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Research paper

Modeling of Kampar River Discharge as a Solitary Wave

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Abstract

The propagation of tidal bore in Kampar River is investigated through a soliton theory. For far field region, the Bono wave can be treated as a solitary wave propagates on the open channel flow. The wave propagation in term of the Korteweg-de Vries (KdV) equations will be described. A single soliton solution and environmental effect will be obtained. The result shows that the amplitude of tidal bore is about 5m it will have the velocity 11.6 m/s and its wavelength 30m. We found that the river discharge will decrease the tidal bore velocity and decay the amplitude.

Keywords: *Bono wave, Kampar River, KdV equations, soliton theory, tidal bore*.

1. Introduction

River of Kampar is one of four largest rivers in Riau, Indonesia having a broad 24.548 $km^2$with the depth is about 7.7 *m* and the width is about 413 *m*. The river flow a crosses two province the West Sumatra and Riau. With the upstream in the Bukit Barisan Mountains and the estuary in the Malaka Strait, this river is a groove of a voyage crowded. The Kampar river is acid enough with 6-5.5 pH. The tide flow though the river until 229*km* long from the estuary to the upstream with the tidal amplitude 2.1 *m* to 4.5 *m*. The Kampar estuary has 'V'morphological form (convergent) where this is a prerequisite for generation of the tidal bore [1].

A tidal bore which is generated by tide is an open channel flow in which a sharp peak in height propagates a long a fluid's surface. In this paper, we study the dynamics of the tidal bore occurring in Kampar River, Riau, Indonesia. The wave has a local name, namely Bono. The Bono meaning is gosh wave. The wave was generated by an interaction between storm surge from the South China Sea with the tidal flow in the mouth of Kampar River. The Bono usually is not a single wave but propagates in wave packages [2,3]. This wave will propagate until to a upstream for long distance. The waves usually occur in the end of November every year.

The wave is not only bringing the energy but also the mass. The wave is a very energetic phenomenon and has destructive properties. However, studying its propagation can assist to identify dangerous region where hopefully human habitat will be avoided [4,5]. The wave also has strong turbulence and rumbling noise.

The quantitative study of this phenomenon in Kampar River is rare. The first investigation used secondary data such as bathymetry, tide and water masses. The result showed that the tidal waves occur at the Muda Island and dissipate at Tanjung Perbilahan. The salinity usually increases when the Bono occur [6]. The paper also gives a quantitative explanation of this wave. Propagation of the wave was studied by using HEC- RAC software that simulates the behavior of tidal bore in one dimension. In this paper, we use an analytical model to study this wave.

This wave is of great importance for the geomorphology of the estuarine zone [7]. For example, a bed erosion and scour may take place beneath the bore front while suspended sediments will be carried upwards in the propagation wave motion. A comprehensive understanding of the phenomena is useful for this purpose. In this paper, we focus to a far field region or far from the mouth of estuary. The Bono waves can be treated as a solitary wave propagating in the open channel flow. The derivative of the wave equation based on the shallow water approximation will be ascribed in Sec. 2. The result of observation and analytic solution based on single and periodic solitons are described in Sec. 3.

2. Tidal Bore Model in Kampar River

We will describe the Bono in the form of solitary waves. The propagation of solitary wave in a river (open channel) is very well known. In this paper, we will discuss briefly related to modeling of tidal bore propagation in Kampar River. Due to the bono wavelength, much longer than its depth so that the shallow water approach is appropriate approximation. The shallow water equation in one-dimension open channel flow can be written as [8].

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial z^2}=0\,,-h(x)<z<\eta(x) \qquad (1)$$

$$\frac{\partial\phi}{\partial x}\frac{\partial h}{\partial x}+\frac{\partial\phi}{\partial z}=0\,,\, z=-h(x) \qquad (2)$$

$$\frac{\partial\eta}{\partial t}+\frac{\partial\phi}{\partial x}\frac{\partial\eta}{\partial x}-\frac{\partial\phi}{\partial z}=0\,,\, z=\eta(x) \qquad (3)$$

$$\frac{\partial\phi}{\partial t}+\frac{1}{2}\left[\left(\frac{\partial\phi}{\partial x}\right)^2+\left(\frac{\partial\phi}{\partial z}\right)^2\right]+g\eta=0\,,\ z=\eta(x) \qquad (4)$$

where ϕ is velocity potential, $\eta(x)$ is tidal elevation, g is gravitation intensity, $h(x)$ is water depth, x is longitudinal coordinate, z is vertical coordinate and t is time. The propagation of a surface wave over varying bottom can be described by the equation as follow [8],

$$\frac{\partial^2\eta}{\partial t^2} - g\frac{\partial}{\partial x}\left(h(x)\frac{\partial\eta}{\partial x}\right) = 0 \tag{5}$$

