Discussion of "Analysis of the Vertical Profile of Concentration in Sediment-Laden Flows" by Q. Q. Liu, A. P. Shu, and V. P. Singh

June 2007, Vol. 133, No. 6, pp. 601–607.
DOI: 10.1061/(ASCE)0733-9399(2007)133:6(601)

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The authors have provided an explanation for the mechanism of two patterns of sediment concentration profiles (Fig. 5 in the discussed paper) in sediment-laden flows using Eq. (28) developed in their study. They defined sediment concentration profiles with maximum sediment concentration points significantly above the channel bottom as type I, and those with maximum sediment concentration points at the channel bottom as type II. Eq. (28) in the paper suggests that with increase in particle size, the shift of maximum concentration point from the bottom will decrease, and thus the type I and type II sediment concentration profiles are most likely to occur for finer and coarser particles, respectively.

The authors have made the following two typographical mistakes in their paper.

First, the entire paragraph below Eq. (28) clearly describes the type II concentration profile shown in Fig. (5) of the paper. The authors take the view that the type II concentration profile occurs for bigger particles having larger deposition velocity (ω), making ω/τ^* rather large compared with $[|\partial(\overline{\upsilon_s'^2})/\partial y|+a]$. Thus the concentration gradient given by Eq. (28) in the paper does not change its sign and vary monotonously (sediment concentration decreases with height from the bed) across the entire cross section of open channel flow. Hence, the second part of the last sentence of the paragraph below Eq. (28), stating "which results in type I profile of the concentration distribution," contains a typographical error and should instead read "which results in type II profile of the concentration distribution."

Second, the sentence below Eq. (30) in the paper clearly describes the type I concentration profile shown in Fig. (5) of the paper. The authors take the view that a type I concentration profile occurs for smaller particles having the smaller deposition velocity (ω), making $[|\partial(\overline{\upsilon_s'^2})/\partial y|-a]>\omega/\tau^*$ in the region near the bed. Thus the concentration gradient given by Eq. (28) in the paper changes its sign near the bed of the open channel. Sediment concentration increases in a thin region and decreases with height from the bed in the remaining cross section of open channel flow. Hence the sentence below Eq. (30) in the paper, stating "In this situation, the sediment concentration will increase with height from the bed in a thin region, and exhibit Type II profile," contains a typographical error and should instead read "In this situation, the sediment concentration will increase with height from the bed in a thin region and exhibit a Type I profile."

The discusser has the following two points of disagreement with the authors.

First, the discusser has taken up a similar type of study in his recent publication (Kaushal and Tomita 2007). In this study, the discusser has attempted to explain the mechanism of two types of concentration profiles on the basis of experimental data collected

