EXPERIMENTAL STUDY ON FLOW AND SEDIMENT MOVEMENT IN CAVITY CIRCULATIONS

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ABSTRACT

This paper reports a flume experiment of flow and sediment movement in a cavity. The flow velocity, sediment concentration and the mechanism of hydraulic sorting in the circulation flow are discussed. The quantity and patterns of sediment deposition in the circulation area are studied as well.

Key Words: Cavity circulation, Radial circulation, Flow velocity, Sediment concentration, Deposition

1 INTRODUCTION

Cavity channels are often found in harbor basins, waterways approaching navigation locks, trench intakes and so on. Because of the expansion of channel section, the main flow is separated from the boundary and forms a circulation flow near the cavity crest. In general, the velocity and turbulent intensity in the circulation flow are lower than that in the main flow, as a result, sediment drawn into the cavity basin is very likely to be deposited there. For instance, the deposit rate in the harbor of Hamburg, Germany, is about 2 million-CM/year and approximately 100,000 m^3 sediment accumulates in the port basin of Kanazawa, Japan every year (Mizumura, et. al., 1997). Sediment deposition in such area is closely related to the properties of flow and sediment movement in cavity circulation. So it is necessary to study such problems.

Sediment movement in cavity basins has been studied previously. Hangen and Dahanak (1966) investigated the momentum and mass exchanges in a rectangular cavity. Xu (1982) obtained a formula for critical diameter experimentally. Yue (1986) examined the process of sediment deposition in a cavity flume and suggested that the circulation flow also has sediment transport capacity. Liu (1999) proposed, based on both of theory and experiment, a formula which could estimate such transport capacity. Experiments (Altai, et al., 2001) have clearly shown the existence of a stationary core region in the circulating flow near the cavity crest where the retention time is significantly greater than the surrounding region. This finding is very helpful for understanding the pattern of deposition in cavity channels. Some researchers also proposed ways to predict and to prevent sediment deposition in cavity channels. For example, Xie and Yin (1983) established a semi-empirical formula to estimate the rate of sediment deposition using field observed data. They also applied this formula to the Gezhouba approaching channel of the ship locks on the Yangtze River and received a good agreement between measured data and theoretical calculation. Hofland, *et al.*(2001) found that current deflecting wall is able to reduce deposition in harbors on tidal rivers. In addition, others used mathematical models to investigate the sediment deposition in the cavity circulation. For example, Dong (1999) established a 2-D depth-average flow and sediment model to simulate the sediment transport in the cavity areas. Such investigations have displayed some characteristics of sediment movement and deposition in cavity channels. However, such previous results could not clearly exhibit the flow patterns and sediment movement in the cavity circulation.

Generally speaking, cavity circulation is nearly an enclosed circulation with vertical-axis under steady conditions. Although the main flow continuously drives the circulation flow, the cavity circulation is relatively independent with itself specialties. The flow can be divided into three regions: the main flow region, the turbulent mixing region and the circulation region. The characteristics of flow and sediment diffusion in the cavity circulation are of fundament for analyzing the sediment deposition process and estimating deposition rate in the cavity channels. The purpose of the current study is to show the patterns of flow and sediment in cavity circulation by means of flume experiments.

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2 EXPERIMENT SETUP

The experiment setup designed consists of a main channel of rectangular cross-section and a cavity flume perpendicular to the main channel as shown in Fig.1. The main channel is 1500×80×40cm in length, width and depth respectively and it is sloped to about 0.1%. The cavity flume connects to the main channel at the position 900cm downstream the entrance. Length (L) and width (B_0) of the cavity flume are adjustable with maximal 200cm and 80cm for L and B_0. The flume bottom is of concrete and the sidewalls are aluminum board.

A triangular-notch weir and a Venturi flowmeter were used to measure the flow discharges of clear and turbid water, respectively. The flow velocity was measured by a tachometer of small propeller with 10mm in diameter, which can measure the smallest velocity about 2.6cm/s. The average value at three points (0.2h, 0.6h, 0.8h) on a vertical profile was used as mean velocity, while the vertical mean sediment concentration was obtained by sampling at five elevations (0.1h, 0.2h, 0.4h, 0.6h and 0.8h). The bed topography in the cavity area was observed with a catalyst topography instrument.

Nonuniform plastic sand with specific weight γ_s=1.05 t/m^3 and median diameter $d_{50}=0.33$ mm was used as suspended material. The size distribution is shown in Fig. 2.

