[Article ID] 1003- 6326(2002)03- 0508- 06

Water hammer in coarse-grained solid-liquid flows in hydraulic hoisting for ocean mining①

HAN Wen-liang(韩文亮)[1], WANG Guang-qian(王光谦)[1], WU Bao-sheng(吴保生)[1], LIU Shao-jun(刘少军)[2], ZOU Wei-sheng(邹伟生)[3]

(1. Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China;
2. College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China;
3. Changsha Research Institute of Mining and Metallurgy, Changsha 410012, China)

[Abstract] The particles of polymetallic nodules in hydraulic hoisting flows that are used for mining in deep sea are rather coarse, therefore their flow velocity is smaller than that of the surrounding water. The characteristics of solid-liquid flows such as their density, concentration, elastic modulus and resistance were discussed. The wave propagation speed and the continuity and momentum equations of water hammer in coarse-grained solid-liquid flows were theoretically derived, and a water hammer model for such flows was developed.

[Key words] hydraulic hoisting; coarse grain; water hammer; numerical model

[CLC number] TV 134 **[Document code]** A

1 INTRODUCTION

In deep-sea mining, the polymetallic nodules, gathered by collecting utilities such as underwater robots, must be transported to mining boats through hydraulic hoisting. Past studies of coarse-grained flows in vertical pipes are mostly about the transport parameters of steady flow, such as energy losses due to resistance and flow velocity. The research of unsteady flow is rather limited. In the operation of hydraulic hoisting system, serious water hammers can be induced by power failure or by mechanical breakdown. Therefore, not only the transport parameters of steady flow, but also the effect of unsteady flow should be considered in the design of hydraulic hoisting systems. The water hammer models for single-phase flow are still employed for the analysis and computation of solid-liquid transport pipelines in engineering practice. However, because of the existence of a large amount of solid particles in pipe flows with high concentration of solid particles, the density, elastic modulus, viscosity and resistance of solid-liquid flow are different from those of single-phase flows. As a result, many problems still exist in the analysis and computation of water hammer in solid-liquid flows.

In hydraulic hosting used for mining in deep sea, because the sizes of the solid particles are large (d = 1 ~ 50 mm) and their inertia is high, the water hammer in the pipe flow is different from that of water flow as well as pseudo-homogeneous solid-liquid flow. The water hammer in pseudo-homogeneous solid-liquid flow has been studied in the past[1, 2]. In this paper, the laws of coarse-grained solid-liquid flows are discussed and a model for unsteady flow is developed to simulate the phenomena of unsteady flow in hydraulic hoisting in sea mining.

2 WAVE PROPAGATION SPEED FOR WATER HAMMERS IN COARSE-GRAINED SOLID-LIQUID FLOWS

The typical case of rapid closure of a valve at the end of a pipe can be taken as an example. When the valve is closed, the pressure in the pipeline will increase due to fluid motion caused by inertia. The principle of continuity requires that the net mass inflow due to inertia be equal to the expansion of the pipe walls plus the volume compression of the water and solid particles. Both the expansion and the compression are very small because of the very high elastic modulus of the pipe material, water and the solids. In order to hold the surplus water and the solids, the expansion front of the pipe will propagate rapidly upwards at a certain speed (Fig. 1). This speed is called the wave propagation speed, which is denoted by a. To separate the wave propagation speed in water flow and pseudo-homogeneous solid-liquid flow, the wave propagation speed in coarse-grained solid-liquid flow is denoted by a_{m2}. The equation to calculate the wave propagation speed can be derived based on the principle of continuity. It is required that the volume enter-

① **[Foundation item]** Project(29879007) supported by the National Natural Science Foundation of China; project supported by the Basic Research Foundation of Department of Hydraulic Engineering of Tsinghua University

[Received date] 2001- 11- 05; **[Accepted date]** 2001- 12- 21

ing into the expanded segment ΔL equals the sum of the volumetric increment of the pipe and the volumetric compressions of water and that of the solid particles in the expanded segment ΔL.