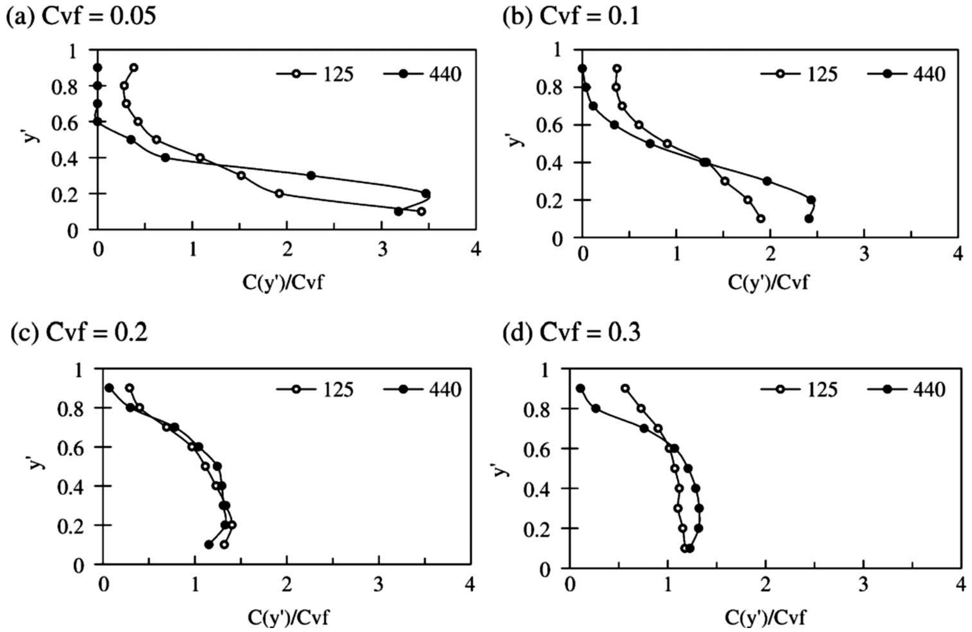

Fig. 1. Comparison of concentration profiles measured by γ-ray density meter for 125 and 440 μm particles at flow velocity of 1 m/s. Reprinted from *Powder Technology*, Vol. 172, Issue 3, Kaushal, D. R. and Tomita, Y., "Experimental investigation of near-wall lift of coarser particles in slurry pipeline using γ-ray densitometer," pp. 177–187, with permission from Elsevier (2007).

in a slurry pipeline using a gamma-ray densitometer. Two sizes of glass beads were used, having a mean diameter and geometric standard deviation of 440 μm and 1.2 and 125 μm and 1.15, respectively. These data were collected for flow velocity up to 5 m/s and an overall concentration up to 50% by volume for each velocity.

Our experimental observations (Fig. 1) clearly show that for finer particles (125 μm), maximum points of concentration are near the pipe bottom (type II sediment concentration profile), and for coarser particles (440 μm), maximum points are relatively further away from the pipe bottom (type I sediment concentration profile). Our experimental results indicate absence of near-wall lift for finer particles because of submergence of particles in the lowest layer into the viscous sublayer, and presence of considerable near-wall lift for coarser particles due to impact of the viscous-turbulent interface on the bottommost layer of particles and increased particle-particle interactions.

The experimental results can be explained physically as follows: in the core of the flow, the turbulent diffusion concept (i.e., the rate of upward transfer of suspended particles due to turbulence is in equilibrium with the downward exchange due to gravitational forces) holds good, but near the wall, turbulence is diminished or eliminated in the viscous sublayer zone. Here, the mirror effect cannot be provided by turbulent diffusion, and the second contribution to suspension, hydraulic lift, comes into prominence.

The near-wall lift force is associated with shifting of the point of maximum concentration away from the pipe bottom, which appears as a result of impact of the viscous-turbulent interface on the bottommost layer of particles. Since the particle size is larger than the viscous sublayer thickness, the interface impacts on the coarser particles to lift upward, whereas submergence of finer particles in the lowest layer into the viscous sublayer results in the absence of near-wall lift. However, it is difficult to give this force as a mathematical formula. Wilson and Sellgren (2003) have also observed near-wall lift of particles in the concentrated slurry flow of coarser particles in a pipeline.

Second, as the near-wall lift phenomenon affects the movement of particles near the solid boundary, it has equal importance in the pipeline flow and open channel in the region near the bed in solid-liquid two-phase flow. Shield's diagram (van Rijn 1984) suggested a critical particle size up to which the shear velocity for incipient motion varies inversely with particle size in an open channel. The shear velocity for incipient motion increases with particle size for the particle sizes more than the critical size.

As the incipient motion of a particle takes place because of the lift of particles at the channel bottom, the near-wall lift may be taken as a reason for existence of a critical particle size. As the viscous sublayer thickness (δs) is inversely proportional to shear velocity, ($\delta s/d$) may be considered as the governing parameter for near-wall lift, where d is the particle diameter. The viscous-turbulent flow interface will not affect the lift of finer particles, and increased gravity will hamper the lift of much coarser particles. Hence, the particles having larger deviation in size from the critical size will not experience near-wall lift.

References

Kaushal, D. R., and Tomita, Y. (2007). "Experimental investigation of near-wall lift of coarser particles in slurry pipeline using γ-ray densitometer." *Powder Technol.*, 172(3), 177–187.

van Rijn, L. C. (1984). "Sediment transport. Part I: Bed load transport." *J. Hydraul. Eng.*, 110(10), 1431–1456.

Wilson, K. C., and Sellgren, A. (2003). "Interaction of particles and near-wall lift in slurry pipelines." *J. Hydraul. Eng.*, 129(1), 73–76.