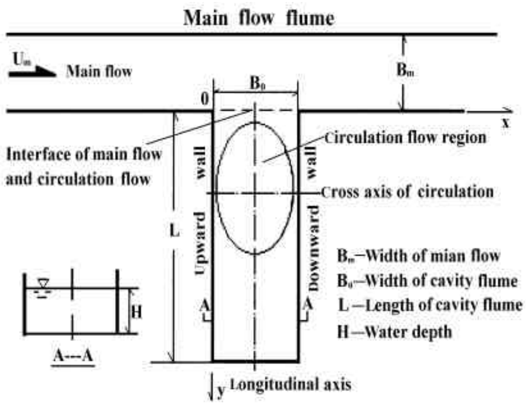


Fig. 1 Sketch of the cavity flume

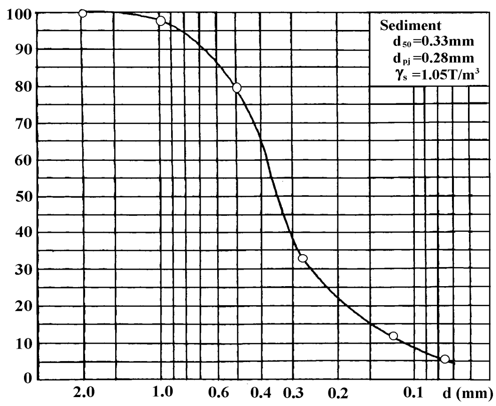


Fig. 2 Grading curve of sediment used in the test

3 INFLUENCES OF THE DRIVING FLOW

3.1 The Main Factors for Flow Circulation

Using the average velocity (U_{rw}) on the transverse-axis of the circulation as the intensity of the circulating flow, it depends on several factors such as cavity width B_0, water depth H and the main flow velocity U_m. The observed results are shown in Table 1, Table 2 and Fig. 3.

Table 1 Circulation intensities (U_{rw}) for different B_0

B_0 (cm)	20	40	60	80
U_{rw}(cm/s)	10.02	9.76	9.71	9.50
L=200cm, H=13.7cm and U_m=60.05cm/s				

Table 2 Circulation intensities (U_{rw}) for different H

H (cm)	10.3	13.7	17.3
U_{rw}(cm/s)	9.12	9.15	9.22
L=120cm, B_0=13.7cm and U_m=56.45cm/s			

The results show that the circulating flow intensity depends linearly on the main flow velocity U_m as

$$U_{rw} = cU_m \quad \text{(c is a constant)} \tag{1}$$

also both B_0 and H affect the circulating flow intensity in some degree. Usually the circulation intensity decreases when B_0 increases and it increases with the increase of water depth H.

The driving of the main flow is of the primary force for the cavity circulation. The driving force (F) can be written as

$$F = \tau B_0 H \; . \tag{2}$$

While the total power (W) that the main flow acts on the water body of the circulating flow is

$$W = kFU_m \, . \tag{3}$$

The volume of the circulation water is B_0LH, so the average power per unit water volume obtained from the main flow can be written as:

$$w = \frac{kFU_m}{B_0 L \; H} = \frac{k\tau U_m}{L} \, , \tag{4}$$

where τ is the shear stress on the interface, k, a coefficient. For normal cavity circulations, there is an empirical relationship from experiments (Hangen and Dhanak, 1966; Yue, 1986) when $L/B_0 \approx 1.5$:

$$w = \frac{k\tau U_m}{1.5 B_0} . \tag{5}$$

These equations reveal that the power per unit volume of water body is proportional to the main flow velocity and is inversely proportional to the cavity width B_0.

