF).

- Hydraulic (9): Wave incidence (β), wave height (H_{m0}), period ($T_{m-1,0}$, T_p and T_m) in deep waters and at the toe of the structure.

- Structural (17): h, h_t, B_t, γ_f, $cota_d$, $cota_u$, Rc, B, h_h, $tan\alpha_B$, B_h, A_c, G_c, see figure 1. Depth at deep water conditions (h_{deep}), slope of the bed in front of the structure (m) and approximation of the global slope of the structure including ($cota_{incl}$) or excluding ($cota_{excl}$) the berm.

- Responses (2): mean overtopping discharge (q), and number of waves overtopping (N_{wo}[%]).
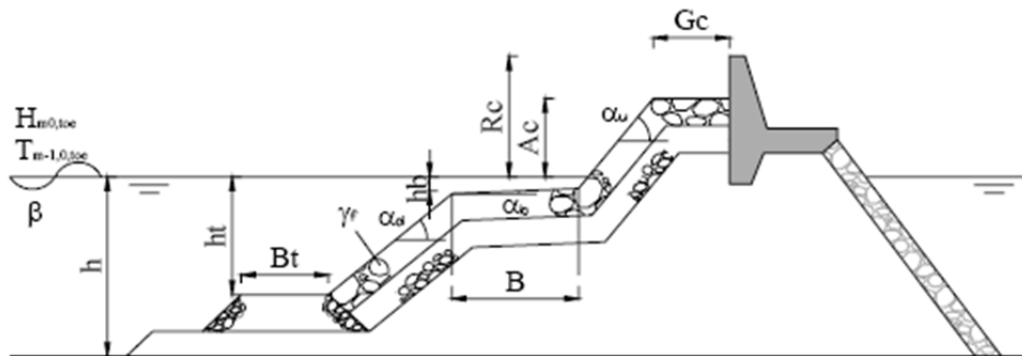

Figure 1 Description of some of the parameters included in the CLASH database, (CLASH Workpackage 8)

New Parameters

The parameters originally identified during CLASH are sufficient to be able to describe wave overtopping processes. To describe the parameters involved in damage responses more information is needed. In particular, type, size and density of the units need to be defined for all parts. Mass is also included, as it is the most used parameter for armour size description.

Roundheads and curved / angled trunk sections will generally need 3D wave basin models. The stability of these kinds of structure is perceptively different than plain 2D trunk sections, and the interlocking of the armour is different in curved surfaces. Diffraction effects can vary the incident waves, and the orientation of each section adds to the number of response definitions that could be categorised. Moreover, defining the size / length of any part of the trunk, or roundhead sector angle, affects the damage description for the area under investigation.

The permeability of the armour layer will have partially been considered in the overtopping roughness / permeability parameter (γ_f), but a specific permeability parameter is needed for the stability analysis of the main layer (Van der Meer (1988b), the packing density has similarly been included.

Overtopping response is generally not affected by test duration, but armour damage is related to the number of loadings. The number of waves during the test for analysing progressive armour damage is therefore included. A summary of these new parameters is given below in Box 2.

Box 2 New parameters for the rubble mound breakwaters database.

- Generic (3): Section type, length of the structure (Ls), angle of the roundhead sector (θ_s)

- Hydraulic (1): Number of waves during the test for analysing progressive damage

- Structural (18): armour type, mass, density and nominal diameter (Dn_{50}) for the main layer, toe and rear slope. Permeability (P) and packing density (Φ) for the main layer, the slope for the rear armour and the unit height, section area and the concrete density for the crown wall.

- Responses (7): damage level at the beginning and the end of every test for the main layer, toe and rear slope. The sliding distance for the crown wall.

The damage analysis has focused on different parts of the section, such as external main layer, rear slope, toe and crown wall. Considering that not all data are available for all tests, a value of -1 has been used for responses without available data, thus differentiating between responses of null overtopping or damage and responses with no available data. The damage value can be given in different damage parameters. N_d is the percentage of units displaced between ±1.5 H_{m0}. N_{od} is the number of displaced units (N_{displ}) related to a width of one nominal diameter (D_{n50}), and the length of the structure (B_s). S_d is the dimensionless damage parameter, obtained from the eroded area (A_e) and the nominal armour diameter.