Closure to "Analysis of the Vertical Profile of Concentration in Sediment-Laden Flows" by Qing-Quan Liu, An-Ping Shu, and Vijay P. Singh

June 2007, Vol. 133, No. 6, pp. 601–607.
DOI: 10.1061/(ASCE)0733-9399(2007)133:6(601)

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The writers thank the discusser for his interest and his useful comments on the paper. First, the writers express their regret that there is a mistake in the caption of Fig. 5 in the original paper. The writers defined the sediment concentration profile with maximum sediment concentration points at the channel bottom as the type I profile, and defined the sediment concentration profile with maximum sediment concentration points significantly above the channel bottom as the type II profile. Therefore, Fig. 5 in the paper needs to be replaced by Fig. 1 given here. This obviates any confusion that may arise in the paper.

Second, the term τ^* in the paper represents the relaxation time of a particle. In general, the relaxation time of particles, τ^*, increases with increasing particle size. *Consequently, it cannot be concluded that* ω/τ^* increases with the increase of particle size, although larger particles have a larger deposition velocity (ω). Hence, the discusser's deduction, "Eq. (28) from the paper suggests that with increase in particle size, the shift of maximum concentration point from the bottom will decrease, and thus the type I and type II [referring to Fig. 5 in the original paper] sediment concentration profiles are most likely to occur for finer and coarser particles, respectively," is incorrect. On the basis of the

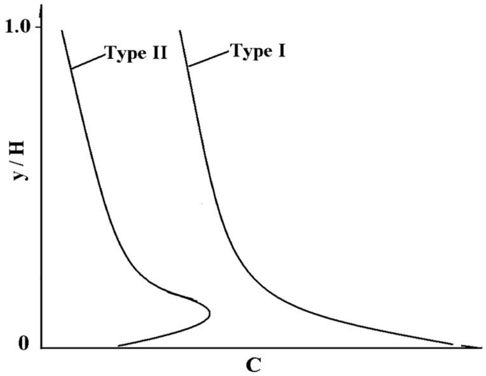

Fig. 1. Two types of sediment concentration profile.

preceding reasoning, the writers respond to the discusser's comments as follows.

Comment 1: Indeed, the second part of the last sentence of the paragraph below Eq. (28) stating "which results in type I profile of concentration distribution" is incorrect, referring to Fig. 5 in the original paper. When Fig. 5 is replaced by Fig. 1 given here, the conclusion "which results in type I profile of concentration distribution" will then be correct. In addition, the writers must indicate that it was not concluded that "bigger particles having a large deposition velocity (ω) certainly make ω/τ^* rather large." That is to say, the statement "the term ω/τ^* is rather large as compared with $|\partial(\overline{v_s'^2})/\partial y|+a$" is not directly related to the particle size. In fact, the expression in the paper is "Commonly, the term ω/τ^* is rather large as compared with $|\partial(\overline{v_s'^2})/\partial y|+a$, especially in the mainstream region where both $|\partial(\overline{v_s'^2})/\partial y|$ and (a) are generally very small." In other words, not exactly knowing the values of ω/τ^*, $|\partial(\overline{v_s'^2})/\partial y|$ and (a), one can only deduce that in most situations the value of $(\partial(\overline{v_s'^2})/\partial y+\omega/\tau^*-a)$ is less than zero because of the small value of $|\partial(\overline{v_s'^2})/\partial y|+a$, which results in the type I (referring to Fig. 1 here) profile of the concentration distribution.

Comment 2: Similarly, the writers respond to the discusser's second comment. Referring to Fig. 5 in the paper, the statement "In this situation, the sediment concentration will increase with height from the bed in a thin region, and exhibit the type II profile" is incorrect, as indicated by the discusser. Again, the problem stems from the mistake in the caption of Fig. 5. When this figure is replaced by Fig. 1 here, the conclusion will then be correct.

However, the writers also need to indicate that it was not concluded that "Type I [referring to Fig. 5 in the original paper] concentration profile occurs for small particles having smaller deposition velocity making $|\partial/\partial y(\overline{v_s'^2})-a|>\omega/\tau^*$ in the region near the bed." The writers do not think that small particles having a smaller deposition velocity certainly make ω/τ^* smaller. That is to say, the analysis in the paper was not directly related to particle size. The writers want to express that when $|\partial/\partial y(\overline{v_s'^2})-a|>\omega/\tau^*$ is near the bed, the distribution of sediment concentration will take on the type II profile (referring to Fig. 1 here). In fact, experimental data also show that the fluctuation intensity of particles sometimes decreases rapidly with height in the closed bed, which commonly leads to a greater value of $|\partial\overline{v_s'^2}/\partial y|$. When $|\partial(\overline{v_s'^2})/\partial y|$ and the flow uplift (a) are sufficiently large in the region near the bed, which may make $|\partial/\partial y(\overline{v_s'^2})-a|>\omega/\tau^*$ or $\partial/\partial y(\overline{v_s'^2})+\omega/\tau^*-a<0$. In this situation, the sediment concentration would increase with height from the bed in a thin region, and exhibit the type II profile (referring to Fig. 1 here).

