# LOCAL SCOUR CHARACTERISTICS OF GROINS AT TIDAL WATERWAYS AND THEIR SIMULATION

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For the channel regulation in tidal rivers, groins are often used as typical hydraulic structures. Precisely predicting the local scour depth at the groin head is the key for the project of river regulation. The local scour of groins for tidal rivers is significantly different from that for the undirectional steady flow of general rivers. In the present paper, a three-dimendional (3D) mathematical model for turbulence and sediment transport are establishmented. The local scour near the groin under the actions of tidal current and steady flow are simulated by established 3D turbulence and sediment transport numerical model.The differences of the scour development and the scour pattern near the groin under these two actions are compared.

*Keywords: tidal river; local scour; groin; numerical model; finite volume method (FVM)*

## INTRODUCTION

With the accelerated development along the coast and the river, the tidal channel and coastal estuary have been vigorously trained. In the regulations, a groin is a commonly-used hydraulic structure. When the groin is used for river regulation, the best embedding depth should be firstly designed so as to ensure the safety of the groin. This is because a larger scour pit is always formed at the groin head, endangering its own safety and restricting the effectiveness of groin works. The flow and sediment movement near the groin are the typical three-dimensional problem. Especially at the tidal river reaches, the tidal movement is characterized as tidal unsteady reciprocating flow at estuaries, and the hydrodynamic conditions and sediment movement show periodical changes, so that this problem becomes more complex. Therefore, it is of far-reaching importance for the construction and protection of navigation channels to conduct research on the local water flow and the law of sediment movement near hydraulic structures like groins at the tidal reaches and to predict the formation of the maximum scour depth of local scour. In this paper, a three-dimensional numerical model of turbulent sediment is established to carry out a simulation research on the local scour of groins at the tidal reaches.

## SIMULATION REACH

The reach to simulate is generalized from the North Passage at the Yangtze River estuary (Fig. 1). The generalized reach is about 10km long, and its longitudinal gradient is designed with reference to 0.027‰ of the actual longitudinal gradient of the North Passage at the Yangtze River estuary. Two guide levees not crossing water are arranged on the southern and northern sides respectively. The reach between guide levees is about 6km long and about 2km wide, and the outlet is a widened section which is 3km at its widest point. The bottom elevation of the channel between the guide levees is -10m and the bottom width is 160m, while the side slope of the channel is 1: 50. The bottom centerline of the channel is about 1.3km away from the north guide levee and about 0.7km away from the south one. The bottom elevation of both sides of the channel is generalized as -6m (Fig. 2). A pair of groins is arranged in the guide levees (Fig. 3). The long groin is about 660m long, while the short groin is about 270m long. Both of them are non-submerged, and vertical to the guide levee.

## MODELS ESTABLISHMENT

The turbulent movement of incompressible viscous fluid can generally be described by the Reynolds Equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

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$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=X_i-\frac{1}{r}\frac{\partial p}{\partial x_i}+n\frac{\partial^2 u_i}{\partial x_j\partial x_j}+\frac{1}{r}\frac{\partial(-r\overline{u_i^{'}u_j^{'}})}{\partial x_j} \qquad (2)$$

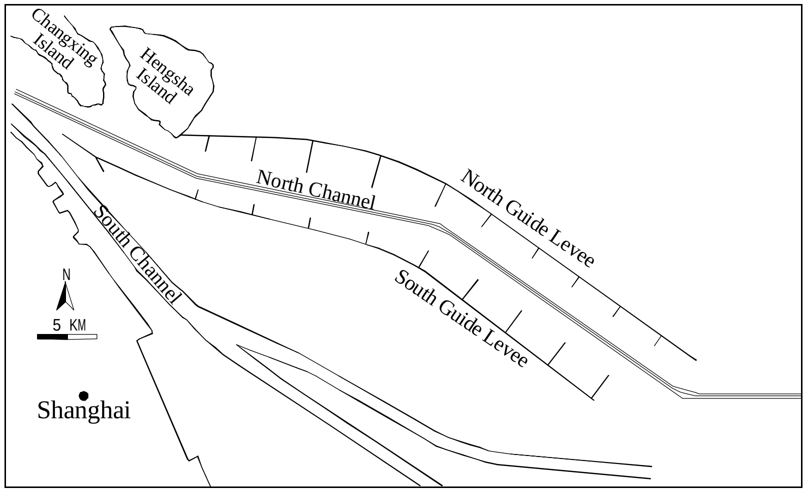



**Fig. 1 Arrangement diagram of guide levees and groins under the deep water channel regulation works at the Yangtze River Estuary**

