# **CHAPTER 161**

## PREDICTION OF WAVE REFLECTION FROM ROCK STRUCTURES: AN INTEGRATION OF FIELD & LABORATORY DATA.

Mark A. Davidson<sup>1</sup>, Paul A.D. Bird<sup>2</sup>, David A. Huntley<sup>1</sup>, and Geoff N. Bullock<sup>2</sup>.

**ABSTRACT:** An empirical predictive scheme for wave reflection from rock island breakwaters is derived from a multiple regression analysis of a large data set (780 data points) which includes both laboratory and full-scale measurements. The large parameter space embraced due to the inclusion of both laboratory and field data leads to a robust solution for the prediction of wave reflection. The resulting equation expresses the reflection coefficient as a function of a number of dimensionless parameters which can be identified with specific physical processes. These include wave breaking, dissipation due friction and turbulence induced by structural roughness, and transmission into and through the breakwater.

### SYMBOLS

- $d_t$  Depth at the toe of the structure relative to the still water level.
- D Significant armour diameter = $(W_{50}/\rho)^{1/3}$
- $H_i$  Significant wave height
- $K_r$  Frequency averaged reflection coefficient =  $\sqrt{S_r df} \sqrt{S_i df}$
- f Frequency
- $L_o$  Deep water wavelength
- *P* Notional permeability (Van der Meer, 1988)
- *r* Multiple regression correlation coefficient
- *R* Reflection number =  $\frac{L_{b}^{2}d_{l} \tan \beta}{H_{l}D^{2}}$ , (Davidson *et al.*, 1996)
- $S_i$ ,  $S_r$  Incident and reflected spectral estimates
- $W_{50}$  Median mass of rock armour
- $\beta$  Average structure slope
- ρ Density of rock armour
- $\sigma$  Standard error in multiple regression analysis
- ξ Iribarren number = tan  $β / \sqrt{H_i / L_o}$

<sup>&</sup>lt;sup>1</sup>Institute of Marine Studies, University of Plymouth, Drake Circus, Plymouth, Devon, PL4 8AA, UK.

<sup>&</sup>lt;sup>2</sup>School of Civil & Structural Eng., University of Plymouth, Palace Court, Palace St., Plymouth, Devon, PL1 2DE, UK.

## **INTRODUCTION**

Much attention has been focused on the prediction of wave reflection from rubble mound structures (e.g. Seelig and Ahrens 1981, Postma 1989, Van der Meer 1992, Allsop and Channell 1989, Hughes 1995, Davidson *et al.* 1994,). A recent review can be found in Davidson *et al.*, 1996. Most predictive schemes for wave reflection have been based on empirical relationships involving the Iribarren number derived from laboratory experiments. Whilst the Iribarren number describes well the form of breaking waves (Battjes, 1974) and hence dissipation due to breaking, the processes of turbulent dissipation due to the roughness of the structure and transmission into and through the structure are not obviously related to the Iribarren number and have normally been accounted for through additional empirical coefficients. The combined effects of the empirical nature of these equations and the inevitable limited parameter space have meant that these solutions are rarely universal particularly at full-scale. This problem is compounded by potential scale effects and inconsistencies in the method of analysing wave reflection.

Davidson *et al.*, 1996, collected full-scale data seawards of a rock island breakwater both before and after the addition of more armour to the seawards face of the structure. This modification was designed to reduce the slope of the structure hence enhancing structural stability and ameliorating wave reflection. Conventional plots of reflection coefficient versus Iribarren number showed the pre- and post- modification data sets as two distinct populations. The failure of the Iribarren number to condense both data sets on to a single curve severely limits the accuracy of predictive schemes which express wave reflection as some function of  $\xi$ .

For these full-scale data an improved parameterization of wave reflection was derived in terms of a dimensionless reflection number R where:

$$R = \frac{L_o^2 d_t \tan \beta}{H_i D^2} = \xi \left( \frac{L^{3/2} d_t}{H^{1/2} D^2} \right) \tag{1}$$

and;

$$K_r = \frac{0.635\sqrt{R}}{41.2+\sqrt{R}}$$
 or  $K_r = 0.151R^{0.11}$  (2)

It can be seen from Equation 1 that R revises the relative weighting of wave height and wavelength in the Iribarren number and includes other physically significant parameters such as the depth at the toe and the characteristic armour diameter.

