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부정확한 인자와 관계된 유사량 산정 오류에 대한 검증
An Examination of Sediment Discharge Computation Errors Related to Imprecise Factors

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Abstract

This study investigates the magnitude of errors that can be expected in integrating sediment concentration in a vertical, based on a single-point measurement, because of errors in input data. Potential error sources, including sampler location, water surface elevation, bed elevation, fall velocity, β value, and κ value were comparatively examined using data from a special study on the Rio Grande Conveyance channel in New Mexico. It is concluded that simple forms of equations for the vertical distribution of velocity and sediment concentration are sufficiently accurate to compute average sediment concentration based on a single-point field sample of suspended sediment. The most uncertain point in the computation is related to the Rouse number z in the equation for the vertical concentration distribution of suspended sediment.

요 지

본 연구는 일점 측정을 토대로 연직 유사 농도 계산시 예상되는 입력 자료의 부정확함 때문에 발생하는 오류의 크기를 연구하였다. 오류 가능성이 있는 원인인 채취기의 위치, 수면 및 하상고도, 침강 속도, β와 κ 값은 미국 리오그란데강으로부터 얻는 자료를 사용하여 비교, 검증되었다. 그 결과 일점 부유사 채취를 토대로 간편한 유사 농도식과 속도 분포식을 사용하여 평균 유사 농도를 산정할 수 있었다. 이 계산 중에서 가장 불확실한 점은 부유사의 연직 유사 분포식에서 Rouse 수인 z였다.

1. Introduction

Research and development work of the Federal Interagency Subcommittee on Sedimentation (1941) in the 1940s and 1950s estab-

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lished procedures, equipment, and techniques for sampling suspended sediment loads that are essentially state of the art even today. The impetus for that work was the need for careful assessment of sedimentation problems in planning and design of Missouri River water resources development projects. The Subcommittee developed a suspended sediment sampler that withdraw a true sample at the velocity of the ambient flow around the sampler nozzle, thus bypassing questions related to velocity and concentration distributions. In their sampling technique, the sampler itself automatically performed the required integration in the vertical, giving a depth-integrated sample. Lowering the sampler at a constant rate (V_t) and raising the sampler at a constant rate (which did not have to be the same) resulted in a correctly weighted average concentration.

$$q_s = \int \eta C\bar{u}\, dx = \int \eta C\bar{u}\, V_t\, dt \qquad (1)$$

$$q = \int \eta C\bar{u}\, dx = \int V_t\, dt \qquad (2)$$

$$C_m = q_s / q \qquad (3)$$

where q_s is suspended sediment load per unit width, q is unit discharge, and C_m is average sediment concentration. Coefficients such as η may be needed because of the units of the variables.

In theory the integration should have been perfect; in practice it was good enough for the purpose. There were difficulties in the field, and there were troubling questions with the data at times. For example, when the sampler touched the bed of the stream, it could nose into the lee of a dune. This problem was solved to some extent by taking two samples, then holding them up to the light and comparing them as the sediment settled. If they seemed different to the observer, he was instructed to take another sample. With three (or even four) samples, there was a good chance the "bad" sample could be eliminated and a "good" determination of the mean concentration made from the remaining samples. there were other questions that were never answered completely and satisfyingly, such as, " Is a pint milk bottle a big enough sample?" The answer was "probably not, but the error should be random with the large-scale features of the turbulence and should average out with many samples over time." The big problem, however, was the typical scatter of plots of instantaneous suspended sediment load versus total discharge (Zernial, 1961; Zernial and Laursen, 1963 ; Laursen et al., 1976). The scatter is usually attributed to the so-called wash load which presumably has no dependence on the flow characteristics.

Whatever the explanation of the scatter, there has been and is a felt need to sample much more often, especially during a flood when the concentration at the same discharge on the rising and falling limbs of the hydrograph can differ remarkably. The use of a single-point sample to compute sediment discharge is a plausible solution, especially if the whole procedure could be automated (Ingram et al., 1991). However, it is not possible to avoid certain problems related to velocity and sediment distribution in the vertical that are inherent in the use of a single-point sample, as was so done successfully with the depth-integrated sampling technique. Therefore, it is advisable to examine possible errors to be guarded against when using a single-point sampling procedure.