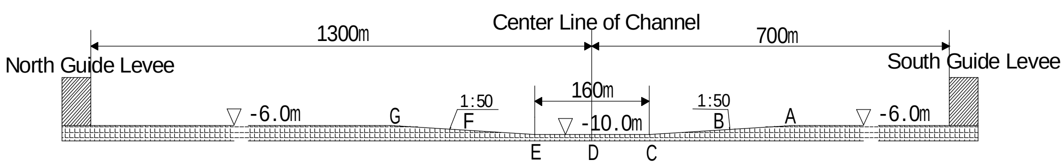



**Fig. 2 Cross-section drawing of the generalized reach**

Wherein, $u_i$ is the component of time average velocity in the direction $i$; $X_i$ is the mass force; $n$ is the coefficient of kinematic viscosity; $r$ is the fluid density; $-r\overline{u_i^{'}u_j^{'}}$ is the Reynolds stress; and $p$ is the pressure.

As an unclosed equation, Reynolds equation contains the Reynolds stress. It needs to be closed by a turbulent model. Currently, the most widely-used equations are $k$ and $e$ equations raised by Launder and Spalding (1974):

$$\frac{\partial k}{\partial t}+u_i\frac{\partial k}{\partial x_i}=\frac{\partial}{\partial x_i}(C_k\frac{k^2}{e}\frac{\partial k}{\partial x_i}+u\frac{\partial k}{\partial x_i})-\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}-e \qquad (3)$$

$$\frac{\partial e}{\partial t}+u_i\frac{\partial e}{\partial x_i}=\frac{\partial}{\partial x_i}(C_e\frac{k^2}{e}\frac{\partial e}{\partial x_i}+n\frac{\partial e}{\partial x_i})-C_{e1}\frac{e}{k}\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}-C_{e2}\frac{e^2}{k} \qquad (4)$$

The three-dimensional suspended sediment transport equation can be expressed as follows:

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial x}\left(e_{sx}\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(e_{sy}\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(e_{sz}\frac{\partial S}{\partial z}\right)+\frac{\partial w_s S}{\partial z} \qquad (5)$$

Wherein: $S$ is the sediment concentration, $w_s$ is the settling velocity of sediment grains, $e_s$ is the sediment diffusion coefficient, $s_s$ is the Schmidt number with a value range of 0.5~1.0. Based on the suspended sediment transport equation, the bottom boundary condition for the suspended sediment movement is:

$$w_s s + \frac{n_t}{s_s}\frac{\partial s}{\partial z} = D_b - E_b \qquad (6)$$

Wherein: $D_b$ is the deposition flux on the riverbed interface； $E_b$ is the uptrend flux of sediment on this interface; according to the conservative flux, the equation for the riverbed deformation caused by suspended sediment is as follows:

$$-g_s'\frac{\partial h_s}{\partial t} = -D_b + E_b \qquad (7)$$

Wherein: $g_s'$ is the dry density of sediment, $h_s$ is the thickness of silt or scour caused by suspended sediment. $E_b - D_b$ represents the net flux on the sediment interface.

