International Conference on Estuaries and Coasts
November 9-11, 2003, Hangzhou, China

TIDAL BORE IN THE NORTH BRANCH OF THE CHANGJIANG ESTUARY

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Abstract: The development, characteristics and causes of the tidal bore in the North Branch of the Changjiang Estuary are expounded, based on in-situ survey, measured and relative historical data. When the velocity of flood current exceeds the tidal wave celerity (the supercritial flow occurs), the water level abruptly jumps and a tidal bore is formed. The Froude number can be used to determine whether a tidal bore will form or not. A analysis indicates that narrowing channel increases flood current velocity and sloping riverbed slows down wave celerity. The North Branch channel has been narrowed and its bed has been silted because of natural processes and artificial reclamation in recent years, which are the main causes of frequent and strong bore occurrence. Furthermore the observed data in April 2001 when the tidal bore occurred at the Qinglong Harbor indicated that a tidal bore was produced when the Froude number F_r>1. The converging funnel shape and submerged sand bars are necessary conditions for the formation of a bore. The Froude number begins greater than 1 at Lingdianxi (50 km upstream from the mouth) for either maximum or minimum bores, which indicates Lingdianxi is the initial site of North Branch bores.

Key words：Tidal bore, tidal wave, Froude number, Conditions of bore formation, Initial site of bore, North Branch of Changjiang estuary

1. INTRODUCTION

A tidal bore is a positive surge of tidal origin that may form when a rising tide enters a shallow, gently sloping and narrowing river from a broad estuary. Although only a few bores have been studied in detail, many tidal bores can be seen worldwide. A United States Geological Survey in 1988 found about 70 occurrences in 16 countries worldwide, on every continent except Antarctica (Bartsch- Winkler and Lynch, 1988). Famous examples include the Qiantang River tidal bore on Qiantang river in China (Dai and Zhou, 1987), the Amazon bore in South America called *pororoca*, the tidal bore on the Seine river (*mascaret*) and the Hoogly (or Hooghly) bore on the Gange. Smaller tidal bores occur on the Severn river near Gloucester, England, on the Garonne and Dordogne rivers in France, at Turnagain Arm and Knik Arm, Cook Inlet (Alaska), in the Bay of Fundy (at Petitcodiac and Truro), on the Styx and Daly rivers (Australia), and at Batang Lupar (Malaysia).

In China, there are tidal bores occurred in several estuaries besides the Qiantang bore, such as Feiyunjiang, Aojiang and Jiaojiang in Zhejiang Province and the North Branch of Changjiang (Yangtze River) estuary. The North Branch tidal bore has been strengthened in recent years due to the North Branch shrinking.

A tidal bore is a peculiar natural phenomenon, which may significantly affect estuarine processes due to its strong energy (Chen et al, 1990; Chen et al, 2003), and also affect shipping industries and estuarine ecosystem. The tidal bore on the North Branch formed due to the evolution of the North Branch, vice visa, the strong tidal bore has became an important factor influencing the evolution of the North Branch.

2. TIDAL BORE DEVELOPMENT

The North Branch bore in Changjiang estuary occurred initially in the1940s (Chen and Shen, 1988), and has lasted more than 60 years to this day. Compared with the Qiantang bore, both the occurrence frequency and height of the North Branch bore are smaller. In recent years, however, with the North Branch narrowed, tidal waves deformed increasingly, the height of the bore increased, which has raised attention of authorities. The tidal bore on North Branch is the result of the evolution of Changjiang estuary. The Changjiang estuary formed the three-grade bifurcation and four-mouths into sea from an open funnel-form embayment in historic period. There had been occurred a tidal bore in 2000 B.P. and it lasted approximately a thousand years, called the Guanglin bore (Chen and Shen, 1988), much like the North Branch bore today.