Whilst equations based on R provide and excellent prediction of wave reflection (r=0.87,  $\sigma = 0.055$ ) for these full-scale data (within the parameter space of the measurements) poor predictions were found for laboratory data. These inconsistencies can be explained in part due to the potential scale effects which may significantly contribute to differences between the field and laboratory data (up to 10%, Shimada *et al.*, 1986), but more significantly to the empirical nature of Equations 1 and 2 and the limited parameter space of the data from which they were derived.

This contribution aims to minimise problems associated with limited parameter space by integrating both laboratory and field investigations. The advantage of this approach is that although it is empirical the resulting predictive scheme is remarkably robust over a broad range of scale and incident wave conditions.

The problem of predicting wave reflection is essentially the solution to the energy balance equation including the processes of wave reflection, dissipation (due to breaking, turbulence and friction) and transmission (both through and over the structure). Therefore an accurate solution for the reflection coefficient intuitively should include parameters which relate (even if only empirically) to each of the most significant processes involved (Figure 1). Thus, solutions based on a single parameter like the Iribarren number which only obviously relate to the process of dissipation due to breaking are only likely to provide a ubiquitous solution for wave reflection where breaking is the dominant process.



Figure 1: Schematic diagram illustrating the dominant processes affecting wave reflection and some of the parameters associated with them. Here  $E_i$  is the incident wave energy.

## DATA BASE

Data analysed here includes laboratory tests from Seelig and Ahrens (1981), Allsop and Channell (1989), Postma (1989), and field data from a natural rock island breakwater, both before and after a modification of the seawards slope of the structure (Davidson *et al.*, 1996). The reader is referred to the original references for details of these experiments. A summary of each of these experiments including the ranges of specific dimensionless variables have been summarised in Table 1. All available information from each experiment was entered into a data base. For each experiment information was available on; wave height, deep/shallow water

Author (s)	Field or Lab. F / L	$\frac{H_i}{L_o}$	cot β	$\frac{D}{H_i}$	$\sqrt{\frac{D}{L_o}} \cot \beta$	P	$\frac{d_t}{L_o}$	H <sub>i</sub> H <sub>b</sub>	ξ	K,	Analysis Method / No. of Gauges
Seelig & Ahrens, 1981	L	0.005- 0.050	2.5	0.52- 1.67	0.12- 0.57	0.04	0.015- 0.369	0.49- 0.11	1.8- 7.5	0.115- 0.561	Goda & Suzuki, 1976 / (3)
Allsop & Channell, 1989	L	0.003- 0.040	1.50- 2.50	0.31- 0.94	0.08- 0.29	0.04 - 0.1	0.075- 0.342	0.06- 0.29	2.0- 11.7	0.170- 0.700	Goda & Suzuki, 1976 / (3)
Postma, 1989	L	0.002- 0.057	1.50- 3.00	0.16- 0.87	0.07- 0.65	0.1- 0.6	0.02- 0.289	0.09- 0.95	0.7- 8.9	0.122- 0.738	Kajima, 1969 / (2)
Davidson et. al., 1996	F	3x10 <sup>-4</sup> -0.036	0.82	1.19- 23.39	0.02- 0.30	0.6	0.003- 0.360	0.03- 0.46	10.0- 113.	0.263- 0.734	Gaillard et al., 1982 / (3)
Davidson et. al., 1996	F	8x10 <sup>-4</sup> -0.021	1.55	0.98- 9.60	0.09- 0.51	0.6	0.007- 0.074	0.08- 0.68	3.0- 26.5	0.274- 0.600	Gaillard et al., 1982 / (3)

wavelength, structure slope, armour diameter, permeability, the number of armour layers and depth at the toe of the structure. In all cases wave overtopping was not significant.

Table 1: A summary of the data sets, parameter space and analysis techniques used in this study.

## RESULTS

A multiple regression analysis technique was used in order to determine the relationship between the frequency averaged reflection coefficient and various non-dimensional variables which are identifiable with of specific physical processes affecting wave reflection. The results of this analysis are summarised in Table 2. A number of parameters were tested, and the impact of each parameter on the wave reflection was assessed through the correlation coefficient (r) and standard error ( $\sigma$ ). If the addition of a parameter led to a reduction in the standard error and an increase in the correlation coefficient then the parameter was assessed as being significant and left in the equation for further analysis. If however, the addition of a parameter lead to an increase or no significant change in the standard error (or rise in correlation coefficient) it was neglected in subsequent tests.

