NUMERICAL EVALUATION OF STABILITY METHODS FOR RUBBLE MOUND BREAKWATER TOES

S.P.K. Verpoorten¹, W.J. Ockeloen² and H.J. Verhagen³

1. LievenseCSO, PO Box 3199, 4800 DD Breda, The Netherlands, Tel. +31-88-910 2433, SVerpoorten@LievenseCSO.com
2. Van Oord Nederland, PO Box 8574, 3009 AN, The Netherlands, Tel. +31-88-826 0000, Wouter.Ockeloen@VanOord.com
3. Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Coastal Engineering, PO Box 5, 2600 AA, Delft, The Netherlands, Tel. +31-15-278 5067, H.J.Verhagen@tudelft.nl

ABSTRACT

Since 1977 dedicated studies are made to the stability of rubble mound breakwater toes under wave attack. A large number of stability methods is available, but prediction accuracy is low and validity ranges are too small for use in practice. In this research the decoupled model approach is used to evaluate prediction capacity of existing toe stability methods. The approach uses numerical model IH-2VOF for a prediction of stability. Review of the model showed that it is highly sensitive to stone properties and that turbulence was not modelled. Under the assumption that the latter is not of major importance, calibration of motion formulae against physical measurements and evaluation of the stability methods was performed. The decoupled model approach appeared to give good stability predictions. Validity limits of the stability methods seemed to be too strict. A ranking of stability methods was made. Future validation should confirm the results before incorporation in design manuals.

1. INTRODUCTION

Many studies have been made on the stability of the toe of rubble mound breakwaters. They resulted in a large number of design formulae and methods. It is generally known that accuracy is low and that the validity range of the input parameters is very limited. A design formula which is both accurate and practical for design purposes is desired by contractors and engineering companies. In the past decade efforts have been made to filter out such a formula. Unfortunately this resulted quite often in a new formula which in its turn did not fit all research data.

In 2008 a new and more fundamental approach is presented in Baart (2008) which gives promising results. In this research Baart's method is implemented and tested by means of computational fluid dynamics model IH-2VOF. Prediction capacity of existing toe stability methods is then reviewed against numerical results.

This research project was conducted as a Master's thesis project at Delft University of Technology, in close cooperation with dredging contractor Van Oord from The Netherlands. An extended report can be found at <http://resolver.tudelft.nl/uuid:3de220e6-34cb-4f0b-b432-791b82f96902>.

2. REVIEW OF LITERATURE

Literature study was conducted to get grip on the issues at hand. The sixteen most recent studies have been reviewed. Physical model tests are up to now most often used to fit a design method. An analytical description would be academically interesting, but it often requires assumptions and simplifications. When it comes to complex situations it could become impossible to solve. Common problems with the empirical and analytical stability methods are that a lot of scatter is present, validity ranges are very narrow and the definition of damage varies. Fitted formulae often lack physical background for dimensionless parameters. Influence of e.g. foreshore steepness or wave length is not always included, although research by others has proven that they do influence stability. It is clear that empirical and pure analytical stability methods impose a lot of issues and considerations. A better approach for toe stability would be useful.

A new approach towards toe stability was investigated by Baart (2008). It will be called the *decoupled model approach*. It is a two-step model, in which one attempts to decouple the relation between boundary conditions (hydraulic and structural) and a prediction of toe stability, see Figure 1. In its first step it determines the local hydraulic conditions right above the toe. These conditions are mainly determined by the horizontal flow velocity, but other measures may be included. The second step then transforms these local hydraulic conditions into a prediction of stone motion, by using e.g. a general formula for stone motion.

Note that the stability outcome is a prediction of motion rather than damage. The first is a more subjective and qualitative measure, though it is used in this research because of the following reasons:

- Damage definition varies between studies and cannot be made uniform.
- Damage is a stochastic and time-dependent process, which is not yet easy to model with numerical methods.
- Even though motion is a subjective criterion, work by Baart (2008) and Dessens (2004) show that it is a workable method for toe stability.

Figure 1. Principle sketch of the decoupled model approach

- For engineering practice it is a comprehensible and practical measure to work with. Designers and contractor clients often choose for a conservative value for the damage number, which corresponds to the subjective levels “hardly any damage” or “insignificant damage”.

3. RESEARCH STRATEGY

In this research the steps of the decoupled model approach were followed. Firstly the IH-2VOF-model was tested to verify its applicability for this study. Secondly the model was used to simulate a large number of toe stability experiments, for which the hydraulic conditions above the toe are determined. General formulae for motion were then calibrated by comparison with physical damage measurements. By this the formulae gave a prediction of motion per case simulated. Finally these predictions were compared with predictions by the existing stability methods. Figure 2 shows the research steps in a diagram.

Figure 2. Diagram of research strategy

4. EVALUATION OF IH-2VOF

4.1. Model description

IH-2VOF is a computational fluid dynamics model developed by the Spanish Environmental Hydraulics Institute “IH Cantabria”. It is a 2D Volume of Fluid model representing a wave flume, see Figure 3. It solves the Reynolds-averaged Navier-Stokes equations and uses volume averaging and the Forchheimer equations to account for porous flow. Turbulence is modelled with the $k-\varepsilon$ model. It is able to simulate on model and prototype scale. An extensive GUI is available for pre- and post-processing. The model version used was distributed on July 28th 2014.

