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Experimental research on the aeration length of Tidal Bore Front

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Abstract. In the estuary zone, tidal bore front with strong aeration has a great impact on the navigation, the transportation of sediment, the diffusion of pollutant and the growth of many species of wildlife, but scarcely any studies have interested in the aeration of tidal bore front. New experiments were accomplished in a horizontal glass flume with generated tidal bore. The form of tidal bore front was observed by a high-speed camera, the aeration process and aeration form of tidal bore were recorded and presented herein. Meanwhile, the relationship among the intensity of tidal bore, the Froude number of tidal bore and the relative aeration length of tide bore is analyzed and discussed by measuring the height, mean propagation velocity and the aeration length of tide bore front. An experimental formula is obtained to calculate the aeration length of tide bore by nonlinear regression analysis, which could have practical implications for represent and indirectly quantify the tidal bore aeration.

1. Introduction
A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. Bores often happen in some locations worldly, where incoming tides are funneled into a shallow, narrowing river or lake via a broad bay with a large tidal range (typically more than 6 meters between high and low water). A tidal bore may take various forms, ranging from undular bore (a smooth wave front followed by a series of secondary waves), weak breaking bore (a single weak breaking wave front with a roller followed by a few secondary waves) to strong breaking bore (a single breaking wave front with a roller followed by violent aeration flow).

It is worth mentioning that strong breaking tidal bore with aeration front is dangerous such as tidal bore in the River Seine (France), the Petitcodiac River (Canada) and the Colorado River (Mexico), especially the tidal bore in Qiantang River (China). A great many fatalities occur each year because of the violent aeration of Qiantang tidal bore front (see as figure 1(a)). Tidal bore with aeration front also affects the shipping and navigation in the estuary zone (see as figure 1(b)). Meanwhile, tidal bores with aeration front are related to the sediment transport and the pollutant diffusion in the estuary zone (see as figures 1(c)-1(d)). Furthermore, the aeration contributes to the abundant growth of many species of fish and shrimps, which are rich feeding and breeding nutriment of several forms of birds (see as figure 1(e)). Otherwise, the tidal bores with aeration front provide the opportunity for tense and exciting recreational inland surfing (see as figure 1(f)).
Figure 1. The strong breaking tidal bore with aeration front in Qiantang River and effect.

However, scientific studies have been just focused on the hydrodynamic characteristics and the turbulence features of the tidal bore. Abbott, Dracos and Glenne, Whitham focused on the conditions and the place when tidal bores are formed in shallow water flow [1-3]; Tricker and Lynch argued that the form of tidal bore depends on the ratio of downstream water depth and tidal upstream water depth, if the ratio is close to 1, bore is not broken, if the ratio is close to 1.4, the bore would break [4,5]; Koch and Chanson used flume experiments to study the critical values of Froude numbers of tidal bore to judge whether the free surface is broken or not [6]; Madsen et al and Svendsen studied the turbulence of surge waves [7,8]; Yeh et al used model tests to study the turbulence of the surge and the difference between the surge and the hydraulic jump [9]; Chanson performed an experiment in a rectangular horizontal channel to analyze the flow field, the effect of its mixing and diffusion of the undular bore [10,11]. Wolanska et al obtained the hydrodynamics of the undular tidal bore in the Daly River Estuary, Australia, with the field observations [12]. Chanson analyzed the process of tidal bore in Mont Saint Michel Bay of Normandy in France (Baie Du Mont Saint Michel) [13]; Chanson et al observed the process and sediment concentration of tidal bore in Garonne River in France [14]; Chanson analyzed the roar of the tidal bore in Gulf of Mont Saint Michel [15]; Simpson et al. measured the water level, the velocity, the Reynolds stress and the turbulent energy of the tidal bore in the Dee River Estuary, UK [16]. Pan et al set up a 2-D numerical model to study the Qiantang tidal bore [17]. Pan et al also built a 2-D mathematical model with the Kinetic Flux Vector Splitting (KFVS) scheme to successfully simulate the formation, the evolution and the dissipation of the Qiantang River tidal bore [18]. Yang et al generated tidal bores in the laboratory flume to measure the tidal bore heights, the propagation speeds and the tidal current velocities [19]. Huang et al simulated the undular bore and the rolling bore in glass flume, and attained some achievements on the propagation velocity, the height and the vertical distribution of the flow velocity [20-23]; Xie et al acquired the hydrodynamic characteristics and the turbulence features of the Qiantang tidal bore with the field measurements [24,25].