Parameters which were found to significantly improve predictions of wave reflection are shown in Figure 1 and listed below:

- 1) The Iribarren number which characterises the form of the breaking waves and hence relates to the dissipation of wave energy due to breaking.
- 2) A relative diameter term  $(D/H_i)$ , referred to here as the transmission parameter) which Van der Meer, 1992 has shown empirically to be related to wave transmission.
- 3) A roughness parameter  $(\sqrt{\frac{D}{L}} \cot \beta, \text{Seelig \& Ahrens, 1981})$ . The effective roughness of the structure increases both as the armour diameter increases relative to the wavelength of the waves, and as the slope of the structure is reduced. Gentler slopes give rise to increased energy dissipation due to the effect of turbulence and viscosity of water close to the sea bed.

4) Van der Meer's Permeability parameter (Van der Meer, 1988).

mean water level) is reduced.

5) The relative toe depth  $\left(\frac{d}{L_{\sigma}}\right)$ . The exact physical significance of this parameter in the process of wave reflection is not clear. The effect of dccreasing the depth at the toe will ultimately lead to breaking offshore of the structure, thus reducing reflection. Conversely, in the case of a fully permeable breakwater transmission of wave energy through the structure may increase (reducing wave reflection) with increasing  $d_t$  as the width of the breakwater (at

The relationship between  $K_r$  and some of the variables tested was non-linear and an improved correlation could be obtained if the logarithm of the variable was taken prior to carrying out the regression analysis. This is true if the effect of a given variable on wave reflection diminishes as the value of that variable increases. The Iribarren number provides a good example of this. When waves are steep enough to break (low Iribarren numbers,  $\xi < 4$ ) wave reflection increases proportionately with the Iribarren number through the continuum of breakers from the extremes of spilling to surging. However, when waves cease to break further increase in wave reflection produces no change in the reflection coefficient.

No. of Variables	$\xi = \frac{\tan\beta}{\sqrt{H_i/L_o}}$	$\frac{D}{H_i}$	$\sqrt{\frac{D}{L_o}} \cot \beta$	P	$\frac{d_t}{L_o}$	с	r	σ
	lribarren Number	Trans- mission	Roughness	Permeability	Rel. toe depth	y-axis Intercept	Correlat- ion coeff.	Standard error
1	0.02					0.203	0.622	0.1218
1	0.442*					0.065	0.828	0.0873
2	0.585*	-0.027				0.024	0.884	0.0727
3	0.354*	0.014	-0.596			0.288	0.904	0.0667
3	0.282*	-0.013	-0.383*			-0.071	0.910	0.0645
4	0.327*	-0.012	-0.388*	-0.192		-0.058	0.931	0.0568
5	0.298*	-0.011	-0.321*	-0.191	-0.358	0.049	0.943	0.0521

**Table 2:** Multiple regression analysis statistics showing parameter coefficients, correlation coefficients and standard errors. Note that \* sign indicates that the logarithm of the variable has been taken prior to the regression analysis.

Table 2 gives a number of predictive equations for wave reflection based on these data. The number of parameters and the accuracy of the equations increasing towards the bottom of the table. Also given are the linear, multiple regression coefficients. The best predictor of wave reflection is given at the bottom of this table (in bold type) and yields the following equation:

$$K_r = 0.298 \log(\xi) - 0.011 \left(\frac{D}{H_i}\right) - 0.321 \log\left(\sqrt{\frac{D}{L_o}} \cot\beta\right) - 0.191P - 0.358 \left(\frac{d_i}{L_o}\right) - 0.049$$
(3)

Predicted and observed reflection coefficients from Equation 3 are shown in Figure 2.



Figure 2: Predicted and measured reflection coefficients for both field and laboratory data.

### DISCUSSION

Inspection of Table 2 shows that the accuracy of the predictive scheme for wave reflection is significantly improved (as indicated by the correlation coefficient and standard error statistics) through the addition of each of the 5 variables. It should be noted that several other combinations of variables (not shown here) were tested and shown not to significantly improve (or even worsen) predictions of  $K_r$ . Equation 3 provides a remarkably robust solution for wave reflection given the exceedingly broad parameter space covered by the 780 data points. The equation includes parameters which have physical significance in the processes of wave dissipation due to breaking ( $\xi$ ), turbulence /friction induced by structural roughness  $\left(\sqrt{\frac{D}{L_o}} \cot\beta\right)$ , and transmission through and into the breakwater  $\left(\frac{D}{H_i} & \mathcal{E} P\right)$  (see Figure 1). The relative toe depth  $\left(\frac{d}{L_o}\right)$  is also seen to significantly improve reflection estimates although the physical significance of this parameter is less clear.