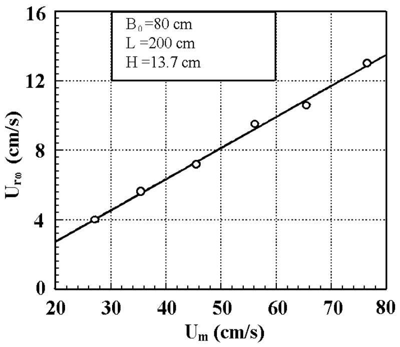


Fig.3 Relationship of U_{Rw} and U_m

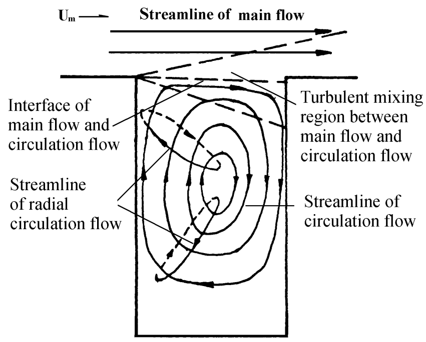


Fig. 4 Sketch of radial circulation in the cavity

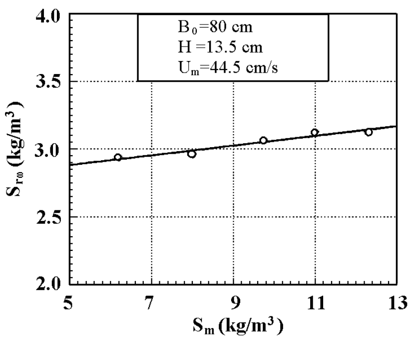


Fig. 5 Relationship of S_{rw} and S_m

The impact of water depth H on the circulating flow intensity is through the way in changing the intensity of the radial circulation. The cavity circulation carries out a curvilinear motion in horizontal plane, and it is balanced by the centrifugal force and the gravity. The water surface falls down in the center of the circulating flow and rises up at the boundary by flow self-adjustment, which leads to an obvious radial direction slope in the circulation region. As shown in Fig.4, the cavity circulation can be approximately considered as a superposition of the horizontal plane circulation and the radial circulation for shallow water flow. Generally, the intensity of the radial circulation increases with the water depth increasing, and the radial velocity increases correspondently. As a result, the circulating flow intensity also increases slightly with the water depth increasing.

3.2 Main Factors for Sediment Movement

Fig. 5 is the experiment result for sediment concentration in the circulating flow, S_r. It is only slightly proportional to the sediment concentration of the main channel flow S_m. This indicates that the sediment concentration in the circulation is not mainly governed by the sediment concentration in the main channel flow although all sediment in the cavity is from the main flow. In fact, the main factors ruling the sediment movement in the cavity should be the sediment transport capacity and the sediment transport process in the cavity circulation. Usually, the transport capacity of cavity circulation is weak and the sediment concentration entering the cavity is much larger than the saturated concentration, more deposition should take place if larger concentration from the main flow. The sediment concentration of the main channel flow has only a definite influences on the sediment concentration in the cavity as a whole because the different sediment quantity coming from the main flow will lead to different processes of sediment transport and deposition in there. If the dimension of the cavity is large enough, namely there is enough distance for sediment depositing and concentration adjustment, the sediment concentration in the cavity will fatefully approach the saturated concentration which is decided by the transport capacity of the circulation flow no mater how dense the sediment in the main channel flow is.

4 PATTERNS OF THE CIRCULATION FLOW

4.1 Distribution of Depth-Averaged Flow Velocity

Fig.6 shows the flow patterns of depth-averaged velocity in the cavity, which is shaped nearly elliptic. The depth-averaged velocity increases gradually with the distance from the circulation center and changes periodically along the elliptic streamline around the center. On the transversal direction of the cavity, the velocity vectors are nearly perpendicular while it is usually not perpendicular to the radial direction from the circulation center. The streamline patterns for different depth are similar, but the flow directions are not the same.

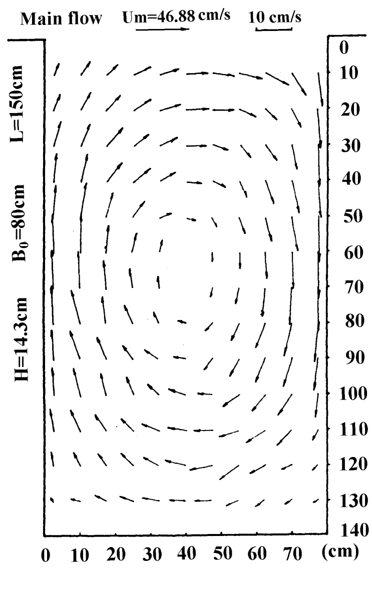


Fig. 6 Depth-averaged velocity in the cavity

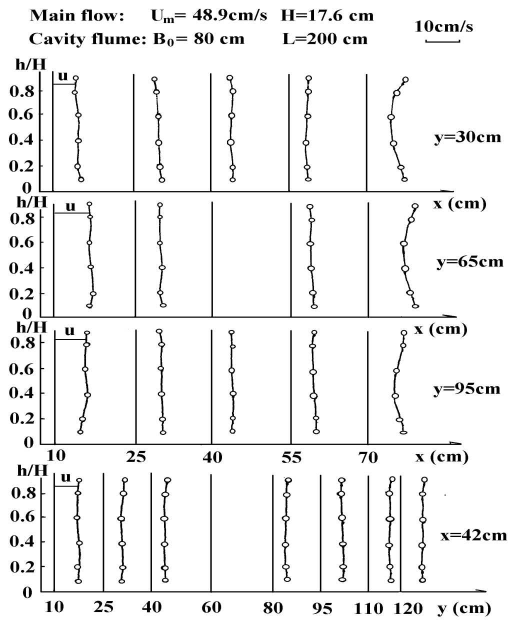


Fig.7 Vertical profile of flow velocity in the cavity

Previously it was supposed that the velocities of rotation flow distributed as :

