Major uncertainties in the prediction of bed evolution behind a groyne
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Abstract

The simulation of the bed evolution around a groyne was investigated by linking a developed sediment transport model (STM-2D) to the FAST-2D flow model. The present state of sediment transport relationships, in particular the relationships for calculating bed-shear stress and bed-load transport rate, was evaluated as an essential step for the computational simulation of the groyne's performance. Sever difficulties were encountered in the development and validation of this model—nevertheless, substantial progress was made. This paper discusses the major uncertainties in the simulation process. It is concluded that a modified bed-shear stress relationship is not sufficient for simulating realistically the bed features behind the groyne. The development of a conceptual method for calculating bed-shear stresses around groynes is a priority and recommended for future studies.

1 Introduction

Groynes are generally oriented transverse to the flow direction, extending from the bank into the channel. The main function of the groynes is to reduce the current along the stream bank, thereby inducing deposition of sediment downstream and between neighbouring groynes. A detailed experimental and numerical study has been carried out to investigate the bed deformation and its relationship to the characteristics of recirculating flow induced by a single groyne in a straight, sand-bed channel Yasi (1997). The prediction of the temporal development of the bed topography behind groynes is a complex process to model numerically. There is a feedback interaction between recirculating flow...
and bed mobility behind the groyne and the subsequent changes in the flow, sediment transport, and bed topography.

Mathematical modelling to predict the bed evolution behind groynes should be possible by linking the water flow model to an appropriate sediment transport model. In the present study, a modified flow model (FAST-2D) was used for the calculation of the depth-averaged flow parameters. A sediment transport model (STM-2D) was developed to be used in conjunction with the FAST-2D flow model in order to test the present state of sediment transport relationships in a straight channel with the groyne present. This paper addresses major uncertainties in achieving the goal of computational simulation of the bed geometry behind groynes, in particular the scour around the groyne and deposition of sediment downstream.

2 Numerical Method

2.1 Flow Model

The FAST-2D model was developed at the University of Karlsruhe, Germany by Rodi (1984), Wenka (1992), and modified by Yasi (1997). The model uses an efficient finite-volume method with boundary-fitted curvilinear grids, and an iterative process to solve the governing equations of continuity and momentum. The numerical scheme uses Cartesian velocity components and the resulting system of linear equations is solved with the Thomas tridiagonal matrix algorithm (Wenka, 1992).

This model was originally tested against the flow situations observed in fixed-bed experiments with the groyne present (Yasi, 1997). It was concluded that the efficiency of the model depends largely on the modification of the k-ε turbulence model, bed-shear stresses, proper adoption of physical and numerical boundary conditions, and the resolution of the numerical grid around the groyne. Subsequently, the k-ε model was modified with the inclusion of correction factors for the effects of the turbulent spiral motion and streamline curvature producing close simulations of the recirculating flow characteristics observed in fixed-bed tests (Yasi, 1997).

The depth-averaged bed shear stress relationship was modified with the inclusion of correction factors for the effects of the local spiral motion and bed slope in the following form:

$$\tau_b = C_f \rho (U^2 + V^2)\left\{K_b\left[1 + \frac{K^2}{s}\right]^{1/2}\right\}$$

(1)

Where $U$ and $V$ are the depth-averaged values of the x- and y- velocity components; $C_f$ = the shear coefficient; $\rho$ = the water density; $K_b$ = the
bed factor; and $K_s$ = the correction factor due to the spiral motion. Equations for $K_b$ and $K_s$ have been developed by Przedwojski (1995,1997).

The application of the model was verified in movable-bed experiments against the equilibrium bed topography induced by the groyne in a sand-bed channel. The reproduction of bed-shear stresses in the movable-bed channel was, however, uncertain because of the lack of specific experimental data (Yasi, 1997). Specific conclusions on the adequacy of Eqn. (1) in predicting the bed-shear stresses around the groyne are presented in the following sections.

### 2.2 Sediment Transport Model

Bathymetric variations are governed by the continuity equation of sediment transport, for which the formulation for the magnitude and direction of sediment transport rate must be included. In the present study, bed load transport only is significant in the bed evolution and is expressed using the standard two-dimensional sediment continuity equation for straight channels (Yasi, 1997).