The model is built to run on a single computer. A large number of simulations was needed for this research and therefore the use of a computer cluster is useful. The computer rooms at the faculty of Civil Engineering of Delft University of Technology were used for this purpose. In total 401 different cases have been run in batches.

Figure 3. Visualisation of a horizontal velocity field as calculated with IH-2VOF

Figure 4. Outline of the NK09 breakwater layout

4.2. Evaluation

To verify whether IH-2VOF was suitable for this research, a simple evaluation of the model was performed. Physical toe stability experiments by Nammuni-Krohn (2009) (in short NK09) were simulated numerically. An outline of the model is given in Figure 4. After simulating the cases with IH-2VOF, qualitative and quantitative comparison between numerical and physical results was performed. Also analytical solutions were added for reference purposes. Focus was on the extrema in horizontal flow velocity above the toe.

First action taken was to perform convergence tests, in order to find optimal computational grid dimensions. During these tests it was discovered that the $k-\varepsilon$ turbulence model did not function properly by an error in the computer code.

This issue imposed a limitation on this research. An assumption had to be made, which reads that *turbulence has a negligible effect on the hydraulic conditions near the toe structure. We cannot verify whether this assumption is valid and therefore great care must be taken when using results from this paper in further work or for design purposes.*

Since evaluation of the model is not the main subject of this paper, only the relevant conclusions will be given. Numerical performance is very good: requested waves are well present in the model results. But generally inconsistent results were found, though. Relative flow velocity differences between numerical and physical velocities often went up to 50%. Reflection coefficients varied to a large extent. It is expected that the lack of model details (layout, stone properties, etc.) was the cause. No well-founded advice on applicability of the IH-2VOF model to this research could be given, based on the NK09 dataset.

A solution was found in work by Peters (2014a) and Peters (2014b). In this research toe stability experiments were performed both physically and numerically, using IH-2VOF for the latter. A major difference is that he directly measured stone properties, i.e. porosity and Forchheimer coefficients, for his structure.

Peters found much better correspondence between physical and numerical measurements than was found for the NK09 dataset. Relative flow velocity errors were in the range of 5-20% with standard deviation of about 10-15%.

From Peter's work it was concluded that (1) the NK09 dataset is not appropriate for evaluation of IH-2VOF due to lacking data and various inevitable estimations on model properties, and (2) that IH-2VOF is appropriate to model flume experiments on breakwater toe stability *given* the availability of accurate dimensions and stone properties. For this research the latter imposed no problem: estimated values are used in both IH-2VOF and the toe stability methods. No discrepancies between model and method parameters will then exist.

5. EVALUATION OF STABILITY METHODS

5.1. Model

Evaluation of the existing toe stability methods was done by simulating a set of physical toe stability experiments with IH-2VOF. The model chosen is the one by Ebbens (2009) (in short Eb09) because of the large number of different cases (296), the occurrence of shallow water conditions in 78% of the cases and the variation in foreshore slope. An outline is given in Figure 5.

Figure 5. Outline of the Eb09 breakwater layout

All cases were run with IH-2VOF on the computer cluster. Due to time restrictions only 185 cases were finished completely. It is not expected that simulating the rest of the cases would add much relevant information to the evaluation hereafter.

5.2. Motion formulae

In the second step of the decoupled model approach a general formula for stone motion is required to transform the local hydraulic conditions above the toe into a prediction of motion. From literature study four formulae were selected, being Izbash (1930), Rance and Warren (1968), Dessens (2004) and Peters (2014b). They will be abbreviated to Izb30, Ran68, Des04 and Pet14 respectively.

5.3. Calibration

Contrary to stability methods, the motion formulae should be applied over all time steps and over all toe wave gauges. It takes some time to dislocate a stone, so it would be nonsense to consider a case having motion if the criterion is passed a single moment in all these steps. A practical approach is then to measure the percentage of motion indications in time and position, and calibrate them to the original (physical) Eb09 damage recordings. Determination of stability is then performed by defining a motion percentage:

$$\text{motion-}\% = \frac{\sum_x \sum_t \text{motion at } (x_i, t_i)}{\sum_x \sum_t 1} \cdot 100\%$$

Motion then occurs when the motion percentage is larger than or equal to the calibrated motion percentage.

For every Eb09 case a physical damage recording was reported, i.e. a N_{od} value. By imposing a limit on this value one can state per case whether considerable motion has occurred in the flume. The limit chosen was taken as $N_{od;c} = 0,6$. Now a graph can be made as shown in Figure 6. Every dot represents a single case with its physical N_{od} -value and its numerical motion percentage. The green dots in area B and C together represent an almost ideal situation. Two lines are drawn at the chosen calibration levels. Area B and C contain points in which motion is given equally by formula and measurement. Note that area C mostly contains points created by initial instabilities. For points within area A the motion formula would give an overestimation of motion; area

D consequently represents underestimation, which is dangerous. Calibration was made by shifting the horizontal division line such that the amount of points in area B and C were maximised.