$$u = cr^m . \tag{6}$$

where *u* is the depth-averaged velocity, *c* and *m* constants ($0<m<1$) and *r* the radial distance from the center of circulation. For general cavity circulations, Eq.(6) is not true because the elliptic streamlines are usually not round and the velocity vector is not truly normal to the radial direction except that in the transverse directions. Only on the transverse axis, the velocity distribution approximately follows exponential law. Xu (1982) proposed a formula like Eq.(6) and fitted by experiment data as $u = cr^{0.5}$ on the transverse axis of the cavity circulation.

4.2 The Vertical Profile of Flow Velocity

Fig.7 is the experimental result of the vertical flow velocity profiles in cavity (the coordinate is defined in Fig.1). It shows that the velocity profiles in the cavity are rather uniformly distributed. It is different from that in open channels. Such profile is similar for different velocities and water depths in the main channel.

In open channel bends with small bed roughness, the vertical distribution of radial velocity components can be simply expressed as (Victor, 1981; Sun, 1992) $V_r = 6UH(2h-1)/R$, and the resultant full velocity is $V = \sqrt{V_r^2 + U^2}$. (V_r is velocity component in radial direction, U depth-averaged velocity component in the tangential direction of the bend, H, h water depth and relative water depth respectively, R the curvature radius of flow). Assuming the flow velocity in the cavity circulation also accords with above law, for same tangential velocity, the radial velocity component in bottom is larger than in surface because the curvature radius of current line in bottom is small than that in surface. This phenomenon is just the reason of leading to the vertical profile of resultant velocities rather uniform in the cavity circulation.

5 DISTRIBUTION OF SEDIMENT CONCENTRATION IN THE CAVITY

5.1 Depth-Averaged Concentration

Fig. 8 illustrates the experiment result of the depth-averaged sediment concentration in the cavity. It shows that concentration near the separate crest is slightly higher than that near opposite crest. The concentration in the central area of the cavity is also slightly higher than out around of the center. These differences are, however, small and it does not display a periodical variation along the elliptic streamlines as it is for the depth-averaged velocity.