Comment 3: The discusser mainly wants to illuminate that for finer particles, the profile of concentration distribution is more likely to take on the type I profile, and for coarser particles, the profile of concentration distribution is more likely to take on the type II profile (referring to Fig. 1 in the present manuscript). First, the analysis presented in the original paper did not directly relate to particle size. The discusser's deduction, "Eq. (28) suggests that with increase in particle size, the shift of maximum concentration point from the bottom will decrease, and thus the type I and type II [see Fig. 5 in the original paper] sediment concentration profiles are most likely to occur for finer and coarser particles, respectively" is incorrect.

Second, the writers' analysis, in fact, is not contradictory to the discusser's point of view. The writers always indicated that the irregular pulsation caused by collision between particles, or particle and wall, is the key reason resulting in a larger fluctuation intensity near the bed (Liu and Singh 2004). Therefore, for coarser particles there may be a much larger fluctuation intensity near the bed than for finer particles, which would lead to a larger value of $|\partial\overline{v_s'^2}/\partial y|$. In addition, similar to the discusser's analysis, coarser particles, in general, more easily obtain a greater near-wall lift because the particle size is larger than the viscous sublayer thickness. Therefore, for coarser particles, the profile of concentration distribution can more likely take on a type II profile (referring to Fig. 1 here) due to greater $|\partial\overline{v_s'^2}/\partial y|$ and uplift (a). Conversely, for finer particles, the profile of concentration distribution is more likely to take on a type I profile (referring to Fig. 1 here) due to relatively smaller $|\partial\overline{v_s'^2}/\partial y|$ and uplift (a).

Comment 4: The discusser wants to further explain the importance of the near-wall lift affecting the movement of particles near the solid boundary. First, the writers maintain that the gradient of the particle's fluctuation intensity is one of the most important influential factors for the particle concentration profile near the bed. However, the writers do not deny that there are also other influencing factors, especially the near-wall lift. As a matter of fact, Eq. (28) in the paper includes the effect of both particle fluctuation $|\partial\overline{v_s'^2}/\partial y|$ and the near-wall lift (a). Ni and Wang (1987) also reported that the greater uplift force near the bed is an important reason leading to the sediment concentration taking on a type II profile (referring to Fig. 1 here).

Second, the discusser gives the example of Shield's diagram to explain the importance of the near-wall lift and thinks that the near-wall lift may be taken as a reason for the existence of critical particle size. However, the discusser still does not provide *quantitative* results. The writers posit that this example, to a certain extent, may prove the important action of near-wall lift on bed-load particles, but cannot sufficiently demonstrate the importance of near-wall lift on suspended particles. In fact, for type II profiles the maximum sediment concentration point, in general, is much higher than the viscous sublayer thickness, as shown in the discusser's experimental results (*referring to Fig. 1 in the discussion*). The effect of the viscous sublayer is commonly limited to a very thin layer near the bed, which would mainly impact the movement of bed load particles. In addition, many investigations (Chien and Wan 1986) have shown that the main reason for the existence of critical particle size for particles' incipient motion is the cohesive force between particles, which increases with the decrease of particle size for finer cohesive particles.

Whatever the conclusions and results given by the discusser, these should be helpful in further discussions of this problem. The discussion by Dr. D. R. Kaushal is much appreciated.

References

Chien, N., and Wan, Z. H. (1986). *Mechanics of sediment transport*, Science Press, Beijing, and Chien, N., and Wan, Z. H. (1999) (translated under the guidance of John S. McNown), ASCE, Reston, Va.

Liu, Q. Q., and Singh, V. P. (2004). "Fluid-solid interaction in particle-laden flows." *J. Eng. Mech.*, 130(12), 1476–1485.

Ni, J. R., and Wang, G. Q. (1987). "Studies on the two patterns of vertical distribution of particle concentrations and their formation cause." *J. Hydraul. Eng.*, 18(7), 60–67 (in Chinese).