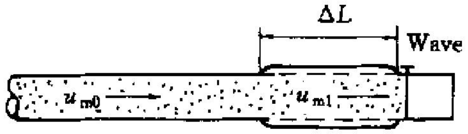

Fig. 1 Propagation of pressure wave $\Delta u_s C_v A\ \Delta t + \Delta u_L(1- C_v) A\ \Delta t = \Delta V_s + \Delta V_L + \Delta V_p$

Assuming that the initial velocities of solids and water are u_{s0} and u_{L0}, respectively, and their velocities after a time interval Δt are u_{s1} and u_{L1}, respectively, the volumetric increment of water and solid particles in the expanded segment ΔL can be expressed as:

$$V = C_v(u_{s0} - u_{s1}) A\ \Delta t + (1 - C_v) \cdot (u_{L0} - u_{L1}) A\ \Delta t \qquad (1)$$

where A is the pipe cross-sectional area; and C_v is the solid concentration by volume.

Assuming that the increment of pressure due to the change in velocity is p, the volumetric compression of water in the expanded segment ΔL can be derived from the definition of elastic modulus of water E_L, i. e.

$$\Delta V_L = \frac{p}{E_L}(1 - C_v) A\ \Delta L \qquad (2)$$

where ΔV_L is the volumetric compression of liquid.

Similarly, the volumetric compression ΔV_s of the solid particles in the expanded segment ΔL can be expressed as

$$\Delta V_s = \frac{p}{E_s} C_v A\ \Delta L \qquad (3)$$

where E_s is the elastic modulus of solid particle.

The volumetric increment ΔV_p of the pipe in the expanded segment ΔL can be obtained from the increment of tangential strain, diametrical strain and cross-sectional area ΔA due to the increment of pressure in the conduit[3], that is

$$\Delta V_p = \frac{pD}{E_p e} A\ \Delta L \qquad (4)$$

where e is the thickness of the pipe wall, D is the diameter of pipe, E_p is the elastic modulus of the pipes' material.

According to the law of continuity, Eqn. (1) is equal to the sum of Eqns. (2), (3) and (4), i. e.

$$C_v(u_{s0} - u_{s1}) A\ \Delta t + (1 - C_v)(u_{L0} - u_{L1}) A\ \Delta t = \left[\frac{p}{E_L}(1 - C_v) + \frac{p}{E_s} C_v\right] A\ \Delta L + \frac{pD}{E_p e} A\ \Delta l \qquad (5)$$

The momentum equation of coarse-grained flow is

$$pA\ \Delta t = \rho_L(1 - C_v) A\ \Delta L\ \Delta u_L + \rho_s C_v A\ \Delta L\ \Delta u_s \qquad (6)$$

where ρ_s and ρ_L are the densities of the solids and water, respectively. Because the distribution of pressure on the cross-section is uniform, the impulse can also be assumed to be volumetrically uniform[4], that is,

$$C_v A p\ \Delta t = \rho_s C_v A\ \Delta L\ \Delta u_s \qquad (7)$$

$$(1 - C_v) A p\ \Delta t = \rho_L(1 - C_v) A\ \Delta L\ \Delta u_L \qquad (8)$$

Considering the definition of wave propagation speed $a_{m2} = \Delta L / \Delta t$, Eqns. (7) and (8) can be simplified as

$$\Delta u_s = \frac{p}{\rho_s a_{m2}} \qquad (9)$$

$$\Delta u_L = \frac{p}{\rho_L a_{m2}} \qquad (10)$$

By substituting Eqns. (9) and (10) into Eqn. (5) and rearranging terms, the wave propagation speed of coarsed-grained flow a_{m2} is obtained:

$$a_{m2} = \sqrt{\frac{E'_L \rho'}{1 - C_{vL} + \frac{E_L}{E_s} C_{vL} + \frac{E_L D}{E_p e}}} \qquad (11)$$

where ρ' is the equivalent density of coarse-grained flow, $\rho' = \rho_s \rho_L / [C_{vL} \rho_L + (1 - C_{vL}) \rho_s]$; and C_{vL} is the local concentration of solid particles in conduit. In hydraulic hoisting, because of particles' slipping, the local concentration is usually greater than that of the outflow of the conduit.

3 CONTINUITY EQUATION OF COARSE-GRAINED SOLID-LIQUID FLOW

When water hammer happens in coarse-grained solid-liquid flow, because solid particles are large and their inertia is high, they will continue moving after halting for a short while. Therefore, analysis of their unsteady flow is very complicated and some simplification must be done to derive the equations.