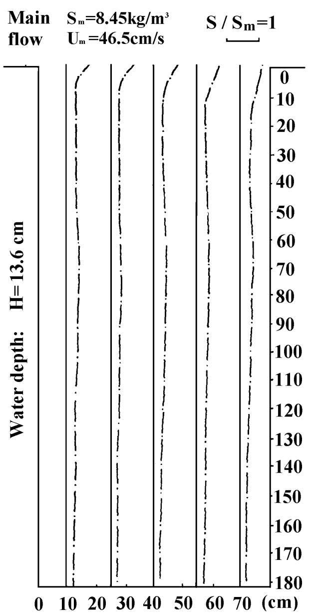


Fig. 8 Distribution of depth-averaged concentration

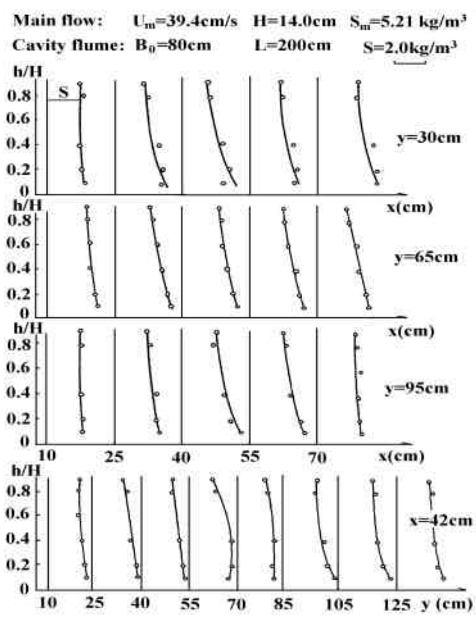


Fig. 9 Vertical profiles of concentration in the Cavity

5.2 Vertical Distribution of Sediment Concentration

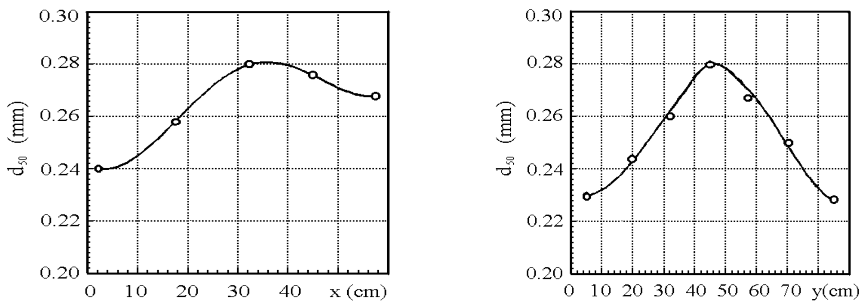
Fig. 9 is from the measured vertical profiles of sediment concentration along different sections in the cavity. It similarities to that in open channels. The concentration near the bottom is higher than that in the upper column. Closing to the circulation center, this similarity is more obvious.

Because of the radial circulation, the circulating flow also hydraulically sorts the sediment particles. In the area close to the circulation center, more coarse sediment particles was sampled and oppositely in the area far from the center. Gravitation action on suspension particles near the center is more intense than in the area around. This is why the vertical distribution of sediment concentration near the center is less uniform than that in other area around.

6 HYDRAULIC SORTING

6.1 Sorting on Suspended Sediment

Fig.10(a) and (b) are the measured results of d_{50} of the suspended sediment. The conditions are $U_m = 39.8 cm/s$, $S_m = 3.15 kg/m^3$, *H=13cm*, *B_0=60cm* and *L=100cm*. The d_{50} variations along the transverse and longitude directions show a resemble distribution that coarser sediment concentrates near the circulation center and finer sediment particles scatters around. The result reveals that hydraulic sorting exists for suspended sediment in the cavity.



(a) in the transverse direction (b) in the longitude direction

Fig. 10 Distributions of d_{50} of suspended sediment

The hydraulic sorting of suspended sediment is a result of the circulation flow. Because of gravitation, more coarse particles are transported near the bottom and it is easier to be moved to the circulation center by the center forwarding radial flow in the lower layers. Because of upward flow in the circulation center, the coarse particles accumulated there are raised and kept in suspension longer. On the other hand, the outward radial flow near the surface carries more fine sediment to the surrounding areas so here usually more fine particles can be found.

6.2 Sorting on Bed Material

Fig. 11 shows the variation of d_{50} of deposited bed material along the longitude direction y. The cavity flume then is 2000cm long, 60 cm wide and 13.8 cm in water depth.

The result shows the trend of d_{50} of the bed material. From the cavity inlet to the circulation center, d_{50} increases, and then decreases beyond the circulation center. This phenomenon repeats further inside of the cavity because here a second circulation exists. The median diameters d_{50} near the circulation center are even coarser than that in the main flow, where d_{50}=0.33mm.

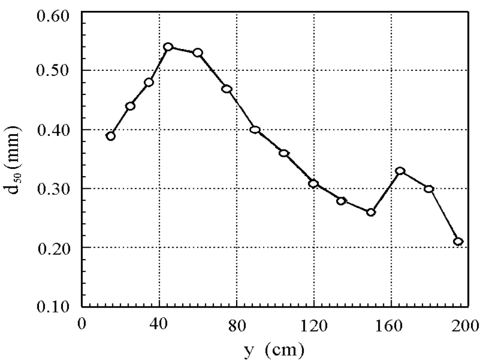


Fig. 11 d_{50} of deposited bed material

Similar to the case for suspended sediment, the secondary flow in radial direction also results in the hydraulic sorting on bed material. Because coarse particles are more likely concentrated near the bottom, the radial flow forwarding to the center continuously moves these particles to the center and more coarse particles deposit. On the contrary, fine particles are likely to be transported to the area around and deposit there. This is also true for the second circulation inside of the cavity.