Nonetheless, only a few have interested in the roller and air entrainment in tidal bores and hydraulic jump. Hager mainly studied the classical hydraulic jump on the roller length [26]. Chanson demonstrated that the strong air entrainment rate and the depth-averaged void fraction data highlight a rapid deaeration of the jump roller [27]. Chanson and Toi found that the roller surface presented a self-similar profile close to classical stationary hydraulic jump results [28]. Leng and Chanson conducted new experiments in a large canal with a focus on breaking bore roller propagation [29]. Wang et al deemed that breaking bores and hydraulic jumps should present a number of similar features [30].

In this study, tidal bores with the different heights were generated in the flume according to various initial water depths and the ebb velocities. In the experiments, the propagation velocity, the height and the aeration form of the tidal bores are measured and recorded. The aim of the experimental study is to seek for factors influencing the change of aerated form and process and to explore the aeration properties of tidal bore front.
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2. Experimental setup

The tidal bores are generated in a 50 m in length, 1.2 m in width, 0.6 m in height and zero bottom slope glass rectangular flume. Figure 2 shows the experimental apparatus for generating the tidal bore at one end of the flume. Number symbols in figure 2 orderly represent the water intake, the water recycling tank, the submersible pumps, the plate of energy dissipation, the gate plate, the flume, the control device of the gate plate, the pull rod. Water was supplied by the submersible pumps to the expectant level in the water intake through the plate of energy dissipation. The bores were generated by laying flat rapidly the gate plate to interlink the downstream end of the flume. As details about the other end of the glass rectangular flume, references also had giving the similar setup to generate the initially steady flow, no longer elaborate here [20-23]. As shown in figure 3, three forms of tidal bore were generated in the glass flume, while they are field observed in the Qiantang River. It is known that forms of tidal bores generated in the glass flume are consistent with those field observations in the Qiantang River [31].

![Figure 2. The experimental apparatus for generating the tidal bore at one end of the flume.](image)

![Figure 3. Three forms tidal bore generated in the glass rectangular flume and field observation in the Qiantang River](image)

The height of tidal bore ($H$), the depth of the ebb flow ($h$) and the velocity of the ebb flow ($v$) can be as the key controllable parameters of the experiment. About the tidal bore heights, ten tests are adopted between 0.03 m and 0.20 m. Therefore, 90 (3×3×10) cases are considered in the flume experiment (see table 1).
Table 1. Experimental parameters of initial ebb flow depths ($h$), initial ebb flow velocities ($v$) and tidal bore heights ($H$).

| parameters | $h=0.042$ m | $h=0.073$ m | $h=0.095$ m |
|------------|-------------|-------------|-------------|
| $v=0$ m/s  | $H=0.015$ m-0.20 m ($U=0.882-1.875$ m/s) | $H=0.031$ m-0.20 m ($U=1.176-1.765$ m/s) | $H=0.045$ m-0.20 m ($U=1.237-2.01$ m/s) |
| $v=0.1$ m/s| $H=0.015$ m-0.20 m ($U=0.791-1.725$ m/s) | $H=0.031$ m-0.20 m ($U=0.997-1.805$ m/s) | $H=0.045$ m-0.20 m ($U=1.101-1.864$ m/s) |
| $v=0.2$ m/s| $H=0.015$ m-0.20 m ($U=0.683-1.667$ m/s) | $H=0.031$ m-0.20 m ($U=0.742-1.698$ m/s) | $H=0.045$ m-0.20 m ($U=0.850-1.745$ m/s) |

Figure 4. Sketch of the measurement method for parameters of tidal bore and ebb flow.

The measurement method for those parameters of the tidal bore and the ebb flow is shown in figure 4. Three capacitive wave-height sensors are equidistantly distributed at 2 m in length ways ($\Delta X = 2m$). During the bore front passage, sensors are used to record the height of ebb flow ($h$) and the levels of tidal bore front ($l$), but also they are used to obtain the interval times ($\Delta t_1$ and $\Delta t_2$) between the three sensors. So the height of tidal bore front ($H$) record by the second sensor could be calculated by $l_h - h$, the mean propagation velocity of tidal bore front ($U$) could be calculated by $\frac{\Delta X}{2\Delta t_1 + \Delta t_2}$. Meanwhile, the velocity of ebb flow ($v$) could be record by an Acoustic Doppler Velocimeter (ADV) paralleling with the second capacitive wave-height sensor.