Consider the constant depth $h_0$then we will arrive in the linear wave equation with the phase speed is given by $c = \sqrt{gh_0}$. The approximation will used to obtain the single wave equation. The first approximation is called Boussinesq approximation using an integration of the Laplace equation as,

$$\phi = \tilde{\phi} - \int_{-h}^{z} dz' \int_{-h}^{z'} dz \tag{6}$$

where $\tilde{\phi}$ is the depth average of velocity potential. Substituting into Equation 4 yields,

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{\partial\eta}{\partial x} = 0 \tag{7}$$

$$\frac{\partial\eta}{\partial t} + \frac{\partial}{\partial x}\left[(h+\eta)u\right] = -\frac{\partial}{\partial x}\left[\frac{1}{2}h^2\frac{\partial(hu)}{\partial x^2} - \frac{1}{6}h^3\frac{\partial^2 u}{\partial x^2}\right] \tag{8}$$

where $u = \partial\phi / \partial x$. This is called Boussines q equation.

By using the traveling wave coordinate $\xi = xct$ and $\tau = \beta t$, where $c = \sqrt{gh}$ is phase speed of linear water wave and β <<1 is a small parameter, then the Boussinesq equation become,

$$\beta\frac{\partial u}{\partial\tau} - c\frac{\partial u}{\partial\xi} + u\frac{\partial u}{\partial\xi} + \frac{\partial\eta}{\partial xi} = 0 \tag{9}$$

$$\beta\frac{\partial\eta}{\partial\tau} - c\frac{\partial\eta}{\partial\xi} + \frac{\partial}{\partial\xi}(u\eta) + \frac{\partial u}{\partial\xi} + \frac{1}{3}\frac{\partial^3 u}{\partial\xi^3} = 0 \tag{10}$$

By assuming the phase velocity is constant, the relation $\eta = u$ will be satisfied, we obtain

$$\beta\frac{\partial\eta}{\partial\tau} - c\frac{\partial\eta}{\partial\xi} + \frac{3}{2}\eta\frac{\partial\eta}{\partial\xi} + \frac{1}{6}\frac{\partial^3\eta}{\partial\xi^3} = 0 \tag{11}$$

By using invers coordinate transform, we arrive to

$$\frac{\partial\eta}{\partial t} + \sqrt{gh}\left(1 + \frac{3}{2h}\sqrt{gh\eta}\right)\frac{\partial\eta}{\partial x} + \frac{h^2}{6}\sqrt{gh}\frac{\partial^3\eta}{\partial\xi^3} = 0 \tag{12}$$

This is the KdV equation describing the tidal bore propagation in Kampar River. The weakly nonlinear approximation can be used to obtain an analytic solution of this Equation [9-11].

3. Result and Discussion

The study area is depicted in Fig. 1. The tidal bore observation is difficult to do so, instead the measurement of velocity and water mass will be done at when the tidal bore does not occur. The observation is held on Kampar River around Muda Island at June, 16 2016 until June, 18 2016. The result of the observation in Kampar River is depicted in Fig. 2. Generally, the Kampar River has a warm temperature 30°-32°C and acid water with the degree of acidity is about 4-6. The current speed tends to faster− is about 1 *m/s* at low tide and slower at high tide (0.4*m/s*). In the rainy season when the runoff is high then the velocity will be high at low tide. The meeting of this water mass and the surge wave from the South China Sea in the mouth of Kampar River may generate a tidal bore.

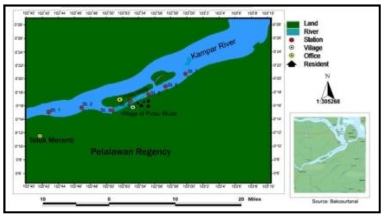

Fig. 1: The observation point at Kampar River. The first station is located in the west and last station east ward.

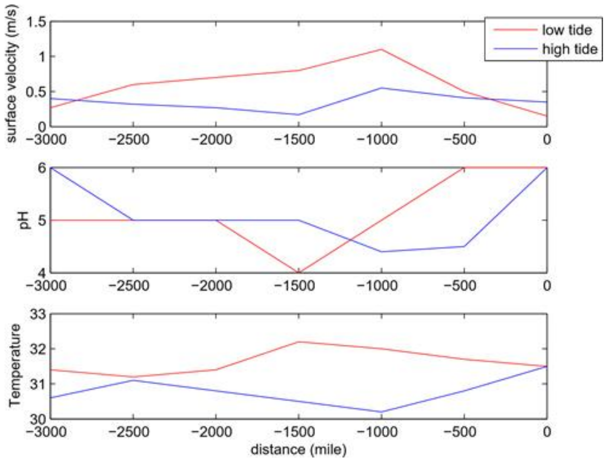

Fig. 2: The water mass (velocity, pH and temperature) observation in Kampar River during low tide and high tide at June, 16-17 2016. The distance measure from the last station (no.7) to the first station (no.1) upstream ward.