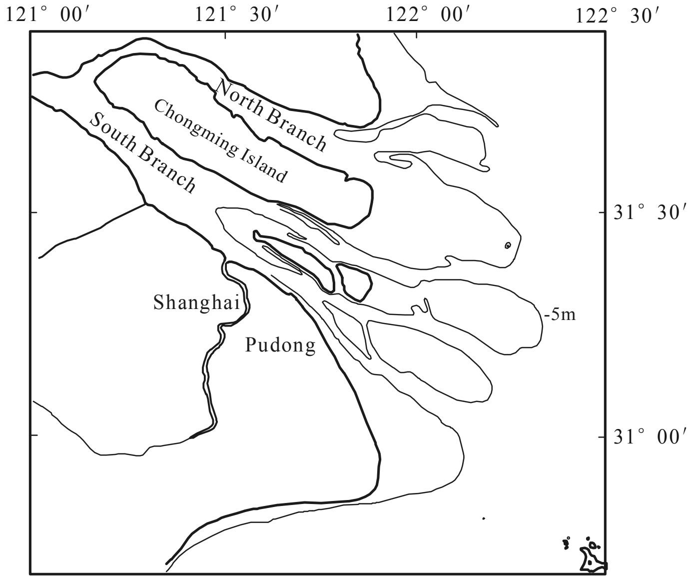

Fig. 1 Changjiang estuary

2.1 NORTH BRANCH EVOLUTION

The North Branch of Changjiang estuary is a first-grade fork (Fig.1), located in the north of Chongming Island, with a length of 80 km and average water depth of 2 to 4 m. Its upper mouth is connected with South Branch, with a width of 3 km, and its lower mouth opens to the sea with a width of 16 km. The North Branch is a quasi-macrotidal estuary, which is funnel shaped. The tide is a semi-diurnal tide, with average tidal range of about 3.04 m and a maximum of 5.95 m (Guo, 1995). Its evolution is greatly controlled by the topographic feature, hydrodynamic conditions and sediment source, especially the changes of the water discharge of Changjiang.

The water discharge of Changjiang into the North Branch has decreased constantly since the beginning of the 20th century. For example, in the 1920s, the water discharge into the North Branch accounted for 25% (1915), and in the beginning of the 1960s, the upstream of the North Branch was further narrowed due to land reclamation, which led to water discharge decreasing greatly. In the 1970s, the water discharge accounted for only 5%, now it has decreased to only 1.3% (Chen et al, 2003). Because the water discharge decreased, the North Branch transformed a channel dominated by ebb to a channel dominated by flood.

The North Branch continues to shrink with water discharge decreasing. After the Changjiang mainstream began to flow into sea through South Branch in the 18th century, the river discharge into North Branch decreased gradually and the river channel shrank, especially in its upper reach (Fig.2). The channel bulk below 0m has decreased steadily since 1950s (Fig.3). The channel bulk in 1958 was 16.0×10^8 m^3, decreased to 6.3×10^8 m^3 in 2001, decreasing approximately 60% during the entire period. In addition, the reduction in discharge has led to a stronger tidal intrusion, so that the entire North Branch is dominated by flood tide. Its upper reaches silted seriously and water depth became continuously shallow. However, its mouth was enlarged, e.g. the cross-section area at Lianxing Harbor enlarged from 36,900m^2 in 1991 to 38,200m^2 in 1998.