Let us consider a segment of Δx in a pipe flow as shown in Fig. 2. At the inflow section, the density of

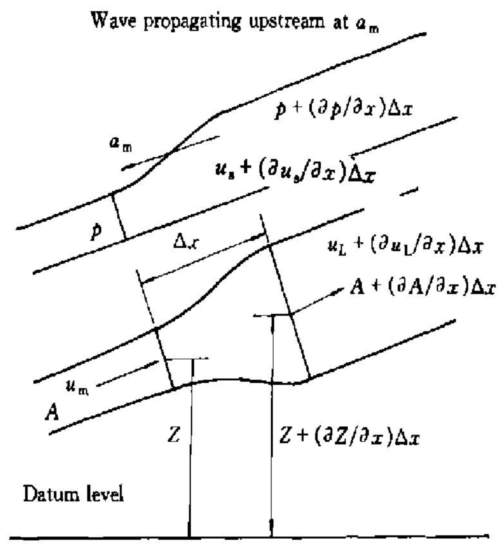

Fig. 2 Diagram of inflow and outflow of control segment

solids is ρ_s, the density of water is ρ_L, the area of the cross section is A, the water hammer pressure is p, the velocity of solid particles is u_s, and the velocity of water is u_L. At the outflow section, the density of water is $\rho_L + (\partial \rho_L/\partial x)\Delta x$, the density of solids is $\rho_s + (\partial \rho_s/\partial x)\Delta x$, the area of the cross section is $A + (\partial A/\partial x)\Delta x$, the water hammer pressure is $p + (\partial p_L/\partial x)\Delta x$, the velocity of water is $u_L + (\partial u_L/\partial x)\Delta x$, and the velocity of solid particles is $u_s + (\partial u_s/\partial x)\Delta x$. According to the principle of continuity, the difference of the inflow and the outflow in a Δt period is equal to the mass increment caused by the volume increment of the water and the solid particles. It is assumed that the concentrations at the inflow section and the outflow section are C_{vL}.

In a Δt period, the mass flowing into the segment is

$$Q_R = \rho_s A u_s C_{vL}\Delta t + \rho_L A u_L(1 - C_{vL})\Delta t \tag{12}$$

and the mass flowing out of the segment is

$$\begin{aligned} Q_C = {} & (\rho_s + \frac{\partial \rho_s}{\partial x}\Delta x)(A + \frac{\partial A}{\partial x}\Delta x) \cdot \\ & (u_s + \frac{\partial u_s}{\partial x}\Delta x)C_{vL}\Delta t + (\rho_L + \frac{\partial \rho_L}{\partial x}\Delta x) \cdot \\ & (A + \frac{\partial A}{\partial x}\Delta x)(u_L + \frac{\partial u_L}{\partial x}\Delta x) \cdot \\ & (1 - C_{vL})\Delta t \end{aligned} \tag{13}$$

The mass increment of solid-liquid flow caused by the volume increment due to pressure variation is

$$W_p = \rho_m A\,\Delta x \frac{\partial p}{\partial t}\Delta t \frac{D}{eE_p} \tag{14}$$

Because the velocity variations of the solid particles and water are different, the local concentration in the segment of Δx may change. Assuming that the concentration after change is C'_{vL}, then the mass increment caused by the volume increment of the solid and the liquid in the Δx segment is

$$W_z = \rho_m A\,\Delta x \frac{\partial p}{\partial t}\Delta t(\frac{1 - C'_{vL}}{E_L} + \frac{C'_{vL}}{E_s}) \tag{15}$$

According to the principle of continuity, Eqn. (12) − Eqn. (13) = Eqn. (14) + Eqn. (15). Neglecting the infinitesimal value with higher order and dividing both sides by $\rho_m A\,\Delta x\,\Delta t$, one gets

$$\begin{aligned} & -\frac{1}{\rho_m}[\rho_s \frac{\partial u_s}{\partial x}C_{vL} + \rho_L \frac{\partial u_L}{\partial x}(1 - C_{vL})] - \\ & \frac{1}{\rho_m}[u_s \frac{\partial \rho_s}{\partial x}C_{vL} + u_L \frac{\partial \rho_L}{\partial x}(1 - C_{vL})] - \\ & \frac{1}{A\rho_m}[\rho_s u_s \frac{\partial A}{\partial x}C_{vL} + \rho_L u_L \frac{\partial A}{\partial x}(1 - C_{vL})] \\ & = \frac{\partial p}{\partial t}(\frac{1 - C'_{vL}}{E_L} + \frac{C'_{vL}}{E_s} + \frac{D}{eE_p}) \end{aligned} \tag{16}$$