The dimensionless eroded area, S_d, is used for rock armour, and the N_{od} value for concrete units. This involves the seaward and the leeward slopes. For the toe the N_{od} value is taken.

$$N_d = N_{displ}^{(*)} / N_{total} \cdot 100 \tag{1}$$

$$N_{od} = N_{displ} / (B / D_{n50}) \tag{2}$$

$$S_d = A_e / D_{n50}^{\;2} \tag{3}$$

$^{(*)}$ units displaced between ±1.5 H_{m0}

Since data are collected under different damage measurement parameters, some investigation has focussed on coupling the descriptions above. An easy transformation between N_d and N_{od} can be found, but not between N_{od} and S_d. That proposed in the Coastal Engineering Manual (CEM) and the Rock Manual is:

$$N_{od} = G(1 - n_v)S_d \tag{4}$$

where G is a grading coefficient (G = D_{n85}/D_{n15}), and n_v is the porosity.

The CEM suggests using the approximation to $S_d = 1.4 \cdot N_{od}$. Recent tests run during this project suggested that the coefficient 1.4 can be higher. More tests will be run to check and improve its accuracy, but this description allows for a cross comparison of the three damage parameters

In order to assess the damage history, damage is measured after every test part. In this way, there are initial and final damage parameters for every part of the structure. Damage at the crown wall is set as its farthest displacement. Horizontal displacement is measured until the crown wall unit reaches and rotates about the rear of the structure, and large displacements with the wall falling to the rear side are considered failures of the structure.

Comparing data with generic formulae – Progressive damage

The majority of the individual test results in the database are grouped according to test series. In most cases the armour layer was not repaired between the individual tests in the series, meaning that each test started with some initial damage. Results of this type allow damage progression in multiple storms to be investigated.

There are a number of formulae for predicting the stability of armour layers on rubble mound structures, but few address the problem of damage progression. Specifically, few studies have been conducted to predict damage progression on rock armour layers in varying wave conditions over the service life of a structure.

Van der Meer (1998b) proposed an adaptation of his single storm formulae to calculate the damage caused by more than one storm event. Melby (2001) provided an equation (5) that predicts the evolution of rubble mound damage over multiple storms:

$$S_{n+1} = S_n + 0.025 \cdot N_s^5 \frac{t_{n+1}^b - t_n^b}{T_m^b} \tag{5}$$

Where S is equivalent to the damage parameter S_d, N_s is the stability number, T_m is the mean wave period, t_n is the time step, and b is an empirical parameter. Melby's formula is based on laboratory tests with a limited range of validity including: depth-limited wave conditions, an armour slope of 1:2, a surf similarity parameter, ξ_m, of between 2 and 4, and a notional structure permeability, P, of ≤ 0.4.
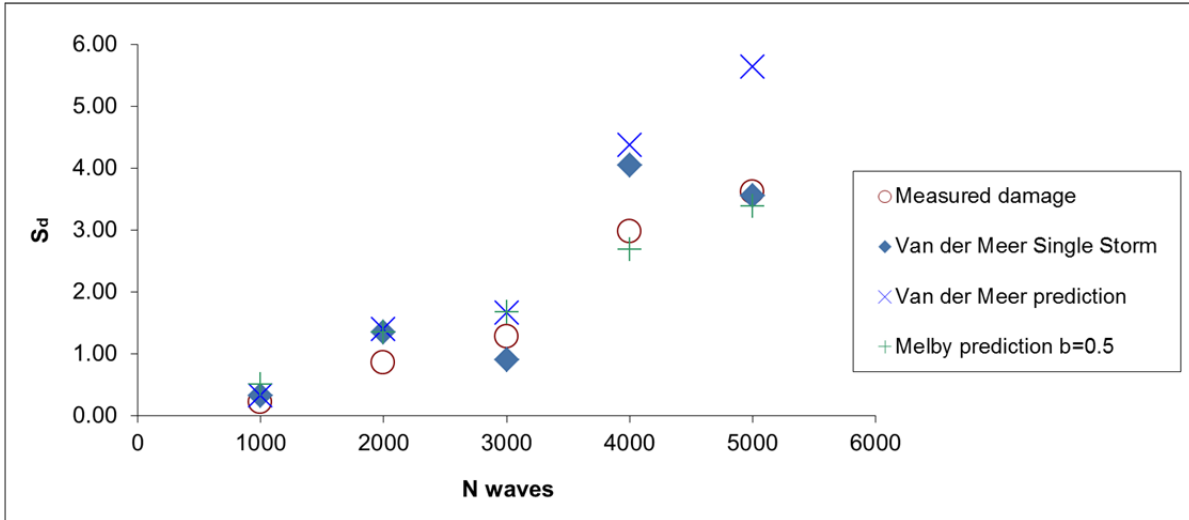
Figure 2 Comparison between measured and predicted damage progression

In Figure 2 and in Table 1, the results of Van der Meer's and Melby's prediction methods for progressive damage are compared with the results of Van der Meer's single storm method and data extracted from the database for rock layers with a mass of M_{50} = 1.0t. In this case, the data extracted from the database are in reasonable agreement with the results of the generic prediction methods.