2. Possible Errors

Several kinds of errors can result in an incorrect determination of the suspended sediment load, such as:

(1) An incorrect sample taken by the sampler.

(2) An inadequate distribution equation for the velocity or concentration.

(3) An error in location of the sampler.

(4) An error in evaluation of the water surface or stream bed.

(5) An error in evaluation of the Rouse number z.

(6) An error in computation or integration.

Other errors are the kind of things that humans do occasionally no matter how hard they try not to; e. g., a typographical error in transcribing data or telling the computer what to do. Such errors can be trivial or devastating, probably can not be entirely eliminated, and their possible occurrence should not be ignored just because nothing bad has happened (or has not been noticed) lately. These are not the errors we are interested in here, but they can be serious; careful checking is required.

The first kind of error listed above presumably was taken care of by the Federal Interagency Sedimentation Subcommittee in developing their samplers and procedures and the criteria they designed their samplers to fulfill. Nevertheless, sampler nozzles can be covered with leaves, the insides can clog, and other things can happen, Checking is required, just as with human errors. The other errors listed above are the subject of this study. They all have to do in some way with integration of the point sample over the vertical.

The velocity and concentration distributions used were presented in detail by Jung et al. (1994).

$$\frac{\overline{u}}{\overline{U}}=(X+1)(yD)^{X} \tag{4}$$

$$\frac{C}{C_a}=\left(\frac{a}{y}\right)^{\frac{w}{\beta K\sqrt{\tau_0\rho}}} \tag{5}$$

$$C_m=\frac{JC_a a^z}{(J-Z)D^J}\left(D^{J-Z}-a^{J-Z}\right) \tag{6}$$

These equations were derived based on some modification of Prandtl's mixing length theory for several reasons; principally for their simplicity, clarity, and computability. As is also true for prandtl's logarithmic velocity distribution and Rouse's concentration distribution, these equations relate the mean flow characteristics to only that turbulence which is a function of the velocity distribution: a circular proposition. A truer description of the behavior of the flow and the sediment particles would require consideration of secondary, three-dimensional flow features, large-scale turbulence (or small-scale random, unstable secondary flow), bed configuration and dunes, etc. Thus, while one should not expect theory to give perfect agreement with reality, one should explore possible sources of errors in order to guard against them. Moreover, the point sample is an absolute, and the equations can be, in effect, calibrated through detailed sampling of the gaging station cross section, more or less as is standard procedure today.

The hardware to be used in single-point sampling is not addressed herein, although some U. S. Geological Survey (USGS) data obtained with standard, available equipment were used in the investigation. It is hoped this investigation of possible errors will be helpful to others in the design of sampling equipment and development of procedures.

3. Field Data Used in This Study

The best and most comprehensive published data set found was the USGS special study on the Rio Grande conveyance channel in New Mexico (Culbertson et al., 1972). Several point samples were taken in a vertical, and a depth-integrated sample was included as well as a bed-material sample. The size distributions of the samples were a vailable, and information on the cross-section characteristics and stream slope was given.

Culbertson et al. (1972) describe the study reaches, the data collection program, and field data for the Rio Grande conveyance channel near Bernardo, New Mexico. Their report provides depth-integrated suspended-sediment data for normal sections and at concrete weir and point-integrated suspended-sediment data for a narrow discharge range at the sampled sections. The bed material samples, depth-integrated samples, and point-integrated samples were collected on the same data at sampling stations near San Marcial and at Nogal Canyon.

The water discharge at the San Marcial gaging station remained relatively constant, at about 54 cms, from December 11 to 15, 1965. The discharge increased to 55 cms on December 18 and then decreased to 53 cms on December 21, when the data in the San Marcial reach were obtained. The discharge was about 50 cms on December 22, when the Nogal Canyon data were obtained. The discharges used in this study are the daily-mean discharge at San Marcial.

The bed form was flat in both reaches during the observations. Standing waves were present near the center of the channel in both reaches, but were most pronounced in the Nogal Canyon reach. Cross-sectional areas were computed on the basis of depth soundings obtained in conjunction with measurements of point velocities. The depths were uniform across the channel at all sections. Water-surface elevations were obtained at approximately 150-meter intervals, one time only, in each reach.