The bottom sediment transport equation is as follows:

$$\frac{\partial N_b}{\partial t} + \frac{\partial u_b N_b}{\partial x} + \frac{\partial v_b N_b}{\partial y} = b_s w_s (N_b - N_b^*) \qquad (8)$$

Wherein: $N_b$ is the amount of bedload sediment in a unit volume, $u_b$ and $v_b$ are the flow velocity at the calculation points near the bottom grid, and $b_s = U_b / L_s w_s$ , $U_b = \sqrt{u_b^2 + v_b^2}$ .The riverbed deformation caused by bed load can be expressed as follows:

$$g_0 \frac{\partial h_b}{\partial t} = b_s w_b (N_b - N_b^*) \qquad (9)$$

There is a great difference between local scour and general scour. Through the study of local scour, many scholars have discovered that local scour is produced when the velocity of approach doesn't reach the incipient velocity of general scour. On the basis of the Carstens formula, Dou Xibing (1997) gained a new formula for the critical incipient velocity of local scour by taking into consideration the action of vertical water flow during local scour. This new equation is as follows:

$$\frac{U_{b,cr}^2}{(r_s / r - 1)gd} = 3.61(\tan f \cos a - \sin a) + \left[ -B\frac{|w|^2}{(r_s / r - 1)gd} \right] \qquad (10)$$

Wherein, B is an undetermined coefficient. This equation takes into consideration the action of vertical flow velocity in addition to the impact of the slope and repose angle, which can be used to calculate the critical incipient velocity of sediment at the time of the occurrence of local scour.

## NUMERICAL SIMULATION OF LOCAL SCOUR UNDER TIDAL FLOW ACTION

Under the action of tidal flow and unidirectional flow, the local scour processes of a pair of groins (only the south groin S1 and the north groin N1) at the generalized river reaches are separately studied through the numerical model, and four points A~D are set at the head of the groin to specifically observe the changes of scour depth at four points (Fig. 3).

The gird used in calculation is an orthogonal curvilinear gird in plane (Fig. 4) and σ coordinate transformation grid in vertical. The total number of girds is 198×46×10. The boundary condition of the upstream is controlled by the flow discharge process and the flow discharge is transformed into the vertical velocity. The boundary condition of the downstream is controlled by the tidal level process. The turbulent viscosity coefficient is determined by turbulent model; and the time step of the flow model is taken as 1.0s. In the sediment model, the volume weight of bed sand is 1.48t/m3, and the volume weight of dry sand is 0.55t/m3. The grain size and settling velocity of the suspended sediment are 0.023mm and 0.014cm/s separately; and the grain size and settling velocity of the bed load are 0.05mm and 0.063cm/s separately. The time step of the sediment model is 5.0s; and the critical incipient velocity of the near-bed load is calculated by Equation (10). The thickness of the bedload transport layer $d_b$ is taken as 5% of the water depth; and the roughness height of the bed is calculated by using $z_0 = k_s / 30$. Wherein, $k_s$ is calculated by using the Equation $k_s = (An)^6$, $A$=22, and $n$ is the Manning roughness coefficient.