3. Aeration analysis of tidal bore front

3.1. Forms of tidal bore front

Figure 5. Tidal bore fronts captured by camera through the glass sidewall when $h=0.042$ m and $v=0.2$ m/s.

Figure 6. Tidal levels of bore fronts collected by the second sensor when $h=0.042$ m and $v=0.2$ m/s.
Through the glass sidewall, a highspeed camera is used to record instantaneous free-surface profiles of bore front where the aeration of tidal bore happens during the bore front passage through the second sensor. Figure 5 shows bore fronts captured by the camera while figure 6 shows tidal levels of the bore fronts collected by the second capacitive wave-height sensor when \( h = 0.042m \) and \( v = 0.2m/s \).

From figures 5 and 6, it can be seen that whether the free surface of tidal bore can be broken depend on the height of tidal bore front (\( H \)) and on the mean propagation velocity of tidal bore front (\( U \)) when the condition of ebb flow is certain. Further to say, the forms of the tidal bores fronts changing from the undular bore to the strong breaking bore depend on the Froude number (\( Fr \)) of the tidal bore and the strength of the tidal bore(\( H/h \)), where the Froude number \( Fr \) of the tidal bore can be calculated by

\[
Fr = \frac{(U - v)}{(gh)^{\frac{1}{2}}}
\]  

(1)

where the symbol ‘−’ is meaning that the direction of the mean propagation velocity of tidal bore front (\( U \)) is opposite to the direction of the mean velocity of ebb flow (\( v \)).

By experiments in the glass flume, the forms of the tidal bores are all recognized and classified by \( Fr \) and \( H/h \), so the figure 7 shows the form of the tidal bore with \( Fr \) and \( H/h \). From figure 7, when \( Fr < 1.4 \) and \( H/h < 0.5 \), the surface of the first wave is smooth and train of waves can be observed; when \( 1.4 < Fr < 1.7 \) and \( 0.5 < H/h < 0.8 \), a single breaking wave front with weak aeration can be observed; when \( Fr > 1.7 \) and \( H/h > 0.8 \), a single breaking wave front with violent aeration can be observed. Montesand Chanson suggested that the shape of the surge front is a function of its Froude number [32,33]. Koch and Chanson considered the form of the bore is characterised by a breaking roller for \( Fr > 1.4 \) to 1.6 [6].

Meanwhile, the results are also in accord with the results by Pan and Xie based on the field measurements in the Qiantang River Estuary [18,24]. Compared to hydraulic jump in a horizontal rectangular channel, there is a simple relationship between \( H/h \) and \( Fr \), since

\[
H/h = \eta - 1 = 0.5[(1 + 8Fr^2)^{\frac{1}{2}} - 1] - 1
\]  

(2)

where \( \eta = (H + h)/h \) is the ratio of the hydraulic jump conjugate depth. The relationship between \( H/h \) and \( Fr \) for hydraulic jump also is shown in figure 5. It is noticeable that tidal bore must be likely
as a moving hydraulic jump as Rayleighand Lighthill stated. All in all, the tidal bore generated in the flume is consistent with the tidal bores in the estuary [34,35]. So it is can be admitted that the characteristics of the tidal bore in the flume should be right with the tidal bore in the estuary.

3.2. Aeration process of the tidal bore front
The aeration process is a complex procedure of air entrance, transport and escape when the breaking tidal bore front is moving upstream against the ebb flow. Through observations in the experimental model (figure 8), the aeration process of the tide bore was mainly composed of four stages when the front of tidal bore goes against the ebb flow.

Firstly, when the wave front is breaking, large pieces of air is involved and closed by the rolled water. Secondly, under the influence of the turbulent shear force, the large pieces of involved air deform and split to a large number of different size bubbles, and they are moving down in the effect of large vortices. Thirdly, as the turbulent shear force is weaker than the force of water pressure difference between the top and the bottom, they are all spiralling up and their size are becoming to bigger. Finally, when they are up to the interface, the bigger size bubbles are broken under the influence of surface tension and the air escape from the flow surface.