Compared with the variations of flow velocities of u_s and u_L with x, the variations of densities of ρ_s and ρ_L with x are small[5]. Assuming $\rho_s u_s C_{vL} + \rho_L u_L(1 - C_{vL}) = \rho_m u_m$, the first term on the left-hand side of Eqn. (16) can be simplified as

$$\begin{aligned} & \frac{1}{\rho_m}[\rho_s \frac{\partial u_s}{\partial x}C_{vL} + \rho_L \frac{\partial u_L}{\partial x}(1 - C_{vL})] \\ & = \frac{1}{\rho_m}\{\frac{\partial}{\partial x}[\rho_s u_s C_{vL} + \rho_L u_L(1 - C_{vL})]\} \\ & = \frac{\partial u_m}{\partial x} \end{aligned} \tag{17}$$

Assuming $u_s \rho_s = K_1 u_m \rho_m$ and $u_L \rho_L = K_2 u_m \rho_m$, the second term on the left hand side of Eqn. (17) can be simplified as

$$\begin{aligned} & \frac{1}{\rho_m}[u_s \frac{\partial \rho_s}{\partial x}C_{vL} + u_L \frac{\partial \rho_L}{\partial x}(1 - C_{vL})] \\ & = \frac{1}{\rho_m}\frac{\partial p}{\partial x}[u_s \rho_s \frac{C_{vL}}{E_s} + u_L \rho_L \frac{1 - C_{vL}}{E_L}] \\ & = \frac{1}{\rho_m}\frac{\partial p}{\partial x}[[K_1 u_m \rho_m \frac{C_{vL}}{E_s} + K_2 u_m \rho_m \frac{1 - C_{vL}}{E_L}] \\ & = \frac{\partial p}{\partial x}u_m(\frac{C'_{vL}}{E_s} + \frac{1 - C'_{vL}}{E_L}) \end{aligned} \tag{18}$$

The third term on the left hand side of Eqn. (16) can be simplified as

$$\begin{aligned} & \frac{1}{A\rho_m}[\rho_s u_s \frac{\partial A}{\partial x}C_v + \rho_L u_L \frac{\partial A}{\partial x}(1 - C_v)] \\ & = \frac{\partial p}{\partial x}\frac{D}{E_p e}\frac{1}{\rho_m}[\rho_s u_s C_v + \rho_L u_L(1 - C_v)] \\ & = u_m \frac{\partial p}{\partial x}\frac{D}{E_p e} \end{aligned} \tag{19}$$

Finally, Eqn. (16) can be simplified as

$$\begin{aligned} & \frac{\partial u_m}{\partial x} + (u_m \frac{\partial p}{\partial x} + \frac{\partial p}{\partial t})(\frac{C'_{vL}}{E_s} + \\ & \frac{1 - C'_{vL}}{E_L} + \frac{D}{E_p e}) = 0 \end{aligned} \tag{20}$$

Considering that the wave propagation speed for coarse-grained flow is a_{m2}, we can further simplify Eqn. (20) as

$$u_m \frac{\partial p}{\partial x} + \frac{\partial p}{\partial t} + \rho' a_{m2}^2 \frac{\partial u_m}{\partial x} = 0 \tag{21}$$

Eqn. (21) is the continuity equation of coarse-grained solid-liquid flow, where ρ' is the equivalent density of coarse-grained flow, $\rho' = \rho_s \rho_L/[C'_{vL}\rho_s + (1 - C'_{vL})\rho_L]$. In hydraulic hoisting, because of particles' slipping, the local concentration C_{vL} is usually greater than that of the outflow. Many researchers have studied this phenomenon in the past. LIANG[6] introduced the BBO equation to the problem. In his analysis, the turbulent frequency of water flow f of 1 Hz and the density of particles ρ_s of 2 650 kg/m^3 were used. LIANG's results gave that $\eta = u_s/u_0 = 0.48$ when the diameter of particles d is 2.3 mm and when $\eta = u_s/u_0 = 0.525$, when d is 0.25 mm. Cloete, et al[7] studied the retention rate in hydraulic hoisting through pipe with diameters of 12.7 mm and 19 mm. The concentration by weight was greater than 40 percent, and the diameters of sand grain and glass grain were changed from 0.178 mm to 0.7 mm. Because of the retention of particles, $\eta = u_s/u_0 = 0.694 \sim 0.763$ and the local concentration changed from 53% to 61% for particles with diameter of 2. 3 mm.