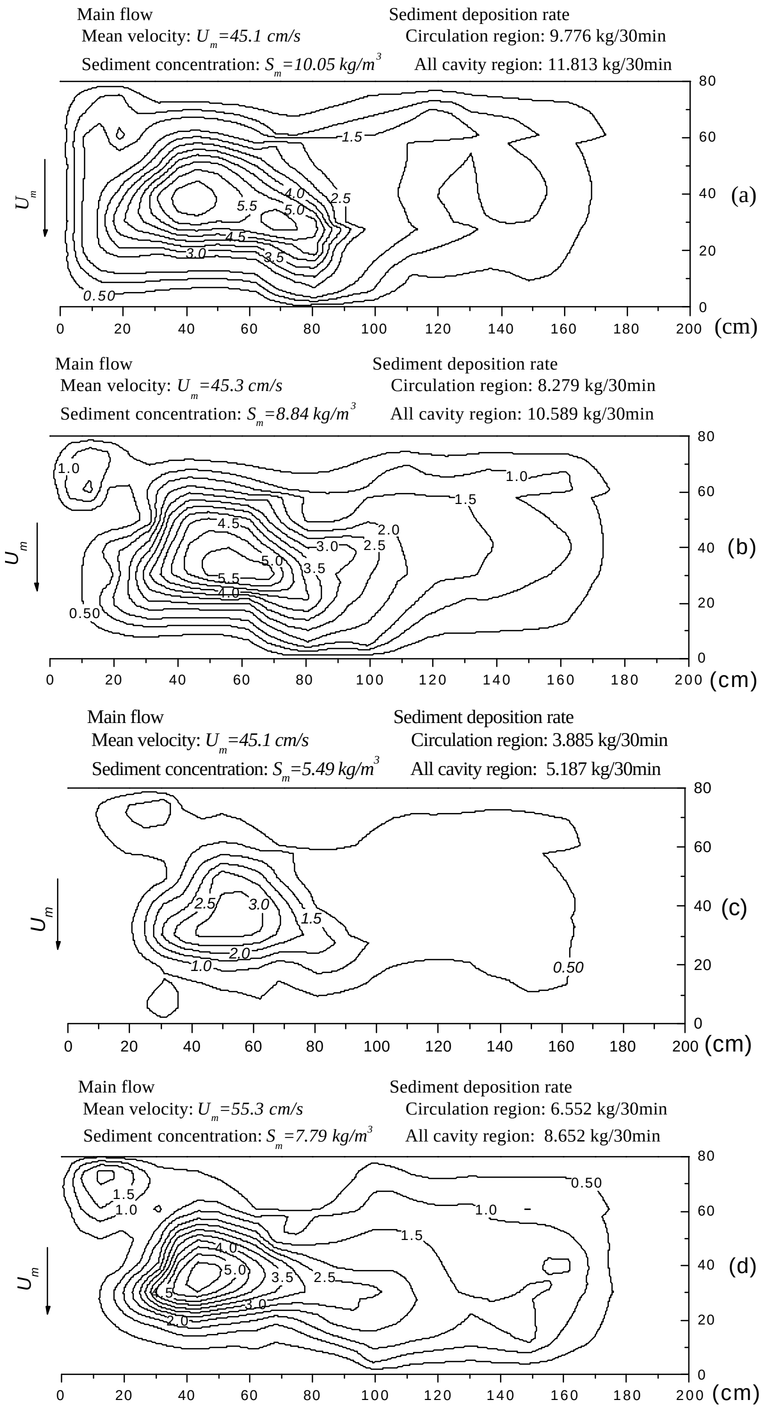


Fig. 12 The topography of deposition in the cavity

7 DEPOSITION IN THE CAVITY

7.1 The Topography of Deposition

For a case the cavity is sized 200cm long, 60cm wide and 13.5cm deep, the topography of bed deposition in the cavity is measured after the test running 30 minutes (Fig.12). Deposition shows that: (1) The deposition is irregularly concentrated in the circulation area with its top located in the circulation center. (2) There exists a boundary between the deposition area caused by the main circulation and the second circulation. The thickness of second deposition distributes, of course, more uniform and much smaller than that of the main circulation. The deposition rate in the circulation is much greater than that in the second circulation.

7.2 The Factors Impacting Sediment Deposition

The main factors impacting the deposition patterns in the circulation are firstly sediment concentration in the main channel flow. It is the ruling factor. The higher such concentration is, the larger and more quick the deposition takes place. The second factor is the main channel flow velocity. Larger main flow velocity will increase more sediment diffusion into the circulating flow area. When the main flow velocity is not so large, sediment deposition will increase with the increase of the main flow velocity. When the main flow velocity is greater than a certain value, however, sediment deposition in the circulation will begin to decrease gradually. This is because the large main flow velocity results in a large transport capacity in the circulating flow. The third factor is the particle size of the suspended sediment.

Fig. 13 (a)-(c) shows the deposition quantity and distribution in the cavity with time, and different B_0 and sediment concentration in the main channel flow. Fig.13 (d) shows the relationship of the main channel flow velocity and the deposition quantity after Yue' s experiment (Yue,1986).