Comparisons of this sort will enable the database user to predict damage progression, providing information that may be needed for planning armour monitoring and repair programmes.

Table 1 Comparison between measured and predicted damage.

h (m)	H_s (m)	N_{od}	S_d (N_{od}*1.4)	Van der Meer (Single storm)	Van der Meer (Dam. evol)	Melby (Dam. evol)
5.38	1.26	0.15	**0.21**	0.32	**0.32**	**0.51**
5.38	1.69	0.61	**0.85**	1.35	**1.39**	**1.35**
2.97	1.47	0.91	**1.27**	0.90	**1.66**	**1.68**
5.44	1.91	2.12	**2.97**	4.05	**4.37**	**2.68**
3.88	1.81	2.58	**3.61**	3.55	**5.63**	**3.39**

Extracting design guidance – Toe Mounds

The database can be interrogated for different purposes, including the extraction of design guidance in areas where the current literature provides limited information. If a user has a specific structure in mind, the database can be used to compare it with similar structures on which a response has already been measured. An example is the prediction of damage to a toe mound.

Van der Meer et al. (1995) formulated an equation (6) relating the stability number ($N_s=H_{m0}/\Delta D_{n50}$), damage ($N_{od}$), toe depth ($h_t$) and rock nominal diameter (D_{n50}):

$$\frac{H_{m0}}{\Delta D_{n50}} = \left(0.24 \frac{h_t}{D_{n50}} + 1.6 \right) \cdot N_{od}^{0.15}$$

(6)

This equation is plotted against three sets of physical model results extracted from the database in Figure 3. In some cases the damage is higher than the predicted level and in others it is lower. Users of the database can use its filtering functions to identify the structure which most closely resembles their design, thus refining the prediction of damage.
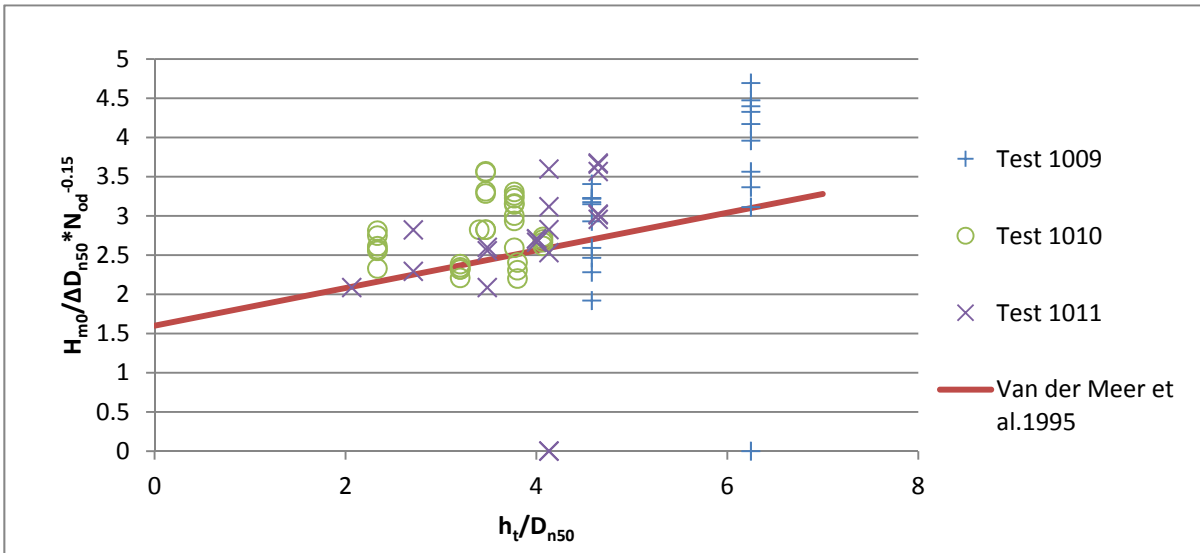