From the above discussion, it can be conclude that the increase in local concentration in the pipe is mainly because the velocity of particles is lower than that of water. The local concentration can be derived from the slipping velocity of particles and can be expressed as[8]

$$C_{vL} = \frac{1}{2}\left(1 - \frac{u_m}{u_{gs}}\right) + \left[\frac{1}{4}\left(\frac{u_m}{u_{gs}} - 1\right)^2 + C_v \frac{u_m}{u_{gs}}\right]^{1/2} \tag{22}$$

where u_m is the average velocity of the solid-liquid mixture; u_{gs} is the slipping velocity of particles; and C_v is the transporting concentration. For unsteady flows, an additional amount of increment can be added to the local concentration, and resulting in C'_{vL} mentioned earlier.

4 MOMENTUM EQUATION OF COARSE-GRAINED SOLID-LIQUID FLOWS

The momentum equation of coarse-grained solid-liquid flows can be derived from the balance of force in the pipe segment as shown in Fig. 2. The resultant of forces acting on the flow segment Δx in the x direction is[9]

$$\begin{aligned} F_z = {} & pA - \left(p + \frac{\partial p}{\partial x}\Delta x\right)\left(A + \frac{\partial A}{\partial x}\Delta x\right) + \\ & \left(p + \frac{1}{2}\frac{\partial p}{\partial x}\Delta x\right)\left(\frac{\partial A}{\partial x}\Delta x\right) - \tau\chi\Delta x - \\ & \gamma_m A\,\Delta x\frac{\partial Z}{\partial x} \end{aligned} \tag{23}$$

where the first term is the normal pressure acting on the left side of the pipe segment; the second term is the normal pressure acting on the right side of the pipe segment; the third term is the component of the reactive force of the average pressure on the pipe segment; the fourth term is the friction force whose direction is opposite to the flowing direction; the fifth term is the gravity component acting on the axis of the pipe segment, whose direction is opposite to the flowing direction; p is the water hammer pressure; χ is the average wetted perimeter of the segment; τ is the shear stress between the flow and the pipe.

If the second order infinitesimal values are neglected, the force acting on the flow segment Δx in the flowing direction becomes

$$F_z = -A\frac{\partial p}{\partial x}\Delta x - \tau\chi\Delta x - \gamma_m A\,\Delta x\frac{\partial Z}{\partial x} \tag{24}$$

According to Newton's second law of motion, the flow segment will accelerate due to the force mentioned above. Therefore

$$\begin{aligned} & -A\frac{\partial p}{\partial x}\Delta x - \tau\chi\Delta x - \gamma_m A\,\Delta x\frac{dZ}{dx} \\ & = \rho_L A\,\Delta x(1 - C_v)\frac{du_L}{dt} \\ & + \rho_s A\,\Delta x C_v\frac{du_s}{dt} \end{aligned} \tag{25}$$

Dividing both sides of the equation by $A\,\Delta x$, Eqn. (25) becomes

$$\frac{dp}{dx} + \gamma_m\frac{\partial Z}{\partial x} + \rho_L(1 - C_v)\frac{du_L}{dt} + \rho_s C_v\frac{du_s}{dt} + \frac{\tau\chi}{A} = 0 \tag{26}$$

By definition,

$$du_m/dt = u_m(\partial u_m/\partial x) + \partial u_m/\partial t$$

and

$$dZ/dx = \partial Z/\partial x = \sin\theta.$$

In an entirely vertical pipe, θ is 90°. As to the hydraulic radius of the rounded pipe, we have $A/\chi = R/2$. Substituting these three relations into Eqn. (26) and dividing both sides by $\rho_m g$, we get

$$\frac{\partial h}{\partial x} + \frac{u_m}{g}\frac{\partial u_m}{\partial x} + \frac{1}{g}\frac{\partial u_m}{\partial t} + \sin\theta + \frac{2\tau}{\rho_m g R} = 0 \tag{27}$$

where u_m is the average velocity of coarse-grained solid-liquid flow; and the last term is the hydraulic gradient of coarse-grained solid-liquid unsteady flow. Water hammer happens in a very short period of time Δt. During this time period, the particle suspension can be regarded as unchanged, therefore the hydraulic gradient of unsteady flow can be assumed to be the same as that of steady flow.