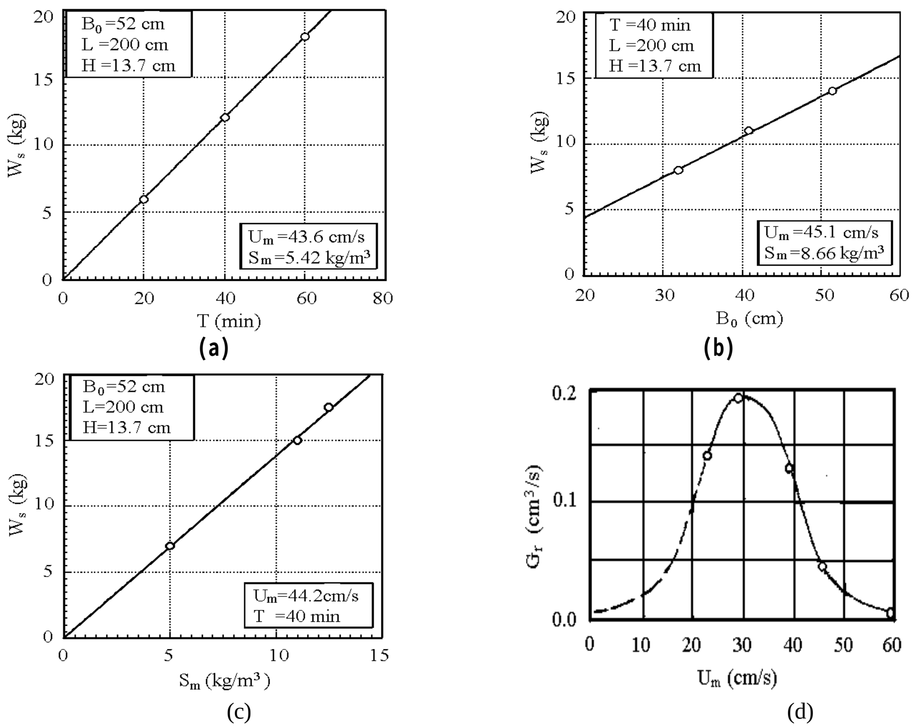


Fig. 13 The deposition amounts and distribution in the cavity

The volume of sediment deposition in the circulation region is proportional to deposition time, cavity width, and sediment concentration in the main channel flow, respectively. The velocity of the main channel flow plays both positive and negative rules on the sediment deposition. In general, with the main channel flow velocity increasing, the deposition increases firstly, then it decreases gradually as the main channel flow velocity goes beyond a certain large value. The sediment deposition volume is mainly dependent on the diffusion from the main channel to the cavity. The diffusion quantity can be expressed as:

$$W_s = g_s AT = g_s B_0 HT \tag{7}$$

where g_S is diffusion rate along the inlet section of the cavity, A the area of the cavity inlet and T time.

It is obvious that sediment deposition rate is proportional to the cavity width and the depositing time. According to the law of turbulent diffusion, the rate of sediment diffusion can be written as:

$$g_s = e_s \frac{\partial S}{\partial y} \tag{8}$$

Taking $e_{sy} = l_s^2 \frac{\partial u}{\partial y}$, and $\frac{\partial S}{\partial y} \approx \frac{S_m - S_r}{b}$, we have：

$$g_s = l_s^2 \frac{S_m - S_r}{b} \frac{\partial u}{\partial y}\,. \tag{9}$$

where S_m, S_r are sediment concentration in the main channel flow and in the circulating flow, respectively; e_{sy} the diffusivity of sediment concentration; l_s mixing length, b the thickness of the mixing layer.

Eq.(9) shows that the rate of sediment diffusion is proportional to sediment concentration and flow velocity gradients across the interface of the mixing layer. In addition, the sediment concentration gradient is also dependent on the sediment concentration in the circulating flow. Assuming the average sediment concentration in the circulating flow, S_r, is approximately equal to the sediment transport capacity (S_{r*}) of the circulating flow, the gradient depends then on the difference of concentration and the transport capacity in the main channel flow and the circulating flow respectively. Liu (1999) suggested a formula for the transport capacity of the circulating flow:

$$S_{r*} = k_0 \left(\frac{U_{rw}^3}{gB_0 w} \right)^m . \tag{10}$$

With Eqs.(10) and (1), it can be revealed that the sediment transport capacity of the circulating flow increases with the main flow velocity increase. Consequently, the flow velocity in the main channel not only directly influences the velocity gradient, but also indirectly influences the sediment concentration gradient by changing the intensity and concentration of the circulating flow. The influence result is dependent on the comparison of the change rates of velocity gradient and sediment concentration gradient. When the main flow velocity is not too large, the increase of velocity gradient takes main action for sediment diffusion, thus leading to sediment diffusion increases with the main flow velocity. When the main flow velocity is large enough in booming up the concentration in the cavity against the diffusion from the main channel, thus leading to the sediment diffusion rate decreases with the main flow velocity increasing.