Figure 3 Comparison between measured and predicted rock toe damage

There is no equivalent equation for the prediction of damage to toe mounds made up of Antifer units, but Burcharth et al (1995a) adapted the Van der Meer formulation to parallelepiped concrete blocks. The adapted equation is as follows:

$$\frac{H_s}{\Delta D_{n50}} = \left(0.4 \, \frac{h_t}{\Delta D_{n50}} + 1.6 \right) \cdot N_{od}^{0.15} \qquad (7)$$

Equation 7 is plotted in Figure 1 along with three sets of data from tests of Antifer toe mounds extracted from the database. As with the rock toe data plotted in Figure 3, some of the damage is higher than the predicted level and some is lower, so the database user should use the filtering functions to determine which data set is most appropriate.
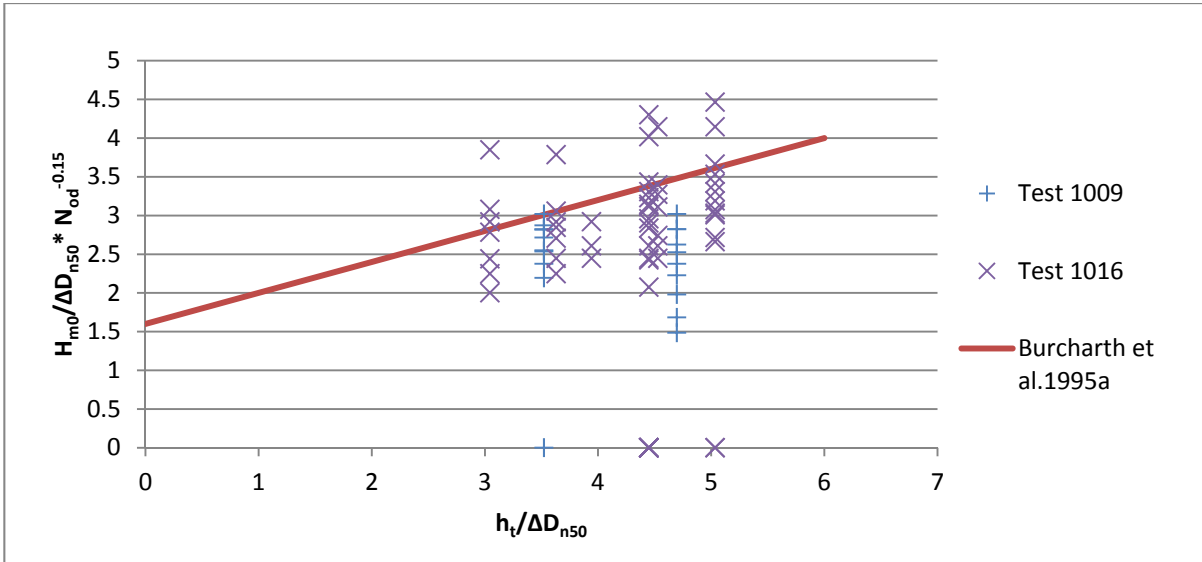
Figure 4 Comparison between measured and predicted Antifer toe damage

