Numerical simulation of groyne placement in minimising Krueng Aceh river bank erosion

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Abstract. This paper presents the prediction of the flow velocity in a 575 meters-long reach of the Krueng Aceh river. It focused on the part of the riverbank where erosion occurred due to the pillars and bridge abutments. One alternative to reduce erosion is using groyne for regulation. The simulations were conducted using the Surface Water Modelling System program (SMS 11.2). The effects of the groyne on the flow changes causing erosion were determined by mathematical simulation of two-dimensional flow using RMA2. The calibration of RMA2 was undertaken by determining the Root-Mean-Square (RMS) error between the measured and mathematical model velocities. Nine scenarios of simulations have been done to investigate the effect of the groyne installation in reducing erosion in the river bend, in term of its length (L), and angle (α), according to river condition. From the simulation results, it can be concluded that the distribution of flow velocities towards the outer river bend for the perpendicular groyne of 9.0m long was smaller compared to the 7.0m one. The groyne with the angle of 10° and length of 7.0m was better in reducing the velocities at the outer riverbank than the 9.0m one. Whereas the groyne with 30° orientation and 9.0m long is better in reducing the eddy than that of the 7.0m.

1. Introduction

Constructing river training structures are necessary for guiding or managing the river water for various beneficial purpose of mankind. The most commonly used river training structures generally are built along the river, placed from the riverbank and extended towards the main channel flow, called a groyne. The construction of structures aims to deflect or repel the velocity away from the bank for reducing river bend erosion and increase the flow depth for smooth navigation. However, local hydrodynamics and the river morphology will change because of these structures, leading to a blockage in the flow.

Krueng Aceh river, located in Aceh, Indonesia, faces many problems related to the bank erosion due to many factors, such as the sand mining at the upstream and downstream of the river, the installation of bridge pillars and abutment along the rivers blocking its cross-section, and the land-use degradation. Hence, it is necessary to eliminate the riverbank erosion due to the bridge pillars using groyne. A case study was selected at the Pango flyover bridge, located in Pango village, Aceh Besar District, Aceh. Before installing the groynes in this reach, it is essential to conduct a model study to evaluate the possible effects of the groynes on the river. These model studies were conducted based on numerical approaches using SMS.
2. Methodology
Numerical study on groyne placements has been widely studied by previous researchers, such as Suharjoko 1999 [1] and (2001) [2]. He has already analyzed and reviewed the influence of the impermeable groyne on a straight channel, concerning the flow pattern and the best distance between the structures using Computational hydrodynamics simulations. He found that the relationship between the Froude number (Fr.) and the length of embankment protected and the other parameters can be used to show the best distance between the groyne.

Mojtahedi A and Basmenji A B (2017) [3] have investigated the influence of the groynes and the embankment dike placement on Ghezel-Ozan River. After the instalment, they found that the groynes in the given interval, the main channel of the river became significantly deeper while the sediment settled between the groynes and made the dikes more stable. They said that the chosen length, the space between the groynes, and their shapes were optimum, and the correct forms of vortexes were made between them. However, it is better to replace the first and the last groynes in the series with an L-shape groyne. While Dutta D and Kalita H M (2018) [4] compared the performance of straight head and T-head groynes for vulnerable channel bend numerically using MIKE21C modelling tool. They concluded that T-head groynes were better for the stability of the outer bank.

2.1. Groyne characteristics
Groyne construction is a form of indirect protection used to protect river banks indirectly from the danger of the local scour and meandering process due to currents directing the river flow. A series of groyne construction also functions as a way to deepen and narrow the river flow, [6] Sunaryo, Daoed D, and Sari F L (2010) [5].

Sosrodarsono and Tominaga (1985: 174) [6] explained that based on the permeability level, groynes are classified into three types of construction, namely: permeable, impermeable and semi impermeable groynes. Generally, the groyne formation applied on the river is perpendicular to the flow, leaning towards the upstream area, leaning towards the downstream area and a combination of both.

2.2. Groyne placement
Groyne placement is adjusted according to its function, either for the directional and alignment repair or for riverbank protection. To function as a riverbank protection, an integrated river planning must be done, so that the river management can be carried out effectively. The results of the velocity distribution formed greatly influence the angle of the groyne placement.

2.3. Groyne formation
Sosrodarsono and Tominaga (1985: 179) [6] argued that there are three groynes orientation applied, i.e. perpendicular, inclined to the upstream, and inclined to downstream. Groyne orientation refers to the groynes alignment for the direction of the current main flow in a channel. The most compatible angle to various types of groynes is described in Table 1.

| Orientation of the groynes | Flow direction and groyne angle |
|----------------------------|---------------------------------|
| 1  Straight Section         | 10° – 15°                      |
| 2  Out Section              | 5° – 15°                       |
| 3  In Section               | 0° – 10°                       |

Based on the results of surveys and observations on the groynes that have been built by Sosrodarsono and Tominaga (1985: 179) [6], then, the length of the groynes can be calculated as follows:
2.4. Flow pattern around the Groynes

Mudjiatko (2000) [7] stated that the water flowing through a bend will experience a centrifugal force, causing water to move out of the bend. The centrifugal force will work if there is no transfer of water mass in the transverse direction. Since the velocity distribution affects the depth, leading to the velocity at the surface being higher than that near the base, it will undoubtedly affect the distribution of the centrifugal force. Centrifugal force will be larger on the surface than near the base.