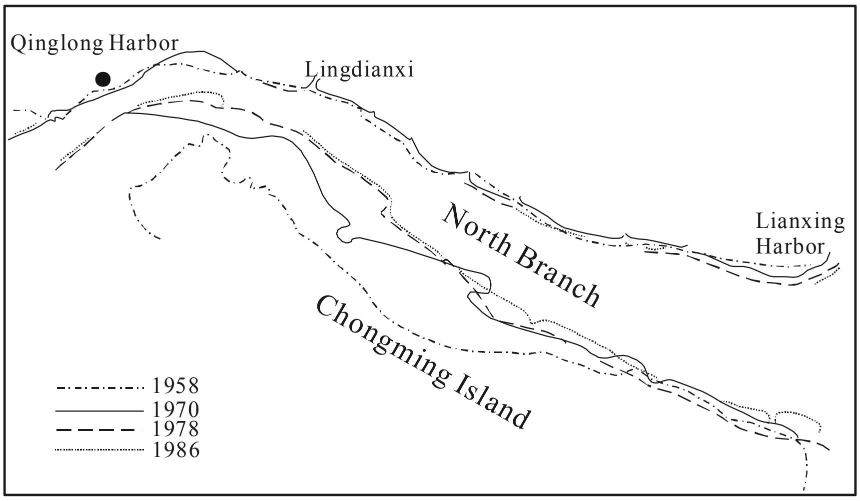

Fig. 2 Channel bank changes of the North Branch from 1958 to 1986

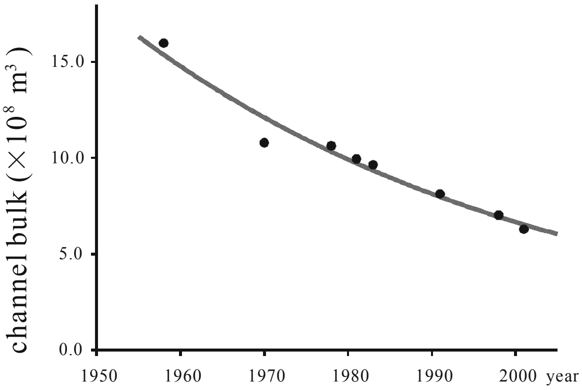

Fig. 3 Channel bulk changes of the North Branch from 1958 to 2001

2.2 BORE CHARACTERISTICS

The tidal bore on the North Branch has three types: 1. Low-head bore, its height is only 10 to 30 cm, and this bore, like a ship wave, is not broken. 2. One-line bore, its height is over 30 cm, and its head is broken, looking like a white line from far. 3. Backtrack bore, is formed when a strong bore propagating to the upper mouth of North Branch is reflected by the South Branch. At the Qinglong Harbor, backtrack bores can usually be seen after 1~1.5 hours when one-line bores passed. The height of backtrack bores are not less than one-line bores, can be much higher.

Fig.3 is a tidal bore observed at the Qinglong Harbor in October 4, 2001. The height of the bore is about 0.6m. Analysis of surface water sampling shows the sediment concentration of the bore head is up to 15.92 kg/m^3, and its salinity is only 1.34 ppt. Two hours later, the sediment concentration is only 2.50 kg/ m^3, while the salinity is up to 8.7 ppt. This suggests that strong turbulent bore head carried a large amount of sediments to push upstream and even into the South Branch, which has a major impact on the estuarine evolution.

Fig. 4 The tidal bore on the North Branch of Changjiang estuary

3. CONDITIONS AND CRITERIA OF BORE FORMATION

A tidal bore is formed under special conditions. Generally, bores occur in estuarine channels with high tidal range, narrowing and sloping entrance, and very small river discharge compared to tidal flow. However, these conditions are only some of the necessary conditions of bore formation. The occurrence of bores still need a sufficient condition, i.e. flood current velocity is greater than tidal wave celerity. Bores are formed only when flood current velocity exceeds tidal wave celerity. The estuarine topography (plane and floor) and tidal pattern may influence current velocity and wave celerity. The bore formation on the North Branch can also be explained by the theory above.

The North Branch is a funnel-shape food-dominated estuarine channel. For the funnel-shape estuary, the area of wetted cross-section decreases upstream, accordingly the speed of flood current increases. The submerged sand bar in the channel causes the depth of water to shoal, thus the celerity of tidal waves decreases. It is obvious that the funnel-shape and submerged sand bar are the necessary condition of tidal bore formation.

A tidal bore is a solitary non-linear shallow water undular wave. In shallow water, wave celerity is proportional to the square root of depth, i.e. $C = \sqrt{gh}$. The fast moving deep water waves carryies the tide into shallow water and interact with the estuary's sloping floor decreasing the wavelength. The crest being deeper than the trough causes the wave to become asymmetric with the advancing side being steeper than the following side (Lynch, 1982). When the velocity of the particle is greater than the wave velocity then a hydraulic jump (a bore) is formed.

In order to better understand how a tidal bore flows, it could be considered necessary to have a comprehension of the role the Froude number plays in the flow. The Froude number (F_r) is a dimensionless number; a description of the appearance and shape of the hydraulic jump (the tidal bore):

$$F_r = \frac{V}{\sqrt{gh}} \tag{1}$$

Where V = flood velocity; h = water depth, g = gravitational force and $\sqrt{gh}$ is the celerity of tidal wave (C) propagating in shallow water.

According to many observations, tidal bores occurred when F_r>1, which means that when flood current velocity exceeds tidal wave celerity, the water particles transfer the kinetic energy to the potential energy, thus the water level abruptly jumps and bore forms. The width of North Branch gradually narrowed from 16 km at mouth to 2 km at upper reach, appearing funnel-shaped. For a shallow and narrow estuary, the tidal wave celerity (C) needs to be revised by runoff velocity (U) (Huang and Lu, 1995). Thus Equation (1) can be written as:

$$F_r = \frac{V}{\sqrt{gh} - U} \tag{2}$$

Where V is maximum velocity of flood ($V_{\max}$), h is the water depth at maximum velocity, and U can be calculated from water discharge and wetted cross-section area, which is considered as a constant in a short time.