The new database also allows damage results to be plotted against other parameters. For example, assuming a fixed toe armour unit type, size and toe depth, the user can explore the relationship between damage and wave height. Figure 5 shows an example for a 15t Antifer toe mound, plotting the damage response (N_{od}/H_{m0}) against loading (N_s/h_t) and determining a trend line.
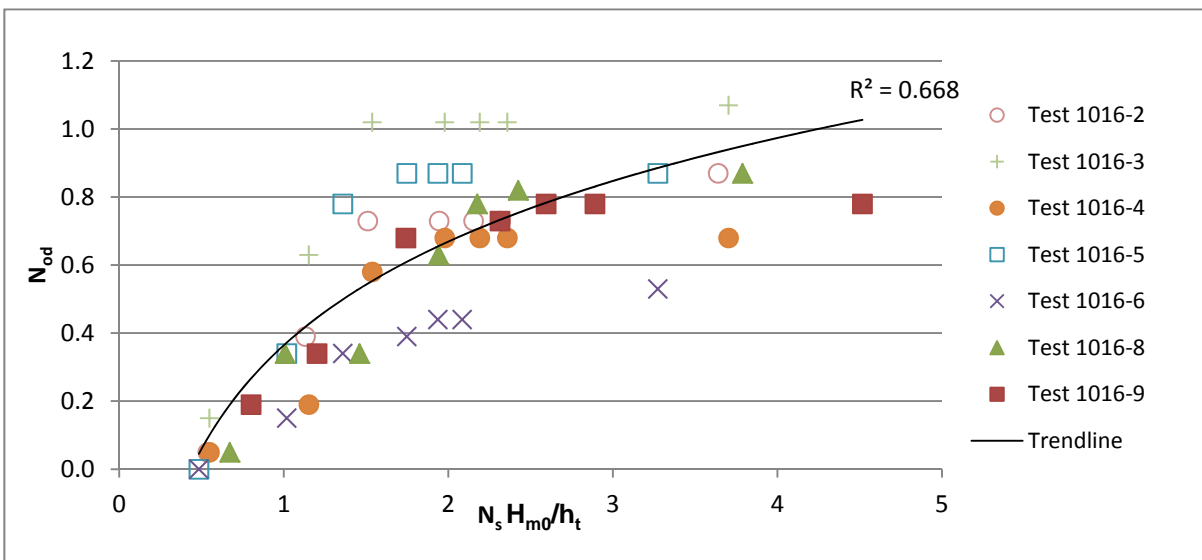

Figure 5 Comparison between toe damage response and loading (15t Antifer toe mound)

Further Work

Initial trials have demonstrated the potential of the database to validate empirical predictions of damage progression in multiple storms. These trials will be expanded to assist in developing a tool for the analysis lifetime risks for armoured rubble mound structures.

Quantitative prediction tools will be developed for the design and analysis of structural elements for which the existing literature provides limited guidance. The possibility of crest damage being analysed is being examined, but as this subject is not often investigated separately in physical model tests the quantity of data available may be limited.

More data from HR Wallingford's archives will be added, and data from other institutions will be collected. A version of the database is expected to form the basis of an artificial neural network prediction method.

Acknowledgements

Notation

Δ	= dimensionless density parameter.	[-]
Φ	= packing density of the layer	[-]
A_c	= armour crest freeboard of a structure = height of armour in relation to swl	[m]
A_e	= dimensionless eroded area of the section of a rubble mound structure	[-]
b	= dimensionless empirical parameter in the Melby formulae for damage evolution	[-]
B	= berm width, measured horizontally	[m]
B_h	= berm width of horizontally schematised berm	[m]
B_s	= width of the flume or length of the stretch of the structure	[m]
CF	= complexity-factor of a structure section	[-]
h	= water depth at the toe of a structure = water depth just before a structure toe	[m] h_{deep}
	= water depth at deep water conditions	[m]
h_t	= water depth on the toe of a structure	[m]
h_b	= water depth on the berm of a structure (negative value if berm above swl)	[m]
D_{n50}	= nominal diameter of rock	[m]
G_c	= crest width of a structure	[m]
H_s	= significant wave height	[m]
H_{m0}	= estimate of significant wave height from spectral analysis = $4\sqrt{m_0}$	[m]
N_{displ}	= number of displaced units in a hydraulic test	[-]
N	= number of incident waves	[-]
$P=$	= permeability of the structure	[-]
q	= mean overtopping discharge per meter structure width	[m³/m/s]

R_c	= crest freeboard of a structure	
	= height of 'wave return point' of a structure in relation to swl	[m]
RF	= reliability-factor of overtopping test = 1, 2, 3 or 4	[-]
t	= time variable	[s]
T_m	= average wave period derived from time domain analysis	[s]
T_p	= peak wave period derived from spectral analysis = $1/f_p$	[s]
$T_{m-1,0}$	= average wave period derived from spectral analysis = m_{-1}/m_0	[s]
α	= slope angle	[°]
$α_B$	= angle that sloping berm makes with horizontal	[°]
β	= angle of wave attack with respect to the normal on a structure	[°]
$γ_f$	= correction factor for the roughness & permeability of a structure	[-]

References

Bradbury, A P, Allsop, N W H and Stephens, R V (1988). *Hydraulic performance of breakwatercrown walls.* Report SR 146, Hydraulics Research, Wallingford.

Brorsen, M, Burcharth, H F and Larsen, T (1975). "Stability of dolos slopes". In: B L Edge (ed), *Proc 14th int conf coastal engg, Copenhagen, 1974.* ASCE, New York.