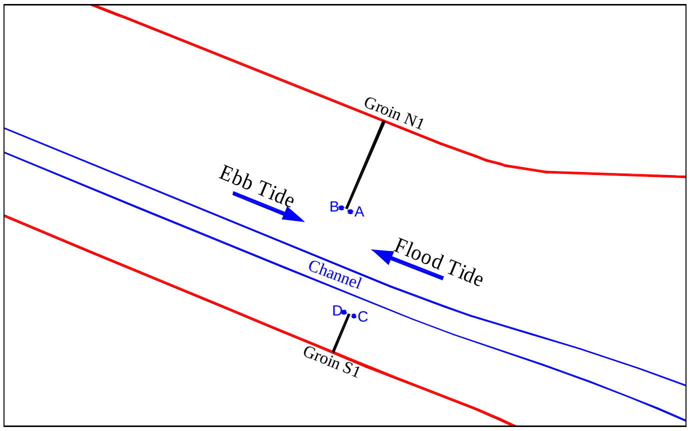



**Fig. 3 Arrangement of groins and observation points of the local scour process**

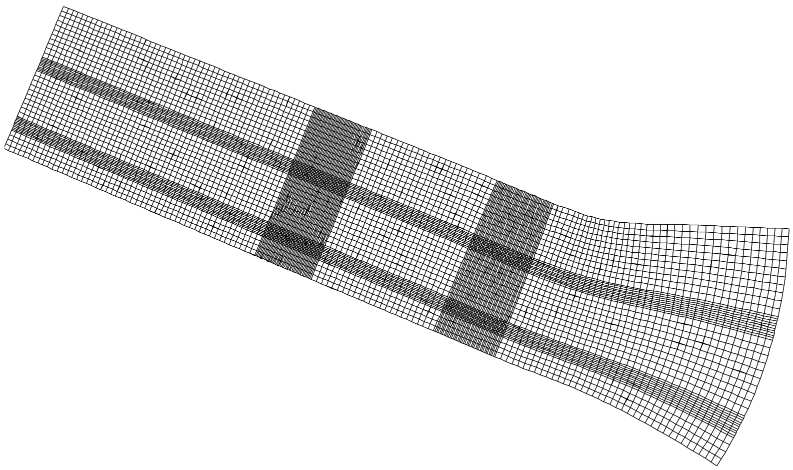


**Fig. 4 Plane gird for mathematical model calculation**

In order to compare with the measured data of local scour at the groin head under tidal flow action in the physical model test, the time used for calculation in the numerical model is identical with the measured time (805 hours). When calculating the local scour under the action of unidiretional flow, the maximum velocity of ebb tide is used as the unidiretional flow velocity. Fig. 5 represents the local scour processes of the N1 and S1 groin heads under the action of both unidirectional flow and tide. According to the calculated results, the scour depth increase trend of the groin heads under the action of tide is consistent with the measured results. For the same time, the local scour depth under the action of unidiretional flow is slightly deeper than that under the action of tide. On one hand, the flow condition selected for use in the local scour under the action of unidiretional flow could be the maximum velocity of ebb tide. On the other hand, the flow is reciprocated under the action of tide, causing the sediment to be transported in a reciprocated manner. So, the effective acting time of the maximum velocity of flood and ebb in respect of the scour pit becomes shorter than that under the action of unidirectional flow, due to the effect of flood and ebb of tidal movement.

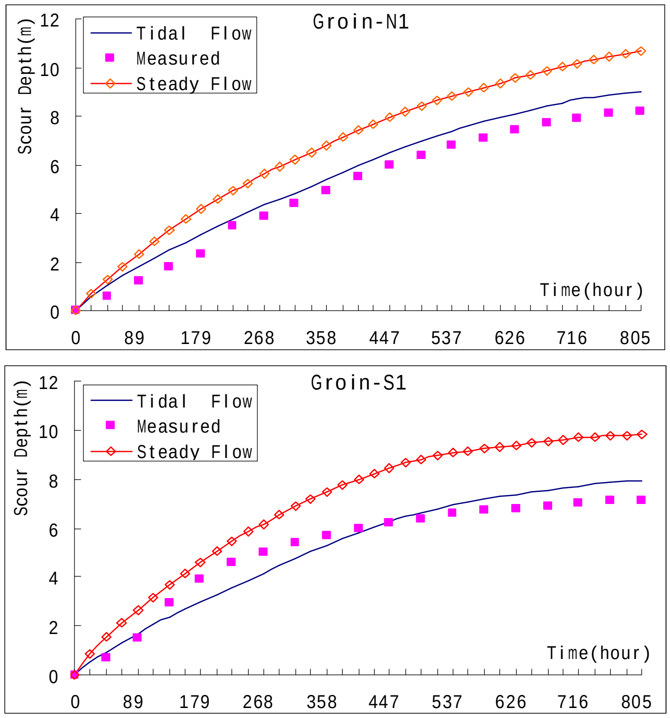
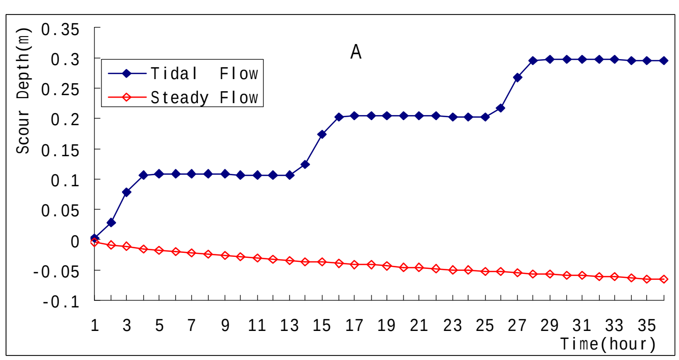