8 CONCLUSIONS

This paper introduces some evident details of flow and sediment movement in channels of rectangular cavities from laboratory test. This could be helpful for the understanding of general cavity basins in practices of river engineering. The main points obtained can be listed as:

(1) Cavity circulation is created by the driving of main channel flow and its intensity is proportional to the flow velocity of the main channel. Sediment concentration in the cavity is mainly dependent on the transport capacity of the circulation flow. The velocity and sediment concentration of the main channel flow impact to some extents the movement of flow and sediment in the cavity by means of modifying the transport capacity of the flow in the basin.

(2) The pattern of streamlines in the cavity is near elliptic. The depth-averaged velocity is proportional to the radial distance from the circulation center and it changes periodically along the elliptic streamlines around. Depth-averaged sediment concentration, however, does not display such periodical variation tendency.

(3) Secondary flow brought about by the circulation deviates the upper layer flow from and concentrates the lower layer flow towards the center of the circulation. This makes to the vertical distributions of flow

velocity and sediment concentration in the cavity more uniform.

(4) The circulation and its secondary flow have hydraulic sorting effects on suspended and bed sediment particles. As a result, particles near the circulation center are coarser than in the area around.

(5) The main channel flow velocity and sediment concentration are major factors affecting the rate of sediment diffusion across the inlet section of the cavity. Deposition in the cavity is proportional to the sediment concentration in the main channel flow. The action of main channel flow velocity on sediment deposition is, however, not so simple. It increases deposition proportional when it is rather small and inversely suppresses the deposition when the main channel flow velocity is large enough.

REFERENCES

Altai, W., Shafie, M., and Chu, V. H. 2001, Recirculating flow in a shallow basin. Proc. 29th IAHR Congress, Theme D, Vol. I, pp. 52-57, Tsinghua University Press, Beijing, Sept. 16-21, 2001.

Dong Y. H. 1999, Calculation and analysis on flow and sediment transport in cavity recirculation. Journal of Sediment Research, No. 2, pp. 34-39 (in Chinese).

Haugen, R.L. and Dhanak, A. M. 1966, Momentum transfer in turbulent separated past a rectanglular cavity. Journal of Applied Mech., ASME, Vol. 33, No. 3, pp. 641-646.

Hofland, B., Christiansen, H., Crowder, R. A., Kirby, R., Leeuwen, C. W. Van, and Winterwerp, J. C. 2001, The current deflecting wall in an estuarine harbour. Proc. 29th IAHR Congress. Theme D, Vol. I, pp. 613-621. Tsinghua University Press, Beijing, Sept. 16-21, 2001.

Mizumura, K. Yamamoto, T. and Fujikawa, T., 1997, Prediction of sand movement bear port of Kanazawa. Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, Vol.123, No.5, pp. 215-222.

Liu, Q. Q. 1999, Saturated sediment carrying capacity of circulating flow. International Journal of Sediment Research, Vol. 13, No. 3, pp. 45-51.

Sun, D. P. 1992, Study of circulating flow and sediment transport along cross direction in bend reach. Proceedings of the National Conference on Basis Theory of Sediment Transport, pp. 471-478, Beijing, China (in Chinese).

Victor, M. P. 1981, Modeling circulation in depth-averaged flow, Journal of Hydraulic Engineering, ASCE, Vol.107, No.11, pp. 1425-1431.

Xie J. H. and Yin R. L. 1983, Sedimentation problems of waterway leading to navigation in low water level hinge engineering. Proceedings of the Second International Symposium on River Sediment, Beijing, Hydraulic and Electric Press.

Xu, J. Y. 1982, Experimental studies on the mechanism of water and sediment movement of circulation flow at the mouth of caecum reach. Master Degree Thesis of Wuhan University of Hydraulic and Electric Engineering. Wuhan, China (in Chinese).

Yue, J. P. 1986, Experimental study on the sediment deposition caused by rotating flow in the closed channel. Journal of Sediment Research, No. 2, pp. 41-50 (in Chinese).