The excellent correlation between observed and predicted reflection coefficient for these data is shown in Figure 2. The correlation coefficient and standard error for the data shown in Figure 2 are 0.943 and 0.0521 respectively. A conservative estimate of  $K_r$  for which 98% of the data does not exceed is given by adding two times the standard error (=0.1042) to Equation 3.

Inspection of Figure 2 shows that there is evidence of some systematic deviation of the reflection estimates for low measured values of  $K_r$  (<0.18). These discrepancies probably arisc due to errors in analysis techniques which are sensitive to bias due to signal noise for low

reflection conditions. However, these deviations are of little significance since reflected wave energy is less than 4% of the incident value in this area of the graph.

Correlation coefficients and standard errors associated with field data alone (r=0.815) are poorer than those associated with the laboratory data (r=0.962). This is perhaps to be expected to some extent since there are a greater number of variables associated with the field situation. For example, non-uniformities in the wave field, oblique wave approach and irregularities in the structure may all contribute to uncertainties in  $K_r$ . However, Davidson *et al.*, (1996) conducted numerical tests indicated that errors in estimates of  $K_r$  due to oblique wave approach and low signal coherence between sensor pairs are generally low (error in  $K_r < \pm 0.09$ ) for these data. It is valid therefore to consider other potential reasons for the increased scatter in the predictions associated with the field data.

Table 1 shows that the field data embraces a considerably broader range of Iribarren numbers. In particular the field data extends to much higher Iribarren numbers where waves of low steepness surge (un-broken) against the structure. In this regime dissipation due to wave breaking is of little importance and the processes of transmission and dissipation due to turbulence and friction promoted by the roughness of the structure most significantly affect the energy balance (Figure 1). It is under these highly reflective conditions that there is considerably more scatter in the estimates of reflection coefficient (Figure 2). This may indicate that the processes of transmission, and dissipation due to structural roughness are less well represented by Equation 3 than those associated with wave breaking. This hypothesis is supported by the fact that the data from the second deployment which has the reduced slopc (tan  $\beta = 1/1.55$ ) and lower Iribarren numbers shows less scatter than the data collected in more reflective conditions in the first deployment (tan  $\beta = I/0.82$ ).

It should also be noted that Equation 3 is some what biased towards the model scale tests since the ratio of laboratory to field data analysis here is of the order 3:1. Hence if the solution given by Equation 3 is more suited to the laboratory data, scale effects may significantly contribute to the scatter in the field data. More field data is required to clarify this issue.

Although Equation 3 provides a good and versatile estimate of wave reflection within a very broad parameter space, an improved prediction of wave reflection (r=0.87,  $\sigma$ =0.055) at full-scale is given by Equations I and 2 within the range of field measurements summarised in Table 1.

Figure 3 shows a series of plots illustrating the relative impact of each of the terms in Equation 3 on the overall estimate of reflection across the measured parameter space. In these figures the range of the value of each term in the field and laboratory is represented by lines joined by open circles and crosses respectively. Also shown are the 95% confidence intervals for each parameter. Inspection of Figure 3 shows that the dissipation, transmission and roughness parameters have a first order effect on wave reflection with relatively small contributions ( $\Delta K_r < 0.15$ ) from the permeability and relative depth terms.



Figure 3: Figure showing the relative influence of each of the five terms in Equation 3 on the reflection coefficient estimate over the field and laboratory parameter space. Note that the field and laboratory range for each variable are indicated by lines joining open circles and crosses respectively.

The relative impact of each term in Equation 3 on the reflection estimate is in some cases very different for the field and laboratory data. For example the Iribarren number is very significant across the full range of the laboratory data but has little impact on  $K_r$  for much of the field data which corresponds to high Iribarren numbers and non-breaking waves. Conversely, the transmission parameter has a much more significant effect on  $K_r$  for the field data. Table 2 (line 3) shows that the addition of the transmission parameter to the equation significantly increases the correlation coefficient ( $r=0.622\rightarrow 0.828$ ). Plots of predictions based on the Iribarren number alone (not included here) show the field and laboratory data as two distinct series. Inclusion of the transmission term effectively brings together the field and laboratory data. This emphasises the importance of the effects of wave transmission which perhaps have not been fully appreciated previously from laboratory experiments which have a much more limited range in Iribarren number.