**Fig. 5 Scour processes of the N1 and S1 groin heads under the action of tidal flow and unidirectional flow**

In order to make a detailed study of the relationship between the scour process of the groin head and the duration and strength of the flood and ebb of tide under the action of the tide, the development process of local scour in the first 36 hours (the tide level rising and falling for three times) at four points A-D of the groin heads, during which the scour depth is measured per 1 hour, the relationships between the scour depth development process and the duration and strength of the flood and ebb of tide are analyzed, and besides, the process is compared with the development processes under the action of unidiretcional flow (Fig. 6).



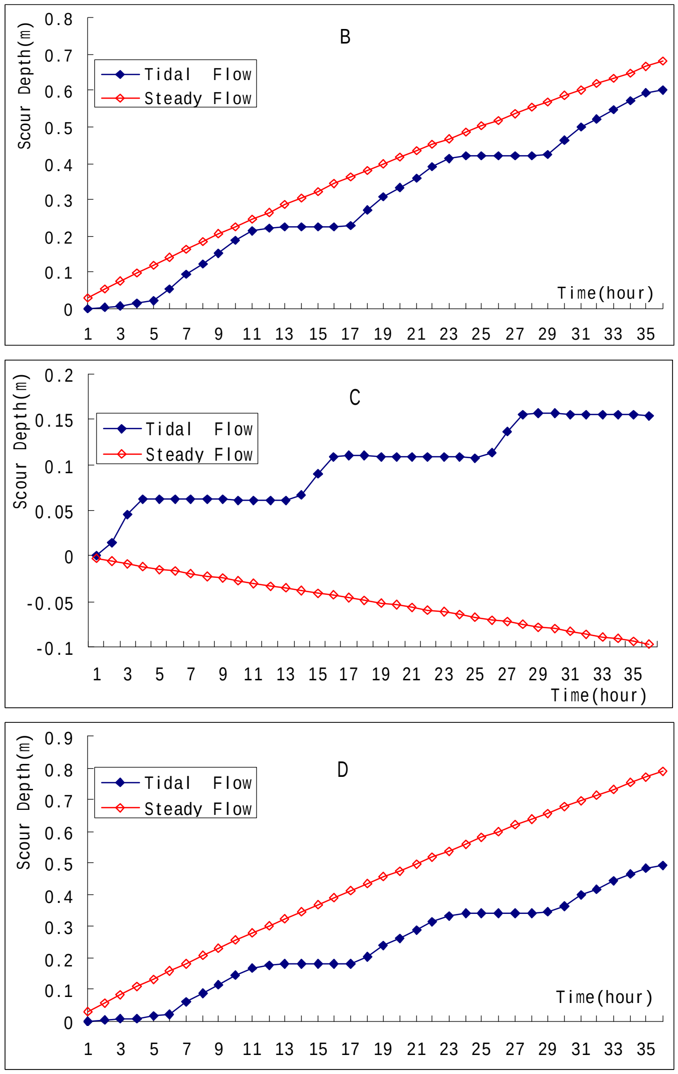



**Fig. 6 Comparison between the development process of local scour at the observation points of the groin under the action of tidal flow and unidirectional flow**

It can be seen from Fig. 6 that the development process of the scour depth at the four observation points under the action of tide and unidirectional flow is different within the observation time. Under the action of unidirectional flow, scour occurs at the upstream face while deposition occurs at the downstream face. Both scour and deposition present a continuous growing trend; under the action of tide, scour occurs both at the upstream and downstream sides of the groin head, which is obviously different from the local scour phenomenon under the action of unidirectional flow. The development of scour depth presents a periodical stepped increase trend according to the duration and strength of the flood and ebb of tide. This tendency can also be figured out from the comparison of the graphs of the scour and deposition shape of the two groin heads when the calculation is finished(Fig. 7 and Fig. 8).

