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Comprehensive Discriminate Method of Water and Sediment on “Ripping up the Riverbed” in the Yellow River

[1]Dong Wensheng, [2]Jiang Enhui, [1]Liu Xuemei, [2]Li Junhua and [2]Zhang Yang
[1]North china university of water resources and electric power, 450045, Zhengzhou, China
[2]Yellow River Institute of Hydraulic Research, 450003, Zhengzhou, China

Abstract: According to the mechanism of “Ripping up the Riverbed” and exposing mode of clay block, building four exposing analytical model of clay block, that is, (1) Due to the role of force moment leading to break clay block model, (2) The forces acting on clay block in the depth direction and shearing force of clay block fractured surface balance model, (3) Due to the role of force moment leading to whole piece of clay block expose model, (4) The forces acting on clay block in the depth direction and adhesive force of clay block boundary balance model. Considering the combined effect factors of clay block exposing, calculate separately the water and sediment indicators of each clay block exposing model, finally, the minimum value of the calculated results as critical water and sediment on "Ripping up the bottom ". The results of this study provide a theoretical support for discriminating whether a flood led to the phenomenon of "Ripping the bottom”, also provides the possibility of real-time data acquisition on “Ripping up the bottom”.

Key word: Ripping up the riverbed, clay block, mechanical strength, exposing model, comprehensive discrimination indexes

INTRODUCTION

“Ripping up the riverbed” is the specific phenomena due to the interaction between the hyper-concentrated flow and the special riverbed boundary conditions. Usually, “ripping up the riverbed” would make the riverbed strongly undercut for several meters and make the water elevation obviously decrease. At the same time the scouring often gets the river main channel to migrate, which would significantly damage the river regulation works. Since the 1970s, scholars home and abroad had paid great attention to “ripping up the riverbed” and had conducted various experimental researches on it. At present, there are three experimental methods to investigate the “ripping up the riverbed”. The first one is to analyze water-sediment condition when “ripping up the riverbed” occurs in Xiaobeiganliu and Weihe River with prototype data measured by hydrologic stations. However, as the water-sediment condition of hyper-concentrated flood changes a lot along the way, it is not that accurate to choose the measured data of hydrologic stations upstream or downstream the “ripping up the riverbed” reaches as the water-sediment calculated data. And due to the special and random forming condition of “ripping up the riverbed”, it is hard to acquire and analyze the “ripping up the riverbed” measured data. Therefore, the water-sediment condition proposed by the first method is not that persuasive. The second method is to study the water-sediment condition when the clay block starts in use of the concept of. But sediment transport capacity reflects the transportation process when sediment transports to downstream, not the dynamic mechanical relationship when the clay block instantaneously lifts up. So, whether the sediment transport capacity could reflect the “ripping up the riverbed” is worth discussing. The third method is the experimental research. In this method, the “ripping up the riverbed” phenomenon is simulated by flume experiment, the clay block exposing models and mechanism are analyzed by experimental observation and two exposing mechanical models of clay blocks are established. One exposing mechanical model is the bottom of the block eroded by water. When the clay block rotates upward along the riverbed continuous portion, its forepart is in cantilever status. So, the water-sediment condition would be calculated with the force balance equation acted on the depth direction of clay block. The other exposing mechanical model is the one which is just considered about the adhesive force between the clay block and the sedimentation.

Whether the riverbed sedimentation could be lifted or not depends on the consolidated results of various

Corresponding Author: Dong Wensheng, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China

conditions, including the pre sedimentation and adjustment of riverbed, the peak flow discharge and sediment concentration, the flood duration, the morphology parameters channels, the vertical pulsating pressure and the density, the relative roughness, the thickness, the boundary conditions and the mechanical strength of the sedimentation. Because of the different research methods, objects and the emphases, a unified understanding of the "ripping up the riverbed" discrimination conditions and indexes is quite poor and the research considered the comprehensive factors and the clay block mechanical strength is still not yet conducted.