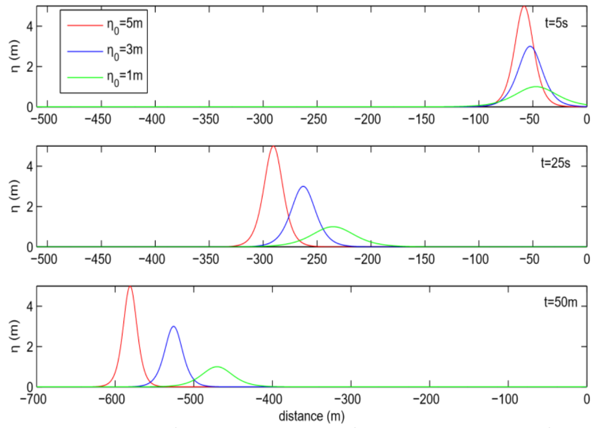

Fig. 3: Propagation of the Bono in term of single solitary wave from the station no 7 of river to the station no 1. The red color represent a tidal bore with amplitude 5 m, the blue color is 3 m and the green color is 1 m.

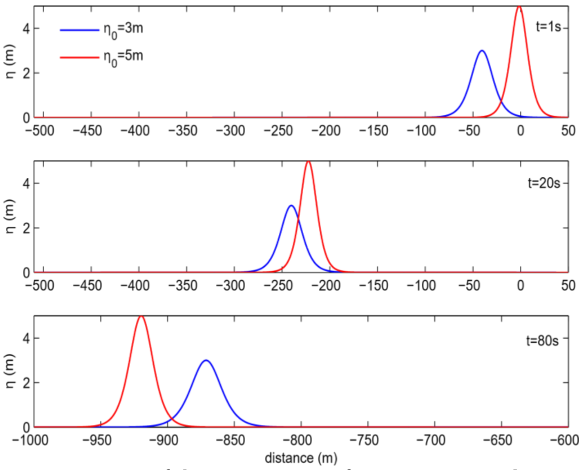

Fig. 4: Propagation of the Bono in term of two successive solitary wave from the station no 7 of river to the station no 1. The red color represent a tidal bore with amplitude 5 m, the blue color is 3 m where the blue color generated first and then follow by the red one.

For the soliton propagates far from the generation zone (mouth of the estuary) then the topography of the river is flat. The single soliton solution of Equation 12 is given by [8],

$$\eta(x,t) = \eta_0 \sec^2\left(\frac{x - Vt}{\Delta}\right) \tag{13}$$

where $\Delta = \sqrt{4h^3 / 3\eta_0}$ and $V = (1 + \eta_0 / 2h)\sqrt{gh}$. The depth of Kampar River is about 8*m* and the amplitude of the Bono is about 4 *m* in high. The simulation of the Bono is depicted in Fig. 3. The result showed that the tidal bore propagates with the velocity is about 11.6 *m/s* for the amplitude 5 *m*. For the tidal bore with the amplitude 3 *m* and 1 *m*, they have the phase velocity about 10.5 *m/s* and 9.4 *m/s*, respectively. There is a relationship between the amplitude and the phase velocity, as depicted in Fig. 4. This relation is linear. The increasing of the amplitude also gives the increasing of phase velocity. This condition is typical of nonlinear wave. This is contrast with the linear or periodic wave where the velocity does not depend on the amplitude but the frequency and the wavelength.

The wavelength of the Bono wave is proportional to its wave height. For instance, when the Bono have 5 *m* in wave high then the wavelength is about 30 *m*. The other hand when the wave height is 1 *m* then the wavelength is about 100 *m*. Sometime the tidal bore was called as the long wave although this is not really good. The Bono generated in the mouth of Kampar estuary that propagate to the upstream with the velocity is about 10 *m/s*. The wave will break at Teluk Meranti with length about 200 *km* from the mouth of estuaries. This mean that the wave has a lifetime is about 5.6 hours.