The placement of the groyne to protect a riverbank and direct the flow or improve the alignment of the river will certainly affect the direction of the river flow, resulting in a whirlpool around the groyne. Whirlpools will form flow patterns, scour patterns around the groyne. Thus, a study of flow patterns is important to plan the groyne placement.

2.5. Surface water modelling system (SMS)

Surface water Modeling System (SMS) is a program designed to draw flow patterns on the surface, with 1D, 2D and 3D modelling in the form of hydrodynamics. To solve the modelling problem, one RMA2 sub-program is used. RMA2 is a two-dimensional sub-dynamic flow equation settlement program, Boss SMS (1995) [8].

2.6. Modelling approach

One of the BOSS SMS (Surface water Modeling System) software modules, RMA2 (Resources Management Association Inc.) version 11.2, is a numerical model for calculating the two-dimensional flow hydrodynamic process at an average depth.

2.6.1. Surface water modelling system (SMS 11.2) governing equations and solution techniques. The SMS software is a post and pre-processing unit, while RMA2 is the running execution program. The water level elevation and flow velocity of each point with the mesh elements as well as water display in digital forms, such as rivers, ports and estuaries are clearly depicted. RMA2 can solve both permanent and temporary flow problems because the boundary conditions (incoming discharge, water level elevation) can be set accordingly. This program is designed to create models with dynamic flow conditions caused by fluctuations in the surface flow or tidal cycles. RMA2 is not used for supercritical flow.

The output of RMA2 is written by the binary solution file. The file contains the completion of one or several time steps depending on whether the flow analysis is specified permanently or temporarily. Solution file can be used as an input for an SMS program to display data in graphically. The general governing equation for shallow water by RMA2 is solved using the following formulas (Boss SMS, 1995) [7].

\[
L_k \leq 10\% \ B
\]  \hspace{1cm} (1)

In which, \(L_k\)=length of the groynes (m), and \(B\)=river width (m)
\[ h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - h \left( \frac{E_{xx} \partial^2 u}{\partial x^2} + E_{xy} \frac{\partial^2 u}{\partial x \partial y} \right) + gh \left( \frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right) + \frac{gun^2}{(1.486h^{1/6})^2} \left( u^2 + v^2 \right)^{1/2} - \zeta \frac{V_a^2}{\alpha} \cos \psi + 2h \omega v \sin \phi = 0 \] (3)

\[ \frac{\partial h}{\partial t} + h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = 0 \] (4)

Where: \( h \)=water depth (m), \( u,v \): velocity on the direction of the x and y axis (m/s), \( x,y,t \)=Cartesian coordinate and time, \( \rho \)=liquid mass density (kg/m\(^3\)), \( g \)=gravitational acceleration (m/s\(^2\)), \( E \)=Eddy Viscosity coefficient, \( xx \)=for the normal direction on the x axis, \( yy \)=the normal direction on the y axis, \( xy \) and \( yx \) the direction=shear on each surface, \( a \)=bed elevation (m), \( n \)=Manning roughness value, 1.486=conversion from metric units to English units, \( \zeta \)=coefficient of wind friction, \( V_a \), \( \psi \)=wind speed and wind direction, \( \alpha \), \( \phi \)=Earth’s angular rotation rate and local latitude (km/h).

2.6.2. RMA2 hydrodynamic model. The selection of the suitable analytical method to adopt during a river hydraulics study depends on many factors, such as the objectives, the level of detail being called for, the regime of flow expected, the availability of necessary data, and the availability of time and resources to properly address all essential issues (EL-Sammany M S and El-Moustafa A M, 2011) [9]. The RMA2 model under the SMS interface was selected in this study.

The main objective of this study was to develop a hydrodynamic model to study the flow fields of Krueng Aceh river, where various scenarios of groynes were installed. The requirements of input data to run the model were related to spatial and temporal parameters, such as computational mesh, bathymetry, simulation length and overall time step.

2.7. Measuring site and data collection

The measuring site with the length of 575m was located at Pango Village in Ulee Kareng Sub-district of Aceh Besar District. The flood discharge with a five year return period was estimated at 405.456m\(^3\)/s. The water elevation data was 6.0m. Krueng Aceh river, as shown in Fig. 1, has an average width of 40.62m for the full bank. Topographic map of the reach considered is given in Fig. 2.

During the mesh generation process, bathymetric values were extracted by the AutoCAD, providing the data compatible with SMS. Mesh independence is essential for obtaining reliable results from the models. In this investigation, Krueng Aceh river was simulated using a grid with flexible meshes, covering the considered reach and a part of the surrounding area (Fig. 3). Simulation time reached its numerical stability after 24 hours running the models.
Figure 1. Measuring site.