Equation (2) is used to calculate Froude number of North Branch and to determine whether a bore will form there or not. According to the measured current velocity and water depth at Qinglong Harbor (about 60 km upstream from the mouth) on April 4, 2001, F_r>1 (1.03 and 1.25) on April 10 and 11, bores occurred with a height of 0.3m and 0.5m, respectively, while on April 12 and 13, the F_r<1 (0.47 and 0.69), no bore occurred.

Through the calculation above, it is suggested that the Froude number (F_r) can be used to determine whether a tidal bore will form or not. The result shows that supercritical flow (the flood flow exceeding tidal wave celerity) is a cause of bore formation. The formation of supercritical flow in the North Branch is due to decreased water depth, which slows down tidal wave celerity and narrowed river channel, which increases flood current velocity. In addition, large tidal influx is also a condition of supercritical flow formation. Tidal bores are formed due to strong tides combined with special estuarine channel features. For the North Branch, bores can be viewed at upstream during spring tides.

Tidal bores are formed, as stated earlier, by a surge of water due to an unusually high tide (determined by estuary shape and location) to be forced upstream in a continuously narrowing environment. For tidal bores to occur, two criteria must be established. The topography of the river itself must be one that allows the tide to 'squeeze' into the river and build in height, and also the need for exceptionally high tidal range. Bores do not occur every day, they are most powerful around the time of a new or a full moon when the tide is at its highest.

4. THE INITIAL SITE OF TIDAL BORE

In the way of tidal waves propagating upstream, the site beginning to form a bore is called initial site of tidal bore. Theoretically, it is the earliest site that a flood current velocity exceeds the wave celerity, i.e. the Froude number F_r>1. Therefore, the initial site of tidal bore on the North Branch can be determined through calculating tidal wave celerity and flood current velocity along the North Branch channel (Fig.5). However, the bore initial site generally changes with tide pattern: it shifts downstream during extremely strong tide, whereas shifts upstream during relatively weak tide action. Here, the two extreme cases of the maximum and minimum bore ever occurred are selected to calculate wave celerity and current velocities, respectively. The maximum bore occurred with a height of 1.6m on August 20, 1974 when the tidal influx was up to 20.7×10^8 m^3 at the mouth (Zhang and Cao, 1998). The minimum bore occurred with a height of 0.3 m on April 10, 2001 when F_r=1.03 at Qionglong Harbor.

The tidal wave celerity (C) can be calculated by water depth along the way of tide propagation: $C = \sqrt{gh} - U$ in Equation (2). The results are listed in Tab.1 for the wave celerity of the two extreme bores.

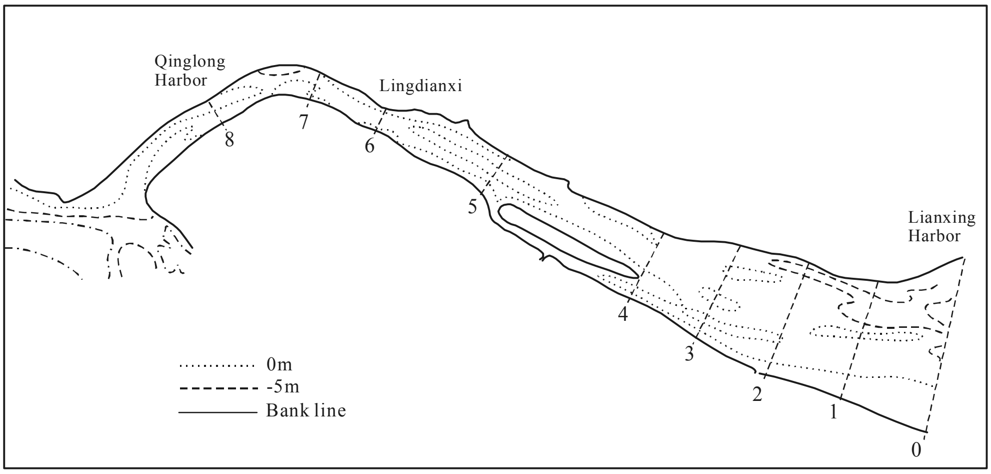

Fig. 5 The North Branch of Changjiang estuary

Table 1 Tidal wave celerity for the maximum and minimum bores along North Branch

Section No.	0	1	2	3	4	5	6	7	8
Channel width (km)	12.00	10.94	10.68	9.00	7.20	4.08	2.10	2.00	2.00
Max bore *C* (m/s)	5.18	4.98	4.79	4.60	4.22	3.88	3.45	3.32	2.57
Min bore *C* (m/s)	5.44	5.24	5.05	4.87	4.50	4.19	3.80	3.49	3.03