3.3. Tidal bore aeration and the tidal bore forms
Using the highspeed camera, the tidal bores aeration was recorded and shown in figures 9-11. From these figures, it can be deduced that:

Firstly, when the wave front is breaking, large pieces of air is involved and closed by the rolled water. Secondly, under the influence of the turbulent shear force, the large pieces of involved air deform and split to a large number of different size bubbles, and they are moving down in the effect of large vortices. Thirdly, as the turbulent shear force is weaker than the force of water pressure difference between the top and the bottom, they are all spiralling up and their size are becoming to bigger. Finally, when they are up to the interface, the bigger size bubbles are broken under the influence of surface tension and the air escape from the flow surface.

Figure 8. The aeration process of the tide bore front.

Firstly, when the tidal bore height is small, the undular bore appears with the series of the propelled waves; when the tidal bore height is becoming larger, the waves front begin to break, and the breaking bore propagates; as soon as the tidal bore height is large enough, the bore front is strong breaking. Secondly, the more breaking of the wave front, the more violent of the aeration; that is, the degree of tidal bore aeration is closely related to the tidal bore forms. The tidal bore forms is dependent on the Froude number of tidal bore, which is changing with the propagation velocity of tidal bore, the height and the velocity of the ebb flow. Meanwhile, the propagation velocity of tidal bore is associated with the height of tidal bore. Therefore, the degree of tidal bore aeration is not only closely related to the Froude number of the tidal bore but also to the strength of the tidal bore.
3.4. The aeration length of tidal bore

From the above analysis, the tidal bore aeration is closely related to the Froude number of the tidal bore \( Fr \) and the strength of the tidal bore \( H/h \), but the tidal bore aeration is hard to be directly quantified up to now, because it was difficult to accurately measured the concentration of clouds of air bubbles by the current technology. However, if the aeration length of tidal bore is defined, it can be accurately measured and may provide a technique to indirectly quantify the tidal bore aeration. Horizontal distance from the impingement point to the point where air bubbles total escape is defined as the aeration length of tidal bore (\( L \)), which are shown in figure 12.

From the previous analysis, if the depth of the ebb flow is certain, when the height of the tidal bore (\( H \)), the propagation velocity of tidal bore (\( U \)), and the velocity (\( v \)) of the ebb flow increases, the more breaking the tidal bore front is, the more turbulence intensity is, the more violent the wave front aeration is, the longer distance air bubbles move. That is, relative aeration length is both closed related to the strength (\( H/h \)) and the Froude number (\( Fr \)) of tidal bore. Therefore, based on the tests to respectively analysis the relationships the relative aeration length with the strength of tidal bore and the Froude number of tidal bore,

\[
\frac{L}{h} = f\left(\frac{H}{h}, Fr\right)
\]
\[ L/h = f(H/h) \]  
\[ L/h = f(Fr) \]

By extracting and calculating the relative aeration length, the strength of tidal bore and the Froude number of tidal bore from all cases in the flume, the functional relationship graphics are plotted as shown in figures 13 and 14.

The regressions for \( L/h \) and \( H/h \) yield

\[ L/h = 3.9765(H/h)^{1.2026} \]

with an excellent correlation coefficient of 0.975 as shown in figure 13.

The aeration length of tidal bore is different from the roller length of tidal bore, and the roller length of tidal bore can be derived by the results about the front steepness of tidal bore (\( \delta \)). According to the results obtained by Huang [22], the front steepness of tidal bore has a positive linear relationship with the strength of tidal bore (\( H/h \)) as

\[ \delta = 0.415H/h + 0.115 \]

while the front steepness of tidal bore (\( \delta \)) basically can be identified as

\[ \delta = H/L_r \]

So, from the equations (7) and (8), it is obtained that

\[ L_r/h = (H/h)(0.415H/h + 0.115)^{-1} \]

\[ L/h = f(H/h) \]  
\[ L/h = f(Fr) \]

And the figure 13 also plots the equation (9) to compare with the experimental data and the regression equation (6). It is easy to know that the roller length of tidal bore is far less than the aeration length of tidal bore. It is all because the roller length just is small apart of the aeration length of tidal bore. The roller length just appraised the intensity of air entrance to the front of tidal bore, but the aeration length fully appraised the intensity of air entrance, transport and escape at the front of tidal bore.

The regressions for \( L/h \) and \( Fr \) yield

\[ L/h = 1.1698Fr^{2.8526} \]

with an excellent correlation coefficient of 0.972 as shown in figure 14.