It should also be mentioned that there may be several other parameters which are significant in the process of wave reflection which have not been considered in Equation 3. In particular, Van der Meer (1992) sites the relative crest freeboard height  $R_d/H_i$  as being an important factor influencing wave transmission. Unfortunately statistics for  $R_c$  (height of the structure crest above mean sea level) were not available for all data and therefore the effect of  $R_d/H_i$  could not be tested here. Other significant factors might include the effective breakwater width corresponding to the still water level and wave frequency. Thornton and Calhoune (1972) found also that wave transmission was a frequency dependent process with lower frequency wave propagating more readily through the structure. The effect of wave overtopping and strongly oblique wave approach are also not accounted by Equation 3.

#### CONCLUSIONS

Multiple regression analysis of this large data base (780 data points) including both field and laboratory data provides a robust predictive scheme for wave reflection and an insight into the relative importance of parameters affecting this process. The results of this study can be summarised as follows:

1) An accurate prediction of wave reflection (r=0.943,  $\sigma$ =0.0521) over the sampled parameter space (Table 1) is given by:

$$K_r = 0.298 \log \left(\xi\right) - 0.011 \left(\frac{D}{H_i}\right) - 0.321 \log \left(\sqrt{\frac{D}{L_o}} \cot \beta\right) - 0.191P - 0.358 \left(\frac{d_i}{L_o}\right) - 0.049$$
(3)

A conservative estimates which of wave reflection not exceeded by 98% of data is given by addition of two times the standard error (0.1042) to this equation. Equation 3 is valid for normally incident waves and no overtopping.

- 3) In Equation 3 the Iribarren number (relating to dissipation through breaking), transmission and roughness parameters exert a first order effect on wave reflection estimates with smaller contributions ( $\Delta K_r < 0.15$ ) from the permeability and relative depth terms.

- 4) More field data is required in order to test the validity of Equation 3 at full-scale and the potential importance of scale effects.
- 5) For conditions corresponding to the parameter space covered in the field experiment (Davidson *et al.*, 1996, see Table 1) Equations 1 and 2 are recommended for the prediction of wave reflection.

### ACKNOWLEDGEMENTS

The authors would like to extend their thanks to the Engineering and Physical Sciences Research Council (EPSRC, Grant no. GR/H17183) and MAST (Grant no. MAS2-CT92-0030) for funding this research. We would also like to acknowledge the technician support in the School of Civil & Structural Engineering and Arun District Council for their co-operation in the field.

#### REFERENCES

- Allsop and Channell, 1989, Wave reflection in harbours. Reflection performance of rock armoured slopes in random waves. Hydraulics Research Report OD 102.
- Battjes, J.A., 1974, Surf similarity. Proc. 14th Coastal Eng. Conf., vol. 1, pp 466-480.
- Davidson, M.A., Bird, P.A.D., Bullock, G.N. and Huntley, D.A., 1994, Wave reflection: Field measurements, analysis and theoretical developments, Proc. Coastal Dynamic, '94 Barcelona, pp 642-654.
- Davidson, M.A., Bird, P.A.D., Bullock, G.N. and Huntley, D.A., 1996, A new non-dimensional number for the analysis of wave reflection from rubble mound breakwaters., Coastal Engineering, 28 pp93-120.
- Hughes, S.A. and Fowler, J.E., 1995, Estimating wave induced kinematics at sloping structures, J. of Waterway, Port, Coastal and Ocean Engineering, pp 209-215.
- Postma, G.M., 1989, Wave reflection from rock slopes under random wave attack, Unpub. M.Sc. thesis, Delft Univ. of technology, 106pp.
- Seelig, W.N and Ahrens, J.P., 1981, Estimation of wave reflection and energy dissipation coefficients for beaches revetments and breakwaters., Technical paper, Tp 81-1, Dept. of the Army Coastal Eng. Research Centre, Kingman Building, Fort Belvoir, Virginia 22060.
- Shimada, A., Fujimoto, T., Saito, S., Sakikiyama, T. and Hirakuchi, H., 1986, Scale effects on stability and wave reflection regarding armour units. Proc. 20th Coastal Eng. Conf., Vol. 3, pp2238-2252.
- Thornton, E.B. and Calhoun, R.J., 1972, Spectral resolution of breakwater reflected waves. Proc. ASCE J. of waterways, Harbours and Coastal Eng., Vol. 98, WW4.
- Van der Meer, J.W., 1988, Rock slopes and gravel beaches under wave attack. Ph.D. thesis, Delft Univ. of Technology. Also: Delft Hydraulics Communication No. 396.
- Van der Meer, J.W., 1992, Conceptual design of rubble mound breakwaters. Proc. of a short course on the design and reliability of coastal structures, 23rd Conf. Coastal Eng., Venice. pp447-510.