In hydraulic hoisting through vertical pipes, the coarse-grained solid-liquid flow is complicated. Because the pipes are vertically fixed, the velocity gradient is high near the pipe wall. Due to the Magnus force, the solid particles tend to move toward the center and the probability of collision between solid particles and the pipe wall decreases. According to experimental investigation, the hydraulic gradient in hydraulic hoisting in sea mining can be calculated using the following formula[10]

$$\begin{aligned} i_m = {} & \left[\lambda_{sw} + \beta\left(\frac{\sqrt{gD}}{u_m - \omega}\right)^{n_1} C_v^{n_2}\frac{\rho_s - \rho_L}{\rho_{sw}}\right]\frac{u_m}{2gD} \\ & \pm\frac{\rho_s - \rho_L}{\rho_L}C_v \end{aligned} \tag{28}$$

where i_m is the hydraulic gradient; ρ_L and ρ_s are the density of water and solids, respectively; λ_{sw} is the resistance coefficient; ω is the fall velocity of particles in sea water; and β, n_1 and n_2 are the coefficients which are depended on experiments. From the experiment of hydraulic hoisting of manganese nodules, we get that β is 0. 258, n_1 is 2. 951 and n_2 is 1. 11.

The first term on the right hand side of Eqn. (28) is the resistance to flow due to pipe wall friction; the second term is the resistance due to particle collision; and the third term is the resistance to overcome the potential energy of particles, which is positive when flowing upward and negative flowing downward. Substituting Eqn. (28) into Eqn. (27), we have

$$\frac{\partial h}{\partial x} + \frac{\partial Z}{\partial x} + \frac{u_m}{g}\frac{\partial u_m}{\partial x} + \frac{1}{g}\frac{\partial u_m}{\partial t} + i_m = 0 \tag{29}$$

Eqn. (29) is the momentum equation of vertical hydraulic hoisting in sea water.

5 VERIFICATION OF WATER HAMMER MODEL OF COARSE-GRAINED SOLID-LIQUID FLOWS

The water hammer experiment for coarse-grained flows was conducted at the Institute of Sea-Floor Mine Resources Development and Exploitation in the Academy of Mine Smelting, Changsha. The height of the pipe is 27.35 m, its diameter D is 149 mm, its wall thickness e is 5 mm, and its relative roughness factor Δ/D is 0.000 815. Fig. 3 shows the layout of the experiment devices. The system of pipes is supplied with power by a centrifugal ore-pulp pump, supplied with water by an inlet barn and supplied with material by a storage silo. The coarse-grained solid-liquid flow is hoisted to the regulated water tank through a lifting pipe by slime-pulp pump. And the solids and liquids flow back into the inlet barn and storage silo through a distribution box. The flow on the top of the hoisting pipe is free flow.

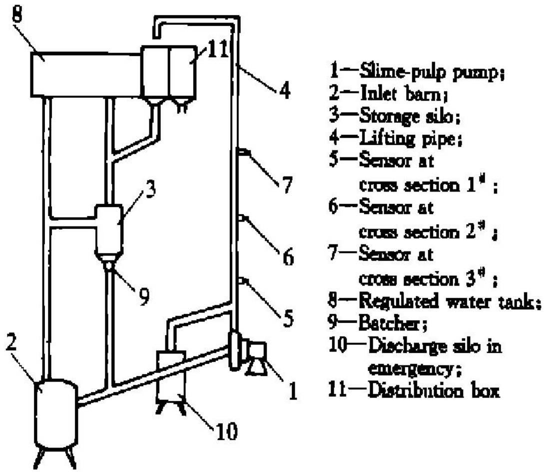

Fig. 3 Layout of hydraulic hoisting experiment in vertical pipes

In order to measure the change of pressure at sections when water hammer happens, three pressure sensors are fixed at cross sections 1#, 2# and 3# above the centrifugal pump. Cross section 1# is located 1 m above the slime-pulp pump. The distance between cross sections 1# and 2# is 5 m. So is that between cross sections 2# and 3#. The pressure fluctuating signals collected by the pressure sensor are modulated and magnified. Then they are recorded on the tape by a tape recorder, changed into digital signals by A/D interface card, and finally transferred into the computer. A flow chart of water hammer measuring is shown in Fig. 4.