Sometime the tidal bore does not appear in the single wave form but in many successive solitons. Let we discuss two solitary waves propagate from the mouth of estuary to the upstream with the first wave is lower than the second wave. The phenomena are depicted in Fig. 5. The first wave is generated and then following by the second wave with the wave high 5 *m* after the first wave propagates 50 *m*. Further at *t* = 20 *s* where the first wave propagates 250 *m* long then the second wave move to close the first one. Finally, at time is 90 *s* then the second wave moves in front of the first one perfectly. This imply when the tidal bore is generated in the term of many solitons then the soliton with the highest amplitude will propagate faster than the lower one.

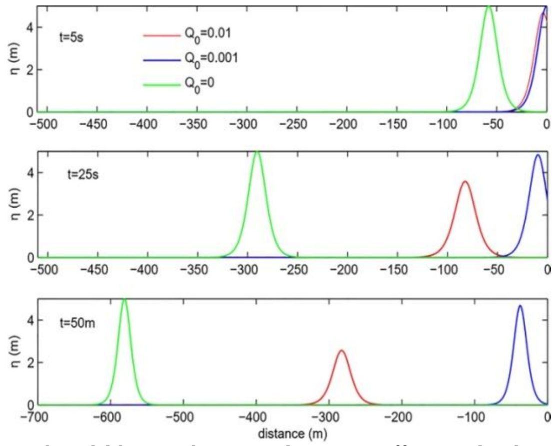

Fig. 5: The tidal bore with various damping coefficient related with the river discharge. The initial tidal bore amplitude is about 5 m.

The tidal bore gives significant impact of the environment, for example it can be induced mixing, bed erosion and deposition in upstream intertidal area. The mixing and dispersion will be strengthened in the river mouth when the tidal bore is present. On the other hand, the environment also influences the tidal bore propagation. Recent study show that the tidal bore will be damped by the freshwater discharge [1]. To study this effect, let it write the KdV Equation in the non-dimensional form of the freshwater effect. By using transformation,

$$t = \frac{h}{A\sqrt{6gA}}\tau \tag{14}$$

$$x = \frac{h^{3/2}}{\sqrt{6A}}\chi - \frac{ch^2}{A\sqrt{6gA}}\tau \tag{15}$$

$$\eta = 4A\psi \tag{16}$$

where A is the wave number amplitude scale then the KdV Equation become,

$$\frac{\partial \psi}{\partial \tau} + 6\psi\frac{\partial \psi}{\partial \chi} + \frac{\partial^3 \psi}{\partial \chi^3} = 0 \tag{17}$$

Due to the freshwater discharge gives the damping effect then the KdV Equation including the freshwater discharge is given by,

$$\frac{\partial \psi}{\partial \tau} + 6\psi\frac{\partial \psi}{\partial \chi} + \frac{\partial^3 \psi}{\partial \chi^3} = Q_0\psi \tag{18}$$

where Q_0 is quantity related to freshwater discharge. This is called the damped KdV Equation. The single soliton solution is given by,

$$\psi(\tau,\chi) = 2\psi_0^2 \exp\left(-\frac{4}{3}Q_0\tau\right)\operatorname{sech}^2\left\{\psi_0 \exp\left(-\frac{2}{3}Q_0\tau\right)\left(\chi - 2\psi_0^2\left[1 - \exp\left(-\frac{4}{3}Q_0\tau\right)\right]\tau\right)\right\} \tag{19}$$

The behavior of tidal bore propagation with the river discharge is depicted in Fig. 6, showing that if the damping factor is large (the red color) then the soliton propagates faster than the lower damping factor (blue color). The amplitude will decay as long as the wave propagation and finally will be dying out. This concludes that the river discharge will decrease the tidal bore velocity and consequently it decays the amplitude. The tidal bore will break at the Teluk Meranti is about 200 *km* from the mouth of Estuary. The breaking of the wave gives the high run up at the edge of the river.

The tidal bore propagation in Kampar River has similar phenomena in communication and optical signal processing. For example the comunication transport by soliton in Kerr and saturable media [12,13]. The soliton pairs will propagate individually and do not interact if the interval is large then the width of their first lobe. These are phenomena similar to tidal bore that propagate far from the generation zone. The tidal bore generation in the mouth of estuary is not well understood. This phenomena may similar to soliton generation in laser-induced atomic greating through four-wave mixing mechanism [13,14].

4. Conclusions

The dynamics of tidal bore in Kampar river have been investigated. By various soliton theory to investigate the behavior of the waves, propagation of the tidal bore in term of single soliton, double solitons, damped soliton and the possibility of soliton breaking. The result shown that the tidal bore propagates from the mouth of the river to the upstream with the velocity is about 11.6 *m/s* for the amplitude of 5 *m* with the wavelength is about 30*m*. When the river discharge, it show that the river discharge will decrease the tidal bore velocity and decay the amplitude.

Acknowledgments

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