The components of the bed-load transport are expressed in terms of the direction angle of sediment transport relative to the x-axis. Among the existing sediment transport formulae, the relationships of Ackers and White (1990), and van Rijn (1993) were adapted to the experimental conditions in the present study. The inclusion of the criterion for the initiation of sediment motion in these relationships has the major advantage of distinguishing the regions where the bed shear stress exceeds the critical value for the bed material. Details of the sediment transport models are presented in the original papers.

The direction of sediment transport, $\alpha$, is calculated with the relation of Koch and Flokstra (1981) as follows:

$$\tan \alpha = \frac{\tau_b \sin \delta - S_p \frac{\partial Z_b}{\partial y}}{\tau_b \cos \delta - S_p \frac{\partial Z_b}{\partial x}}$$

where $S_p = \frac{2}{3} [\rho g (S_g - 1)] \frac{D_{50}}{f_s \lambda_b}$

in which $S_p$ represents the characteristics of the bed material; $f_s$ = the shape factor of sediment particles; $\lambda_b$ = the sheltering coefficient for the effects of the resistance force due to the friction and keying between neighbouring particles and $\delta$ = the direction of bed-shear stress relative to the x-axis. The effects of the main flow direction and local spiral motion are included in the calculation of $\delta$ using the following relationship:
\[ \delta = \arctan \left( \frac{V}{U} \right) - \arctan \left( A h \left( \frac{1}{R_s} \right) \right) \]  

(3)

in which \( h \) = the local water depth; \( A \) = the weighting coefficient for the influence of spiral motion; \( k = 0.4 \) is the von Karman constant; and \( R_s \) = the local radius of streamline curvature. Details are described elsewhere by Yasi (1997).

A computer program, (STM-2D), was developed to solve numerically the sediment continuity for a given flow condition and a prescribed bed topography in straight channels.

3 Evaluation of The Model

3.1 Model Application

A typical experiment, M1, was conducted in a straight, rectangular channel of length 12-m, width 1.2-m, and depth 0.5-m with smooth-glassed bed and sides. The bed level was relocated 260 mm above the glass bed allowing for the placement of bed material. The bed material was a quartz-based sand, with specific gravity of \( Sg = 2.65 \). The grain size ranged from 1.0 to 2.4 mm, with \( D_{50} = 1.7 \) mm. The critical bed shear stress was 1.02 N/m². The groyne comprised a rectangular-sheet metal plate 3-mm thick, 0.5-m high of length, \( b \), 100 mm projecting perpendicular to the flow field.

The flow rate was \( Q = 36 \) l/s, with water depth of \( h = 110 \) mm at the downstream section of the test reach and a channel slope of 0.5%. The Froude Number of the approach flow was 0.26. The bed-shear stress in the approach flow, \( \tau_{bc} \), was calculated to be 0.342 N/m², ensuring upstream clear-water conditions.

Figure (1): Observed bed evolution behind the groyne in Test M1
During the experiment, the process of interaction between the flow and the bed was initiated by an interference mechanism between the groyne and the approach flow in the channel. A system of vortices was observed to be the main reason for developing the scour around the groyne. Figure (1) shows the bathymetry 24 hours following the commencement of the test. Contours of negative values indicate the scouring area relative to the initial bed level, while positive ones show the extent of deposition. Details of the experimental design and procedure, and the results on the structure of the recirculating flow and bed geometry behind the groyne are presented by Yasi (1997).

In the numerical modelling, the channel bed was initially considered to be flat. A boundary-fitted grid size of (88x65) was adopted. Input flow characteristics were the same as for the experiment. The initial and boundary conditions were specified at the inlet, outlet, and rigid walls. The plan form of the groyne was considered as a blocked-off region into the flow field.

Computations began with the prescribed flat bed and proceeded in time to determine the transient development of the bed. For the flow calculations with the FAST-2D model, the solution converged with 264 iterations at each time step. For the sediment transport component, an initial time interval $\Delta t$ was set to 100 sec. This time increment could be refined automatically to achieve a convergence criterion of a maximum of 5.5 mm change in the bed level in each time step.