Table 1 shows that the wave celerity changes as either the maximum bore or minimum bore occurrences decrease from the mouth to upstream, and the decreasing rate from Section 5 (the Sanhe Harbor) increases significantly. The wave velocities of maximum bore are less than these of minimum bore, and decreasing rate of maximum bore from Section 5 is larger than that of minimum bore.

The flood tidal current velocities ($\overline{V}$) for the two extreme cases can be calculated through tidal influx (Q):

$$Q = \overline{V}St \tag{3}$$

Where $\overline{V}$ =sectional flood mean velocity; S =wetted cross-section area, approximately the product of channel width (B) and tidal range (H); t= duration of flood. Thus the Equation (3) can be written:

$$\overline{V} = \frac{Q}{BHt} \tag{4}$$

The sectional flood mean velocities for each cross section along the North Branch can be calculated from the above equation. In the Equation (4), the channel width (B) can be obtained from topographic map, and the tidal range (H) and duration of flood (t) for each section are obtained through interpolating linearly based known sites The tidal influx (Q) for each section can be calculated based length of channel, cross-section width and tidal range. Results indicate that the minimum tidal influx for bore occurred is 18×10^8 m^3 per tidal cycle at the mouth of the North Branch or 1.5×10^8 m^3 at Qinglong Harbor.

The Froude number is the ratio of maximum flood velocity to tidal wave celerity. The maximum flood velocity $V_m = 1.84\overline{V}$ is based on measured data (Chen, 2003). Thus the Froude number for each section can be obtained (Tab.2).

From the Table 2, the Froude numbers of both the maximum bore and minimum bore F_r>1 from the Section 6 (at Lingdianxi, about 50 km upstream from the mouth). Therefore, Lingdianxi is the initial site of bores on the North Branch. All bores begin to occur from the site.

Table 2 Froude number changes along North Branch during maximum or minimum bore

	Site (Section)	0	1	2	3	4	5	6	7	8
Minimum bore	V_m (m/s)	3.00	2.69	2.26	2.41	2.26	3.09	4.58	3.92	3.12
	C (m/s)	5.44	5.24	5.05	4.87	4.50	4.19	3.80	3.49	3.03
	F_r	0.55	0.51	0.45	0.49	0.50	0.74	1.21	1.12	1.03
Maximum bore	V_m (m/s)	3.09	2.82	2.49	2.47	2.30	3.19	4.81	4.26	3.38
	C (m/s)	5.18	4.98	4.79	4.60	4.22	3.88	3.45	3.32	2.57
	F_r	0.60	0.57	0.52	0.54	0.55	0.82	1.39	1.28	1.32

5. CONCLUSION

The tidal bore on the North Branch of Changjiang estuary forms when the flood current velocity exceeds the tidal wave celerity, the water particles transfer the kinetic energy to the potential energy. The Froude number can be used to determine whether a tidal bore will form or not. The narrowed river channel increases flood current velocity and silted riverbed slows down tidal wave celerity. The river channel of the North Branch has been narrowed and its bed has been silted because of natural processes and artificial reclamation for recent years. The converging funnel shape and submerged sand bars are the necessary conditions for the formation of a bore on the North Branch. The flood influx over 18×10^8 m^3 per tidal cycle at the mouth of the North Branch are the sufficient conditions for bore formation. Although the maximum flood influx may reach up to 20.7×10^8 m^3 at the mouth, a tidal bore begins to occur only at the Lingdianxi (50 km upstream from the mouth). Therefore, the Lingdianxi is the initial site of North Branch bore. With the bore head advance, a great amount of sediments flow upstream, and flow backward into the South Branch of Changjiang estuary, which have major impacts on the river channel evolution and environment of the estuary.

ACKNOWLEDGEMENTS

This study was supported by Shanghai Priority Academic Discipline and National Natural Science Foundation of China, No. 40276027.

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