With the flume experiment, Yellow River Institute of Hydraulic Research (Jiang *et al*., 2010) had simulated the "ripping up the riverbed", constructed the erosion models and offered the real mechanism how the "ripping up the riverbed" occurred. According to the "ripping up the riverbed" erosion mechanism and the exposing models of clay blocks, four different clay block exposing models had been conducted in this study. And considering the comprehensive factors and the most unfavorable conditions of load combination, the clay block critical exposing mechanism equation of each model would be conducted and simulated.

What is studied in this study has enriched the critical water-sediment condition computational theory when the "ripping up the riverbed" occurs, provided theoretical support to determine whether a particular flood would lead to "ripping up the riverbed" or not and made the real-time data acquisition be possible.

CLAY BLOCK EXPOSING MODEL

"Ripping up the riverbed" usually occurs on the floodplains, the channels formed after river diversion, or the riverbed which is exposed to the sun. Some workers of Longmen Hydrological Station expressed that channels always suffered serious sedimentation before the "ripping up the riverbed" occurred and the riverbed longitudinal gradient and the cross-sectional shape changed. The reason why the "ripping up the riverbed" often occurs on such riverbeds is because of the presence of cracks. When the flood passed through, due to the oscillating water and the fluctuating pressure between cracks, the cracks developed, which made the adhesive force decreased and created the appropriate conditions for the sedimentation to be exposed. For the clay blocks with strong anti-erosion properties, sedimentation around the blocks would be scoured because of the diving water flow. And with the scouring lasts, the hang-up area increases until the clay block is exposed. The scouring schematic diagram of stratification siltation structure riverbed is shown in Fig. 1.

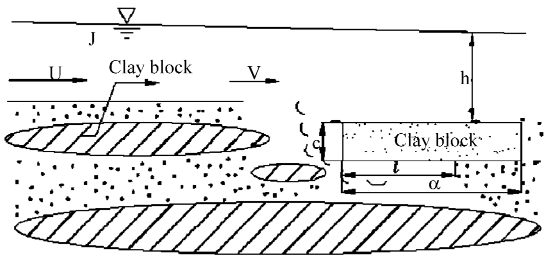

Fig. 1: Scouring schematic diagram of stratification siltation structure riverbed

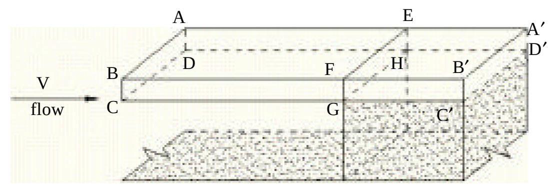

Fig. 2: Schematic diagram of clay block exposing lifting on "Ripping up the riverbed "

The schematic diagram of clay block exposing lifting on "ripping up the riverbed" is shown in Fig. 2. The clay block is broken to expose along section EFGH and the whole piece of clay block AA'BB'CC'DD' is exposed. For theoretical analysis, the clay block is assumed as a hexahedron, of which the length is a, the width is b, the thickness is c, the undercutting cantilever length is l and the bulk density is γ_S. The water depth on the surface of clay block is h. The bulk density of muddy water is γ_m, the water surface slope is J and the acceleration of gravity is g.

MODEL SOLUTIONS

Solutions to clay block exposing models due to moment loading: Stress analysis diagram of exposed clay block is shown in Fig. 3.

F_D: The positive thrust force of flow (Han, 2005):

$$F_D = \frac{\gamma_m C_D}{2} V_{b1}^2 bcg \tag{1}$$

In the function above, V_{b1} is the water velocity at the riverbed bottom. C_D is the drag coefficient. γ_m is the bulk density of muddy water. b is the width of the clay block and c is its thickness.

F'_D is the reaction force to F_D:

$$F_D^{'} = -\frac{\gamma_m C_D}{2} V_{b1}^2 bcg \quad (2)$$

τ' is the vertical shear force of the clay block which can be ignored because it produces no torques on y-axis. τ is the water drag force on the upper surface of clay block:

$$\tau = \frac{\gamma_m C_D}{2} V_{b1}^2 lbg \quad (3)$$

τ'' is the water drag force on the lower surface of clay block which can be ignored because it produces no torques on y-axis.