In the experiment, the sand pump is firstly run. When its rotation rate and the conduit flow are steady, the initial flux, velocity and concentration are measured. Then the water flow in the pipe is cut off by suddenly turning off the power, resulting in the close water hammer. The pressure fluctuation is measured and recorded in synchronism, as shown in Fig. 5.

The diameter of coarse grains used in the experiment changes from 15 mm to 25 mm and their specific mass is 2 201 kg/m^3. Two groups of coarse-grained water hammer experiments with different volumetric concentrations are conducted, and the initial hoisting velocity is 3.1 m/s. A numerical model for the computation of water hammer in coarse-grained solid-liquid flows is developed based on the continuity equation Eqn. (21) and the equation of motion Eqn. (28). This model is used to simulate the experimental flows and the computed results are shown in Figs. 6 and 7. It can be seen that, except for the low head portion, the simulation results are fairly good.

6 CONCLUSIONS

1) Because the flow velocities of solid particles

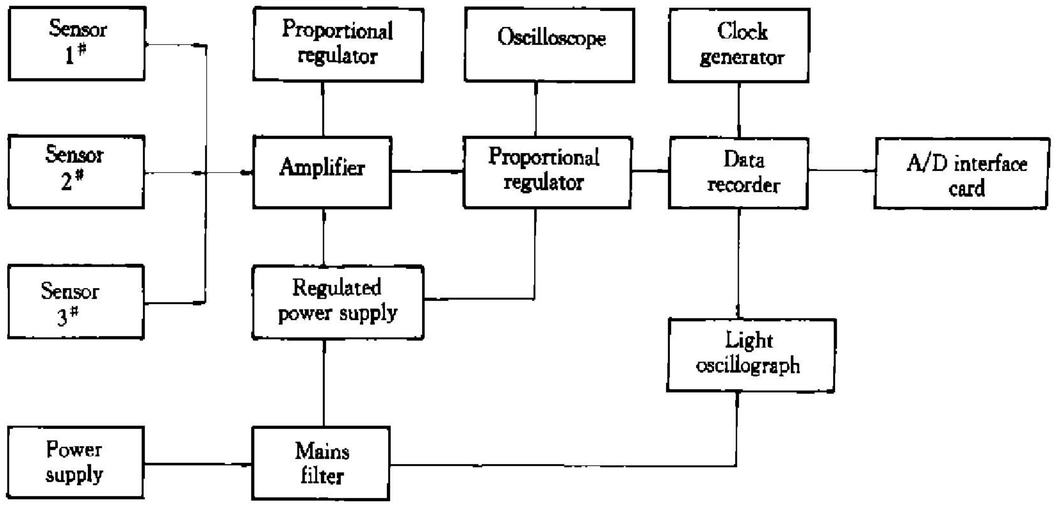

Fig. 4 Diagram of measuring water hammer

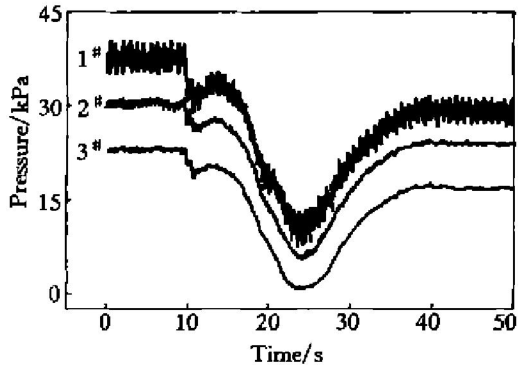

Fig. 5 Pressure signals measured by three pressure sensors in conduit

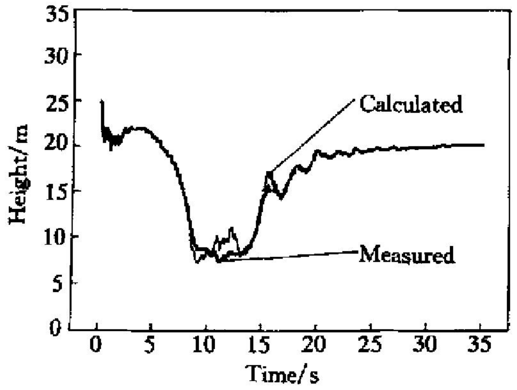

Fig. 6 Variation of calculated and measured water hammer pressures

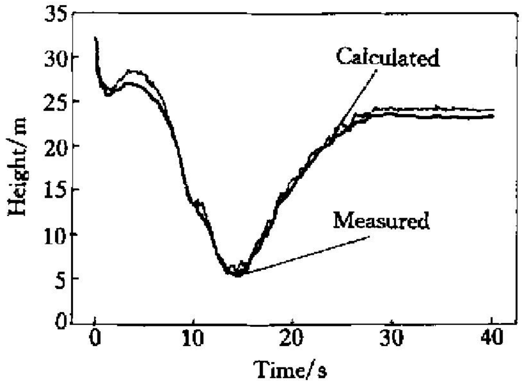

Fig. 7 Variation of calculated and measured water hammer pressures

and water are different, the flow in hydraulic hoisting through vertical pipes is typical coarse-grained solid-liquid flow. The equations for water hammer in coarse-grained solid-liquid flows, which are derived by considering the difference in flow velocities between the particles and water and by introducing the concept of local concentration, are correct.

2) The derived formula of wave propagation speed, continuity equation and momentum equation of coarse-grained two-phase flow have fairly high precision because not only the effects of the density and elastic modulus of solid-liquid two-phase flow are considered, but also the law of coarse-grained flow is considered.