Point-integrated samples were obtained with a modified DH-48 sampler at five points in three verticals at each section. Depth-integrated samples were obtained with a DH-48 sampler by the equal-transit-rate (ETR) method at verticals spaced at 3.049m intervals at both reaches. The suspended sediment samples were divided into four size fractions for analysis: d1 = 0.0465mm; d2 = 0.0935mm; d3 = 0.1875mm; d4 = 0.375mm. Bed-material samples were ob-

Fig. 1. Comparison of Measured and Computed Sediment Concentration Distributions Using Nominal and Site-Corrected z Values

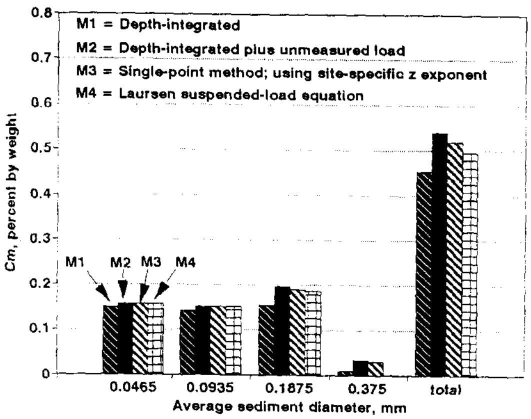

Fig. 2. Total Sediment Load Computed by Four Methods

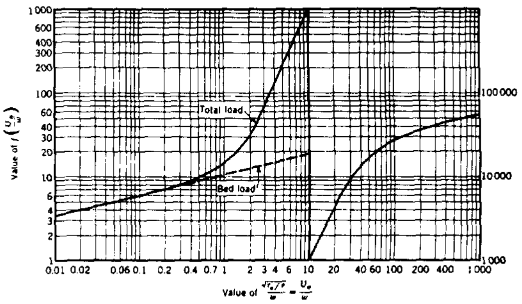

Fig. 3. Function $f(U^*/w)$ for Laursen Formula

tained at verticals spaced at 3.049m intervals. The bed-material samples at each cross-section were composited in the field for analysis in the laboratory.

Fig. 1 compares the sampled concentrations at gaging station 2249 in Rio Grande River with Eq. (5) using a nominal z exponent (β = 1.0, κ = 0.4, uncorrected w) and a site-specific exponent. It is readily apparent that the curve with the nominal z does not quite fit the data and the site-specific z does as well as could be asked for.

Fig. 2 shows the total suspended-sediment load based on four methods of computation: M1 is based on the uncorrected depth-integrated concentration, M2 is based on the depth-integrated concentration corrected for the unmeasured load, M3 is integrated from the lowest point sample using the site-specific z exponent, and M4 is calculated by the Laursen suspended-load concentration equation using a bed material compatible with the measured suspended load.

These two Fig.s are ample evidence that the distribution equations and the computation procedures used are capable of acceptable evaluations of suspended load from a single point-integrated sample. The remainder of this paper examines possible errors to be aware of.

Laursen formula (Laursen, 1958) used in this study was developed to calculate sediment discharge concentration.

$$C_m = {}_{0.01}\gamma\, \Sigma p_i\left(\frac{d_{si}}{D}\right)\left(\frac{\tau_0'}{\tau_{ci}} - 1\right) f\left(\frac{U_*}{w_i}\right) \quad (7)$$

$$\tau_0' = \frac{\rho V^2}{58}\left(\frac{d_{50}}{d}\right)^{1/3} \quad (8)$$

$$\tau_{ci} = \tau_{*c}(\gamma_s - \gamma)d_{si} \quad (9)$$

$$g_s = C_m q \quad (10)$$

in which C_m = sediment discharge concentration, in weight per unit volume; D = depth of flow; τ_0' = Laursen's bed shear stress due to grain resistance defined by Eq. (8); τ_{ci} = critical shear stress for particles of size d_{si}, $U_* = \sqrt{gDS}$ = total bed shear velocity; w_i = fall velocity of particles of mean size d_{si} in water; $f(U_*/w_i)$ = the function show in Fig. 3; and τ_{*c} = dimensionless critical shear stress.