G_S is the weight of clay block:

$$G_S = \gamma_S lbcg \quad (4)$$

P_1 is the water pressure suffered by clay block:

$$P_1 = \gamma_m lbhg \quad (5)$$

P_2 is the clay block buoyancy force:

$$P_2 = \gamma_m lb\ (h+c)g \quad (6)$$

Maximum water pulsation lifting force (Jiang *et al*., 2010):

$$F_{d\max} = K\gamma_m J V_{b1}^2 lbg \quad (7)$$

K is the comprehensive impact factor, of which the unit is kg·m·s and the range is 3 to 4.2. J is the water surface slope.

The moment equilibrium equation on y-axis is established considering the most unfavorable load combination as follows:

$$F_{d\max} l + P_2 \frac{1}{2} + \tau c - G_s \frac{1}{2} - P_1 \frac{1}{2} = M_c bc \quad (8)$$

M_c is the flexural strength of the clay block.

Substituting Eq. 3-7 into Eq. 8:

$$V_{b1}^2 = \frac{2M_s c + l^2 cg(\gamma_s - \gamma_m)}{2KJl^2\gamma_m + lC_D cg\gamma_m} \quad (9)$$

The undercutting cantilever length of clay block is calculated by experienced formula as follows (Zhou *et al*., 2010):

$$l = C_1\Delta t(\tau - \tau_c)e^{-0.013\tau_c} / \gamma_c \quad (10)$$

C_1 is the riverbed erosion coefficient. τ is the drag force suffered by sedimentation around the clay block. τ_C is the critical shear stress and γ_c is the bulk density.

τ is the water bed shear stress:

$$\tau = C_D \frac{\gamma_m V_{b1}^2}{2} \quad (11)$$

$$l = C_1\Delta t\left(\frac{C_D\gamma_m V^2}{2} - \tau_c\right)e^{-0.013\tau_c/\gamma_c} \quad (12)$$

Using shear test data τ' replace riverbed sludge critical shear stress τ_C

V_{b1}^2, l as variables, Substituting Eq. 9 and 12 to obtain Eq. 13:

$$\begin{aligned}&4KJl^3 + [C_D cg - C_1\Delta t C_D cg(\gamma_s - \gamma_m) + 4C_1\Delta t\tau' KJ]l^2 \\ &+2C_1\Delta t\tau' C_D cgl - 2C_1\Delta t C_D M_s c = 0\end{aligned} \quad (13)$$

Solving Eq. 13 obtained l, l substituted into the Eq. 9, V_{b1}^2 can be obtained:

$$V_{b1}^2 = F_1\left(C_1, \Delta t, C_D, \gamma_c, \gamma_s, \gamma_m, c, J, K, M_s, \tau'\right)$$

Solution to equilibrium model of clay block force in the depth direction and the shear force of clay block broken section: As is shown in Fig. 3, the force equilibrium equation in the depth direction of clay block is the following one:

$$F_{d\max} + P_2 - P_1 - G_s = \tau' bc \quad (14)$$

τ' is the clay block shear strength which can be acquired in shear strength experiment:

$$\begin{aligned}&K\gamma_m J V_{b2}^2 lb + \gamma_m lb(h+c)g - \gamma_m lbhg \\ &-\gamma_s lbcg = \tau' bc\end{aligned} \quad (15)$$

Finishing the equation above:

$$V_{b2}^2 = \frac{\tau' c + lcg(\gamma_s - \gamma_m)}{KJl\gamma_m} \quad (16)$$

Simultaneous Eq. 9 and 16 can obtain Eq. 17:

$$\begin{aligned}&2KJl^2 + \left[2C_1\Delta t KJ\tau' - C_1\Delta t C_D cg(\gamma_s - \gamma_m)\right]l \\ &-C_1\Delta t C_D c\tau' = 0\end{aligned} \quad (17)$$

Solving Eq. 17 to obtain l. l is substituted into the Eq. 16, V_{b2}^2 can be calculated:

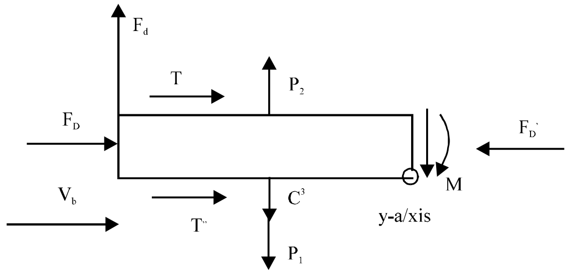

Fig. 3: Stress analysis diagram of broken clay block

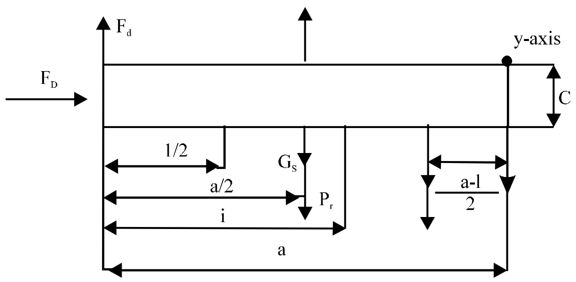

Fig. 4: Stress analysis diagram of the whole piece of clay block lift off from the riverbed

$$V_{b2}^2 = F_2\left(C_1, \Delta t, \gamma_c, \gamma_s, \gamma_m, c, J, K, \tau', D\right) \tag{18}$$

Solution to the exposed model of whole clay block as the moment effect: Stress analysis diagram of the whole piece of clay block lift off from the riverbed is shown in Fig. 4.

F_D is the positive thrust force of flow. G_s is the weight of clay block. P_1 is the water pressure suffered by clay block. F_{dmax} is the flow pulsating lifting force suffered by clay block. $F_{\mu 1}$ is the adhesion force between clay block and the bottom riverbed. $F_{\mu 2}$ is the adhesion force between the side faces of clay blocks. $F_{\mu 3}$ is the adhesion force of clay block lower side face. $fF_{\mu 2}$ and $fF_{\mu 3}$ are friction forces turned by $F_{\mu 2}$ and $F_{\mu 3}$. f is the friction coefficient with the value of 0.4:

$$G_s = \gamma_s abcg \tag{19}$$

$$P_1 = \gamma_m habg \tag{20}$$

$$P_2 = \gamma_m (h+c)abg \tag{21}$$

F_d is calculated by Eq. 7:

$$F_{dmax} = K\gamma_m JV_{b2}^2 lb$$

Calculating equation of $F_{\mu 1}$, $F_{\mu 2}$, $F_{\mu 3}$ are shown as follows[2]:

$$F_{\mu l} = \frac{\pi}{2} q_0 \frac{(a-l)b}{(D+2t)^2} \frac{\delta_0^3}{\delta_1^2} D\left[\frac{\delta_1^2}{t^2} - 1\right] \tag{22}$$

δ_0 (3×10^{-10}) is the thickness of a single water molecule. δ_1 (4×10^{-7}) is the thickness of thin film water. $q_0 = 1.3\times10^9$ kg m^2:

$$F_{\mu 2} = \frac{\pi}{2} q_0 \frac{(a-l)c}{(D+2t)^2} \frac{\delta_0^3}{\delta_1^2} D\left[\frac{\delta_1^2}{t^2} - 1\right] \tag{23}$$

$$F_{\mu 3} = \frac{\pi}{2} q_0 \frac{bc}{(D+2t)^2} \frac{\delta_0^3}{\delta_1^2} D\left[\frac{\delta_1^2}{t^2} - 1\right] \tag{24}$$

The moment equilibrium equation when the clay block is instantaneously exposed:

$$F_{dmax} a + P_2 \frac{a}{2} - G_s \frac{a}{2} - p_1 \frac{a}{2} - F_{\mu l} \frac{a-l}{2} - fF_{\mu 2}(a-l) = 0 \tag{25}$$

$$S = \frac{\pi}{2} q_0 \frac{D\delta_0^3}{(D+2t)^2 \delta_1^2}\left[\frac{\delta_1^2}{t^2} - 1\right]$$