### 3.2 Computational Results

The predictive capability of the model depends to a great extent on the relationships for calculating bed-shear stresses, $\tau_b$, and bed-load transport rate, $q_b$. Consequently, the development of the bed was evaluated by:

1. The application of the bed-shear stress relationship with and without the modification for the effects of the local spiral motion and bed slope;
2. The application of the bed-load relationships of Ackers and White, and of van Rijn (both deterministic and stochastic methods).

The results are evaluated in terms of the bed variations around the groyne as follows.

#### 3.2.1 Bed Shear Stress Relationship

The bed-shear stresses, $\tau_b$, were calculated in the program using Eqn. (1), initially without the modification for the effects of local spiral motion and bed slope ($K_s = 0$ and $K_b=1$) and then with modification for these effects.

Without modification of Eqn. (1), the bed shear stress was everywhere calculated to be less than the critical value for the bed material, leading to zero bed load transport and no bed change.
The bed shear stress field calculated with the modified bed-shear stress is presented in Figure (2). Near the tip of the groyne, the maximum bed-shear stress increased from 0.58 N/m$^2$ in for the unmodified Eqn. (1) to 2.3 N/m$^2$ as a result of the high velocity gradients and strong flow curvatures in this area. Since the ratio of $\tau_b/\tau_c$ is significantly greater than one around the groyne nose, the bed level will evolve with time. This situation was using different bed-load relationships.

![Contour map of bed-shear stresses at the initial stage (Test M1), with correction factors $K_b$ and $K_s$ in Eqn. (3).](image)

**Figure (2):** Contour map of bed-shear stresses at the initial stage (Test M1), with correction factors $K_b$ and $K_s$ in Eqn. (3).

### 3.2.2 Bed-Load Relationship

The sediment transport relationship of Ackers and White (1990), was found to be inappropriate for simulating bed variations because the computed bed-load transport, $q_b$, was zero everywhere in the flow field. Both the deterministic and stochastic bed-load relations of van Rijn (1993) was found to be sufficiently responsive to the local variation of $\tau_b/\tau_c$ around the groyne, producing significant bed-level variations.

The computed bathymetry was very similar for both the deterministic and stochastic relationships. Figure (3) presents the bathymetry for the stochastic method for the same development time as that in Figure (1).
Comparison of Figures (3) and (1) shows poor agreement. It is evident that the modification imposed in the form of Eqn. (1), although magnifying the bed shear stresses sufficiently to produce sediment motion, is insufficient for reproducing a realistic distribution of the bed-shear stresses in flows with the groyne present. The discrepancy between the observed and calculated bed topography around the groyne is primarily related to the proper prediction of bed-shear stresses in the recirculating flow area around the groyne.

4 Conclusions

The prediction of time-dependent bed topography behind groynes is an important objective in numerical modelling. The simulation process was investigated by linking the two models (FAST-2D and STM-2D) for an interactive solution between the flow parameters and bed variations. It is concluded that the mean velocities are not sufficient alone for calculating $\tau_b$ in the recirculating flows with the groyne present. The inclusion of correction factors for the effects of the local spiral motion ($K_s$) and of the local bed slope ($K_b$) in the form of Eqn. (1) imposes a significant magnification in the calculated $\tau_b$ around the groyne within a distance range of $-1.5 < X/b < 1$ and $Y/b < 2$. Consequent significant bed variations occur around the groyne when both the deterministic and stochastic bed-load relationships of van Rijn (1993) were tested.
separately. The application of the stochastic method was not superior to the deterministic method. The simulated bed topography is considered to be unrealistic when compared with that observed.

It is evident that the proper formulation of bed-shear stresses in the recirculating flow area around the groyne is the first priority. Because of the specific mechanism of the local scour process, it is concluded that the effect of generated downward currents, vortices, and turbulence intensity must be included in the bed-shear stress relationship. The development of such a conceptual method is necessary to improve the sediment transport model. The efficiency of the bed-load transport relationships of van Rijn is considered to be a second priority in this process.

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References


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