Figure 6. Principle of calibration.
The graph contains arbitrary values.

Figure 7. Calibration of Izb30

Figure 8. Calibration of Ran68

Figure 9. Calibration of Des04

Figure 10. Calibration of Pet14

Table 1. Calibration results

	Calibrated motion-%	Joint equal prediction
Izb30	55%	75%
Ran68	0.1%	78%
Des04	8%	72%
Pet14	0,6%	84%

In Figure 7 to Figure 10 the simulation results are shown. The calibrated motion percentages with corresponding joint equal prediction values are given in Table 1. All together most formulae perform reasonably well in calibration. Agreement of more than 70% was obtained, which is a sign that the decoupled model approach is capable of predicting stone motion. No perfect prediction is present, though. Overestimation of motion is present in all formulae, but this would not lead to an unsafe design. Issues with the definition of the measurement level for velocities might be a cause.

Ran68a and Pet14 were considered as best predictors; evaluation of stability methods is made based on these two formulae. They have highest joint equal prediction and a low amount of cases in which motion is underestimated (leading to an insecure design). Furthermore they have very low motion percentages, so almost no calibration is required. This makes them more robust and perhaps more generally applicable.

5.4. Results

Now calibration had given us the percentages determining motion for the four motion formulae, evaluation was continued. The stability methods were given a critical value for their damage parameters, based on recommended values for “start of damage” or “hardly any damage”. Motion has been recalculated for all cases. Joint equal prediction between all stability methods and the two motion formulae was calculated. The results are shown on the number axis in Figure 11. The stability method abbreviations are described in Table 2.

Before drawing conclusions it is interesting to have a look at the amount of cases for which the stability methods are valid, i.e. where the parameters are within the validity ranges. This is given in Table 3. The validity range is quite low for some methods. It is then questionable how robust this top three is, since their validity is low and statistical sensitivity accordingly high.

Evaluation was repeated while simply ignoring the validity limits. The results are shown in Figure 12. In general one can conclude that the range of performance values becomes narrower. VdM91, Ger93 and VdM98 are still at the top, but with slightly lower agreement (about 75% instead of 80%). However now VGe14 and Mut14 are joining the top. Based on these results one could argue that the stability methods might have too strict validity limits.

To further verify these results a sensitivity analysis has been performed on the chosen critical values for the damage or stability parameter ($N_{od,c}$ etc.). In general sensitivity to the damage parameters chosen is rather low. Mostly a maximum of 5 to 10% deviation was found.

Figure 11. Joint equal prediction of stability methods

Figure 12. Joint equal prediction of stability methods, with ignored validity limits

Table 2. Abbreviated names of stability methods and their originating reports

VdM91	Ger93	Bur95	VdM98	Say07
Van der Meer (1991)	Gerding (1993)	Burcharth and Liu (1995)	Van der Meer (1998)	Sayao (2007)
Baa08	Ebb09	Mut13	VGe14	Mut14
Baart (2008)	Ebbens (2009)	Muttray (2013)	Van Gent and Van der Werf (2014)	Muttray et al. (2014)

Table 3. Percentage of cases simulated for which the stability method is valid

VdM91	Ger93	Bur95	VdM98	Say07
29%	41%	100%	41%	100%
Baa08	Ebb09	Mut13	VGe14	Mut14
76%	66%	96%	3%	100%

6. CONCLUSIONS AND RECOMMENDATIONS

From this research on toe stability the following conclusions can be drawn:

- IH-2VOF is capable of modelling toe stability experiments, as long as information on stone properties is present. If lacking, one can still use the model for benchmarking different breakwater layouts, as long as the stone properties are kept equal.
- The effect of turbulence modelling on toe stability is unknown.
- The decoupled model approach is considered appropriate to determine toe stability. High correspondence was found between physical and numerical measurements. It is capable to predict stone motion for the Eb09 cases with accuracy up to 84%. It enables to model complex breakwater geometries
- Calibration of motion formulae is possible by comparing numerical prediction with original damage measurements in the lab. The approach is generally applicable, though current knowledge implies that recalibration of formulae to each new dataset is mandatory. The motion formulae by

Rance and Warren (1968) and Peters (2014b) probably do not need calibration and are therefore interesting for design purposes.

- Validity ranges of existing stability methods might be too strict.
- A definition of motion rather than damage is a workable concept in toe stability research.
- Before using evaluation results for design purposes, calibration results should be verified by reviewing other datasets.

Recommendations for future research are the following:

- Model other toe stability tests to verify calibration results and to study performance of the toe stability methods in these cases.
- Investigate the effect of turbulence.
- Obtain better estimators for the Forchheimer coefficients.
- Verify where and how long the stability criterion of the motion formulae is exceeded.

ACKNOWLEDGEMENTS

This research would not have been possible without valuable support by prof.dr.ir. Wim Uijttewaai, dr. Barbara Zanuttigh and dr. Markus Muttray. Their comments and suggestions were greatly appreciated.

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