3) The numerical model of coarse-grained unsteady flow, developed by using the finite difference method based on the continuity and momentum equations proposed in this paper, has fairly high precision.

4) When the water column is broken, the cavity or vacuum segment is formed. The processes of the close of vacuum segment and the abruption of cavity are rather complicated, as a result, the model proposed in this paper is not suitable to simulate such conditions. The negative water hammer, formed when water column is broken, needs to be further studied.

[REFERENCES]

[1] HAN W L, DONG Z N, CHAI H E. Water hammer in pipelines with hyperconcentrated slurry flow carrying solid particles [J]. Science in China (Series E), 1998, 41 (4): 337- 347.

[2] HAN W L, DONG Z N, CHAI H E, et al. Computing equations of water hammer in pseudo-homogeneous solid-liquid flow and their verification [J]. Science in China (Series E), 2000, 43(2): 215- 224.

[3] WANG S R, Dong Y X. Construction of Hydropower Station [M], (in Chinese). Beijing: Tsinghua University Press, 1984. 96- 98.

[4] Wood D J, Kao T Y. Unsteady flow of solid-liquid suspensions [J]. ASCE, 1966, 92(EM6): 116- 118.

[5] Hydraulics Program at Tsinghua University. Hydraulics (Vol. I) [M], (in Chinese). Beijing: The People's Education Press, 1981. 539.

[6] LIANG Z C. Turbulent Mechanics [M], (in Chinese). Zhengzhou: Henan Science Press, 1988. 253.

[7] Cloete F L D, Miuer A L, Streal M. Dense phase flow of solids-water mixtures through vertical pipes [J]. Trans Instn Chem Engrs, 1967, 45: 392- 400.

[8] XIA J X. Hydraulic hoisting of polymetallic nodules in two-phase fluid dynamics in the ocean and its application [D], (in Chinese). Beijing: Tsinghua University, 2000.

[9] WANG S R. Theory and Computation of Water Hammer [M], (in Chinese). Beijing: Tsinghua University Press, 1981. 17- 20.

[10] XIA J X, NI J R, HUANG J Z. Pressure loss in solid-liquid flow with coarse manganese nodules in vertical pipeline [J]. Journal of Sediment Research, (in Chinese), 2002(2): 23- 28.

(Edited by HE Xue-feng)