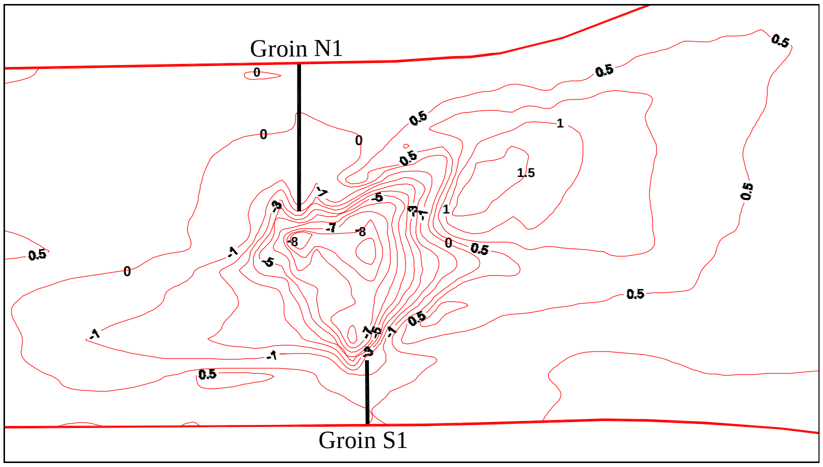



**Fig. 7 Scour topography of the N1 and S1 groin heads under the action of tidal flow (unit: m)**

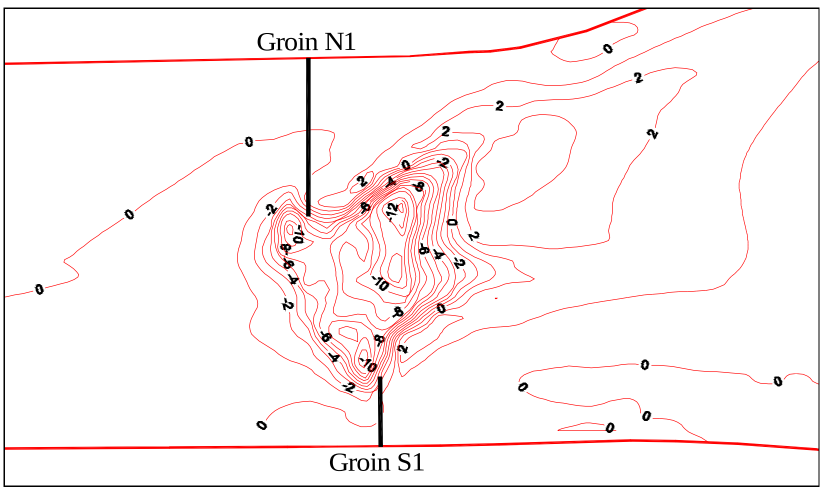



**Fig. 8 Scour topography of the N1 and S1 groin heads under the action of unidirectional flow (unit: m)**

From the figure it can be seen that the direction of the flow under the action of unidirectional flow remains unchanged, the groin head is only under the impact of flow from a single direction, and the scour pit is only formed at the upstream face of the groin head; the slope of the scour pit is quite steep; and deposition occurs at the downstream face. Under the action of tide, scour occurs at the upstream faces of flood tide and ebb tide at the groin head due to the combined action of flood tide and ebb tide. However, the scope and depth of scour is varied with the duration and strength of flood and ebb tide. Besides, the scour pit is relatively gentle at its slope.

## CONCLUSION

In this paper, the three-dimensional flow and sediment numerical model is utilized for simulation calculation and comparative analysis of the local scour of groins under the action of tide and unidirectional flow. It is concluded that under the action of unidirectional flow, scour occurs at the upstream face while deposition occurs at the downstream face. Both scour and deposition present a continuous growing trend. Under the action of tide, scour occurs both at the upstream and downstream sides of the groin head, which is obviously different from the local scour phenomenon under the action of unidirectional flow. The development of scour depth presents a periodical stepped increase trend according to the duration and strength of the flood and ebb of tide.

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