It is well known that the tidal bore aeration length is likely to the roller length of hydraulic jump.
Wang et al obtained that the roller length of hydraulic jump follows a linear function of the Froude number for $Fr < 10$ as equation (11) [30].

$$L_r / h = 6(Fr - 1)$$  \hspace{1cm} (11)

Figure 15 also compares the equation (11) with the experimental data for tidal bores with the Froude number. Figure 14 shows the tendency that the roller length of hydraulic jump is far less than the aeration length of tidal bore when the Froude number becomes bigger. It is proved from another side that the aeration of tidal bore is far more violent than the aeration of hydraulic jump.

Figure 15. Diagram of comparison between theoretical values and experimental values of $L/h$.

From the data obtained from the experiments, it is obvious that $L / h$ is a power functional relationship with $H / h$ and $Fr$, respectively. If the strength of tidal bore and the Froude number of tidal bore are both considered into the relationship of the relative aeration length, the equation (3) must be rewrite as:

$$L / h = f(H / h, Fr) = a(H / h)^b Fr^c$$  \hspace{1cm} (12)

by nonlinear regression analysis, $a=1.993$, $b=0.555$, $c=1.592$, with a coefficient of multiple determination of 0.975. Eventually, an experimental equation is obtained to calculate the aeration length of tide bore,

$$L / h = 1.993(H / h)^{0.555} Fr^{1.592}$$  \hspace{1cm} (13)

Where $H / h$ is the strength of tidal bore, $H / h > 0.8$; $Fr = (U - v) / (gh)^{1/2}$, is the Froude number of tidal bore, $Fr > 1.7$.

Through comparison between theoretical values and experimental values of $L/h$ as shown in Figure 15, they are in accord with each other and the errors are less. Meanwhile, to verify the practically application and the accuracy of the experimental equation (13), several cases comparisons between the field observation [35] (Yanguan Segment of Qiantang River, 2010) and the experimental formula calculation are listed in the table 2. From table 2, the experimental calculation is less than the field observation, the main reason must be that aeration scale in the experiment is smaller than the actual scale of aeration in the field. However, the calculation results and the measured values are very close and the relative errors are relatively small. Hence, as an empirical equation, equation (13) can be applied to calculate the aeration length of tidal bore, which could be used to indirectly quantify and
Table 2. Comparisons between the field observation and the experimental formula calculation.

| case | h (m) | v (m/s) | U (m/s) | H (m) | H/h | Fr | Form of tidal bore | L (m) | Relative error (%) |
|------|-------|---------|---------|-------|-----|----|-------------------|-------|-------------------|
| 1    | 1.20  | -0.60   | 2.90    | 0.50  | 0.42| 1.02| undular           | --    | --                |
| 2    | 1.40  | -0.76   | 3.20    | 0.68  | 0.49| 1.07| undular           | --    | --                |
| 3    | 1.08  | -0.75   | 3.89    | 0.70  | 0.65| 1.43| weak breaking 0-3 | 2.99  | --                |
| 4    | 1.35  | -1.20   | 5.36    | 1.42  | 1.05| 1.80| strong breaking 7.5| 7.05  | -6.04             |
| 5    | 1.65  | -1.10   | 7.15    | 2.25  | 1.36| 2.05| strong breaking 13 | 12.23 | -5.93             |
| 6    | 1.30  | -0.83   | 8.58    | 2.44  | 1.88| 2.64| strong breaking 18 | 17.25 | -4.16             |
| 7    | 1.23  | -0.91   | 9.24    | 3.05  | 2.48| 2.92| strong breaking 23 | 22.35 | -2.84             |
| 8    | 2.00  | -1.60   | 9.88    | 3.88  | 1.94| 2.59| strong breaking 27 | 26.20 | -2.98             |

4. Conclusions

In this study, an aeration analysis of the tide bore front caused by the wave front breaking was performed. It was obtained that the degree of tidal bore aeration is not only closely related to the Froude number of the tidal bore but also to the strength of the tidal bore. The definition of aeration length of tidal bore was proposed and measured to indirectly quantify the tidal bore aeration. According to the non-dimensional aeration length of tidal bore, the strength of tidal bore and the Froude number of tidal bore are both considered as equally important parameters to nonlinear regression analysis. It is revealed that a power function relationship during the relative aeration length of tidal bore, the intensity of tidal bore and the Froude number of tidal bore. The aeration length of tidal bore could be estimated by equation (13). The relative aeration length of tidal bore could represent and indirectly quantify the tidal bore aeration.

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