Figure 2. Topographic map.
The length of the groyne was 6.16% of the river width (B). The variation of the distance (L) intervals were considered 2.8 and 3.6 times the length of the groyne (Lₜₐₜ), and the variation in the number of groynes (N) was set to be five units. The groyne was placed to flow in three angular variations, namely perpendicular to the riverbank, 10° and 30° facing towards the downstream area. Groyne stability is not considered in this report. The groyne placement scenario is summarized in Table 2.

| Discharge (Q5 m³/s) | Groyne position | Groyne distance (L=m) | Number of groyne (N-Unit) |
|---------------------|----------------|-----------------------|---------------------------|
| 405,456             | Perpendicular | GT                    | GT5L7 GT5L9               |
|                     | 10° downstream | G1a                   | G1a5L7 G1a5L9             |
|                     | 30° downstream | G1b                   | G1b5L7 G1b5L9             |

### Table 2. Groyne placement scenario.

2.8. Validation of numerical model

In this study, the value calibrated is the value of the manning coefficient (n). Based on the results, the velocity measurement in the first (upstream) and the second (downstream) cross-section was 0.659 m/sec and 0.622 m/sec, respectively. While the numerical velocities in the first and second cross were 0.583 m/sec and 0.710 m/sec, respectively. The absolute error values were 0.039 for cross 1 and 0.051 for cross 2. Hence, the data is valid since the magnitude of the absolute error value is less than 1, as shown in Figure 4.
3. Results and discussion

Fig. 5 shows the flow pattern in the Krueng Aceh river without any groyne instalment. Simulation results indicate that the red covers a very critical area and brick red is a critical area. Whereas, yellow, green, and blue refer to a medium area, a normal area, and no flow area, respectively. It can be seen that there are three bridge pillars transverse the river cross-section. Due to these pillars, the velocity at the downstream of the pillar is high (critical to very critical) compared to the velocity at the pillar vicinity. Besides, the river width at this section is also smaller than that of the pillar vicinity.

Field measurement at the riverbank, in the inner and outer bend, was found eroded. However, velocities at the inner bend were higher than that at the outer bend. Theoretically, river bank at the outer bend is the most vulnerable to the bank erosion than the inner bend. This phenomenon can happen due to the pillar that may alter the thalweg of the river. Thalweg is defined as the middle pattern of river flow with the highest velocity value formed in river flow in the middle of the river, illustrated by a long river crossing line. It occurs because of the changes in river morphology, the changes in flow patterns and the magnitude of flow velocity. The middle flow pattern of the river (thalweg) must be controlled so that it remains in the central position of the flow, to prevent meandering or erosion of the river bank. Brown (1985) [8].

![Figure 4](image-url)  
**Figure 4.** Calibration graph of the measured and simulated velocity.

![Figure 5](image-url)  
**Figure 5.** Flow pattern without groyne placement.
3.1. Flow pattern based on perpendicular angle groyne and two difference length (L)

Fig. 6 depicts the flow pattern around the 5-unit of groynes, 7.0 m and 9.0 m long, installed perpendicular to the river bank. The 9.0m groyne was narrower than the river width than the 7.0m. Flow velocities at these two formations accelerated at the tip of each groyne at the outer bend due to deflection. Velocities at the inner river bend decreased significantly because of the blocked area, but the high velocity was transmitted to the other side (outer river bend) and the downstream area. It is fascinating to note that velocities distribution at the outer river bend for GT5L9 was lower than that of GT5L7. The presence of groyne affected the turbulent flow field, and the separation zone length of GT5L9 was better than that of GT5L7. Eddy distribution occurred at GT5L9 was pushed towards the middle of the river and extended downstream. Whereas at GT5L7 eddy distribution was concentrated at each nose of the groins and was not swept away the inner river bend. Hence, the eddy overlapped each other and was then transmitted away to the outer river bend and downstream as well.

![Figure 6. Flow pattern for GT5 groyne placement scenario.](image)

3.2. Flow pattern based on groyne angle and groyne distance

Flow variation for groyne angles of 20° and 30° and the length of 7.0 and 9.0m are shown in Fig. 7. The GIa5L7 formation resulted in smaller velocity vector distribution in the reach. One can see that at the deflection angle of 10°, the groyne spread out eddy to the middle and downstream of the river and the critical velocity was lower compared to that of GIa5L9 groyne type. Whereas for deflection angle of 30° groyne type spreading out eddy occurred at each tip of the groynes and critical velocity extended to the outer river bend.
Figure 7. Flow pattern for GIa and GIb groyne placement scenario.
4. Conclusion
Nine scenarios of groyne instalment at the Krueng Aceh river have been simulated using SMS software. It can be concluded that the distribution of flow velocities towards the outer river bend for 9.0m perpendicular groyne was smaller compared to the 7.0m. Groynes with the angle of 10° and the length of 7.0m were better in reducing the velocities at the outer river bank than the 9.0m one. Whereas groyne with 30° orientation and 9.0m long was better in reducing the eddy than that of 7.0 m.

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