4. Sensitivity of Computed Average Concentration to Potential Errors

In the customary one-point method of sediment sampling, the concentration is usually measured at the surface or at an a/D = 0.4 (or 1-a/D = 0.6) (Federal Interagency Sedimentation Subcommittee, 1941), where a is measuring point above the bed and D is depth of flow. An empirical coefficient must then be applied to the measured concentration to estimate average concentration. Sampling at (or near) the surface is well suited for unskilled observers because they can see where the sampler is, but a surface sample is not a good sample because it has a low concentration, especially for larger sediment particles. Also, the empirical coefficient needed is large and is different for different size fractions in any one is large and is different for different size fractions in any one sample and for different compositions of sampled sediment (or different bed material). Some observers have sampled at 0.4 depth (measured above the bed) in the hope of measuring the average concentration, presumably because average velocity occurs at approximately this level.

Analysis of a wide range of data indicates that, for reasonable accuracy, a one-point sediment measurement should be made at a/D values between 0.4 and 0.2 depth (measured above the bed), with the smaller value being more suitable for coarser sediment (Federal Interagency Sedimentation Subcommittee, 1941). This recommendation was based on empirical calculations and statistical analysis; apparently no attempt was made to determine logically and mathematically where the best level is for sampling average concentration.

The question of the best depth at which to measure average concentration was the first examined in this study. Intuitively it seems that the "best a" would be where the measured concentration, C_a, equals the average concentration, C_m, in the vertical. If the concentration distribution or velocity distribution is other than assumed, errors should be minimized. For fine material, "a" would be slightly less than D/2; for coarse material "a" would be much smaller. Unfortunately, suspended sediment contains fine, medium, and coarse particles.

The relative concentration versus relative depth is plotted for the four size fractions of the Rio Grande in Fig. 4 together with calculated values of C_m/C_a with an arbitrary a/D of 0.1. For the finest fraction (0.0465 mm), the relative concentration C_m/C_a is less than unity because a is not the "best a" and the curves intersect at y

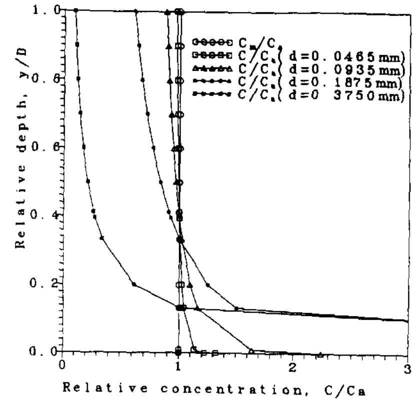

Fig. 4. Graphical Solution of "best a" for $\beta=1.0$, $\kappa=0.4$, and a=0.1D

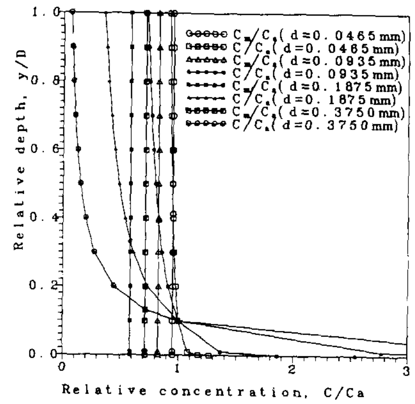

Fig. 5. Graphical Solution of "best a" for $\beta=1.0$, $\kappa=0.4$, and a=0.41D for d1, a=0.39D for d2, a=0.33D for d3, and a=0.13D for d4 (Cm/Ca = relative mean concentration)

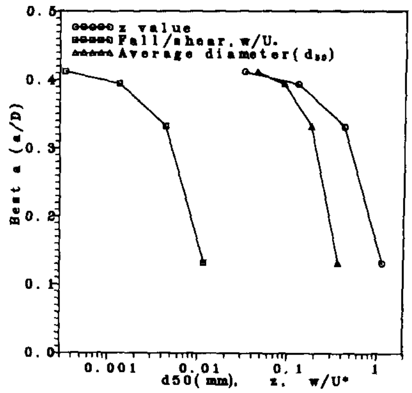

Fig. 6. Variation of "best a" (a/D) vs. z Value, w/U_*, and Sediment Size ($\beta=1.0$, =0.4)