Burcharth, H F (1993). *The design of breakwaters.* Internal report, Aalborg University.

Burcharth, H F and Liu, Z (1993). "Design of dolos armour units". In: B L Edge (ed), *Proc 23rd int conf coastal engg, Venice, 1992.* ASCE, New York.

Burcharth H. F., Frigaard, P., Uzcanga, J., Berenguer, J. M., Madrigal, B. G., and Villanueva, J. (1995a). " Design of the Ciervana Breakwater, Bilbao," *Proceedings of the Advances in Coastal Structures and Breakwaters Conference,* Institution of Civil Engineers, Thomas Telford, London, UK.

Burcharth, H. F., Jensen, M. S., Liu, Z., van der Meer, J. W., and D'Angremond, K. (1995b). "Design Formula for Tetrapod Breakage," *Proceedings of the Final Workshop, Rubble Mound Breakwater Failure Modes*, Sorrento, Italy.

Burcharth, H. F., Christensen, M., Jensen, T. and Frigaard, P. (1998). "Influence of Core Permeability on Accropode Armour Layer Stability," *Proceedings of International Conference on Coastlines, Structures, and Breakwaters '98,* Institution of Civil Engineers, London, UK.

U.S. Army Corps of Engineers, (2011). "Coastal Engineering Manual" 1110-2-1100, Washington D.C., USA. (in 6 volumes).

CIRIA, CUR, CETMEF (2007). "The Rock Manual. The use of rock in hydraulic engineering" (2nd edition), C683, CIRIA, London.

CLASH. "Crest Level Assessment of coastal Structures by full scale monitoring, neural network prediction and Hazard analysis on permissible wave overtopping". Fifth Framework Programme of the EU, www.clash-eu.org.

De Rouck J.; Allsop W. ; Franco L ; van der Meer J.; Verhaeghe H. (2002), "Wave overtopping at coastal structures: development of a database towards up-graded prediction methods". Proceedings of the 28th Int. Conf. on Coastal Engineering (ASCE), Cardiff, UK.

Gent, van M & Pozueta, B. van den Boogaard, H. & Medina, J (2004) *CLASH D42 Final report on generic prediction method* http://www.clash-eu.org/results.

Hudson, R Y (1959). "Laboratory investigations of rubble mound breakwaters". *J Waterways & Harbors Div, Am Soc Civ Engrs*, vol 85, no WW3, Paper no 2171, pp 93–121.

Hudson, R Y (1953). "Wave forces on breakwaters". *Trans Am Soc Civ Engrs*, vol 118, pp 653–674.

Jensen, O J (1984). "A monograph on rubble mound breakwaters". Danish Hydraulic Institute, Hørsholm.

Jensen, O. J. (1983). "Breakwater Superstructures," *Proceedings of Coastal Structures '83*, American Society of Civil Engineers, New York.

Melby JA (2001) *Damage development on stone armoured breakwaters and revetments*, ERDC/CHL CHETN-III-64, US Army Engineer Research and Development Center, Vicksburg, MS.

Melby, J A and Turk, G F (1997). *Core-Loc concrete armor units: technical guidelines.* Technical Report CHL-97-4, US Army Corps of Engineers, Washington DC].

Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A, Schuttrumpf, H. & van der Meer, J.W. 2007 EurOtop: European Overtopping Manual, , www.overtopping-manual.com

Turk, G. F., and Melby, J. A. (1997). "CORE-LOC7 Concrete Armor Units: Technical Guidelines," Miscellaneous Paper CHL-97-6, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Van der Meer JW, Verhaeghe H, Steendam, JG. (2008) "The new wave overtopping database for coastal structures", Coastal Engineering (2008).

Van der Meer, J W, D'Angremond, K and Gerding, E (1995). "Toe structure stability of rubble mound breakwaters". In: J E Clifford (ed), *Advances in coastal structures and breakwaters.* Thomas Telford, London.

Van der Meer, J W (1993). "Conceptual design of rubble mound breakwaters". Publication no 483, WL|Delft Hydraulics, Delft.

Van der Meer, J W (1988a). "Stability of cubes, tetrapods and Accropode". In: *Design of breakwaters. Proc conf Breakwaters '88, Eastbourne.* Thomas Telford, London.

Van der Meer, J W (1988b). "Rock slopes and gravel beaches under wave attack". PhD thesis, Delft University of Technology, Delft. Also Delft Hydraulics publication no 396.