Substituting the force formulas into Eq.25:

$$KJa^2\gamma_m lV_{3b}^2 - \frac{1}{2}a^3 cg(\gamma_s - \gamma_m) - \frac{1}{2}Sa(a-l)^2 - fSc(a-l)^2 = 0 \tag{26}$$

If F_D is ignored:

$$V_{b3}^2 = \frac{a^3 cg(\gamma_s - \gamma_m) + Sa(a-l)^2 + 2fSc(a-l)^2}{2KJa^2\gamma_m l} \tag{27}$$

t/δ_1 is determined by clay block dry bulk density:

$$\gamma_s' = \left[0.698 - 0.175\left(\frac{t}{\delta_1}\right)^{\frac{1}{3}\left(1-\frac{t}{\delta_1}\right)}\right]\left(\frac{D}{D+2t}\right)^3 \gamma_s \tag{28}$$

γ'_s is the clay block dry bulk density. t is determined by Eq. 28.

Simultaneous Eq. 12 and 27 can obtain Eq. 29:

$$a_3' l^2 + b_3' l + c_3' = 0 \tag{29}$$

$$a_3' = 4KJa^2 - C_1\Delta tC_D Sa - 2C_1\Delta tC_D fSc$$
$$b_3' = C_1\Delta tC_D Sa^2 + 4C_1\Delta tC_D fSac + 4C_1\Delta tKJa^2\tau'$$
$$c_3' = -[C_1\Delta tC_D a^3 cg(\gamma_s - \gamma_m) + C_1\Delta tC_D Sa^3 + 2C_1\Delta tC_D fSa^2 c]$$

Solving Eq. 29 can obtained l, l substituted into Eq. 27 to give V_{b3}^2:

$$V_{b3}^2 = F_3\left(C_1, \Delta t, \gamma_c, \gamma_s^{'}, \gamma_s, \gamma_m, c, J, K, D\right) \tag{30}$$

Solution to the equilibrium model of force on clay block in the depth direction and adhesion force: As is shown in Fig. 4, the equilibrium equation as in Eq. 31:

$$F_{d\max} + P_2 - G_s - P_1 - F_{\mu1} - 2fF_{\mu2} - fF_{\mu3} = 0 \tag{31}$$

$$K\gamma_m JV_{b4}^2 lb + \gamma_m(h+c)abg - \gamma_m abhg - \gamma_s abcg - Sa(a-l) - 2fSc(a-l) - Sac = 0 \tag{32}$$

$$V_{b4}^2 = \frac{a^2cg(\gamma_s - \gamma_m) + Sa^2 + 2fSac + Sac - (Sa + 2fSc)l}{KJal\gamma_m} \tag{33}$$

Simultaneous Eq. 12 and 33 can obtain Eq. 34:

$$2KJal^2 + C_1\Delta t\left[C_D(Sa + 2fSc) + 2KJa\tau^{'}\right]l - C_1\Delta tC_D\left[a^2cg(\gamma_s - \gamma_m) + Sa^2 + 2fSac + Sac\right] = 0 \tag{34}$$

Solving Eq. 34 can obtained l, l substituted into Eq. 33 to give V_{b4}^2:

$$V_{b4}^2 = F_4\left(C_1, \Delta t, \gamma_c, \gamma_s^{'}, \gamma_s, \gamma_m, c, J, K, M, D\right)$$

So, the critical flow average velocity when the clay block is to expose is as follows:

$$V_b = \min\{V_{bi}\}\ I = 1, 2, 3, 4 \tag{35}$$

CONCLUSION

According to the mechanism of “ripping up the riverbed” and exposing mode of clay block, four exposing analytical model of clay block are built in this study. Considering the comprehensive factors and the most unfavorable conditions of load combination, the clay block critical exposing mechanism equation of each model would be conducted and simulated. As is shown in Eq. 35, the critical flow average velocity is determined by various parameters. That equation is the one which is considered the most comprehensive factors of clay block exposing models. The results of this study not only provide a theoretical support for discriminating whether a flood could lead to the phenomenon of "ripping up the riverbed” or not, but also provide the possibility of real-time data acquisition on “ripping up the riverbed”.

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