/D = 0.41. The first trial, shown in Fig. 3, was with an a/D of 0.1. The concentration ratios were then recalculated with a/D values of 0.41, 0.39, 0.33, and 0.13, respectively, for the four size fractions (Fig. 5). In Fig. 5 for the finest fraction, C/C_a is now 1.0 at the best a, and C_m/C_a is 1.0. As suggested previously, the results show that the "best a" for the finest fraction is 0.41 of the flow depth (less than half the flow depth measured up from the channel bed), and the "best a" for the coarsest fraction is 0.13 of the flow depth (much closer to the bottom of the channel). The positive and negative areas between the two curves do not match because it is not concentration that is averaged but the product of concentration and velocity.

Next, the variation of the exponent z, fall/shear velocity ratio w/U_* and average diameter d50 with variation of the "best a" (a/D) was examined; results are shown in Fig. 6. Because κ and β are relatively constant, although their values are still arguable, the fall/shear velocity ratio dominates variation of the exponent z. The simplest, but not the best, parameter to use for an approximate notion of best a/D is the sediment diameter.

The solution for the variation of a/D vs z and w/U_* in Fig. 6 should be generally applicable to any sediment in any stream. When the fall velocity is half (or more) of the shear velocity, the concentration will be low and probably measurable only near the bed because the vertical turbulent fluctuations are barely enough to overcome the fall velocity. While data in Fig. 6 are strictly applicable only to streams very like the Rio Grande conveyance channel, the plot gives insight into the "best a" for sizes from silt to sand. Data for the variation of a/D vs sediment size in Fig. 6 should be used with caution and only as a quick, very approximate answer.

To test the intuitive belief that the best a is the level where $C_m = C_a$, data in Fig. 5 were recomputed with arbitrarily increased and decreased z values and the measured concentration of each size fraction at the San Marcial location. The question is, "If a "best a" is selected and a sample taken, what will be the error in C_m if the correct concentration distribution is different than that assumed?" As shown in Fig. 7, the error in C_m (in percent by weight) is negligible for changes in z from -20% to +20% for the finest material (0.0465 mm). For the coarsest material (0.375 mm), C_m is increased from 0.025 to 0.07 for changes in z from -20% to +20% with a C_m of 0.04 for the "correct" z.

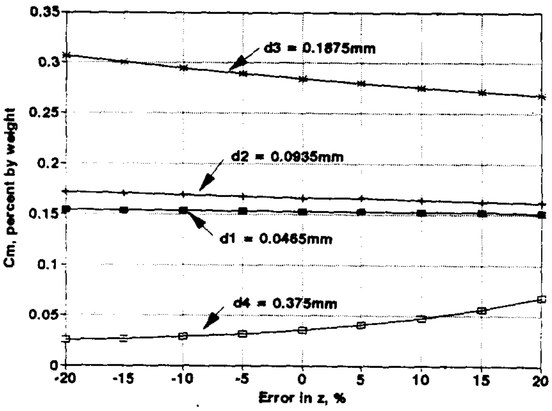

Fig. 7. Sensitivity of "best a" to Error in z Value ($\beta = 1.0$, $\kappa = 0.4$)

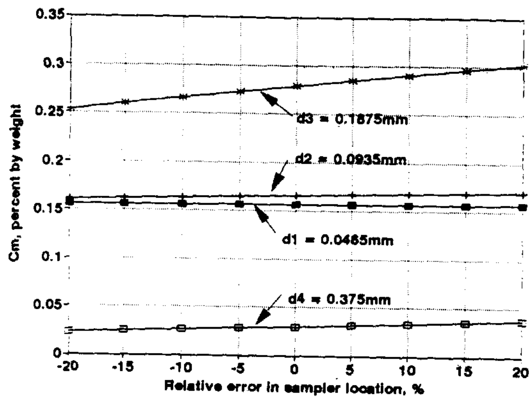

Fig. 8. Sensitivity to "best a" Error in Sampler Location ($\beta = 1.0$, $\kappa = 0.4$)

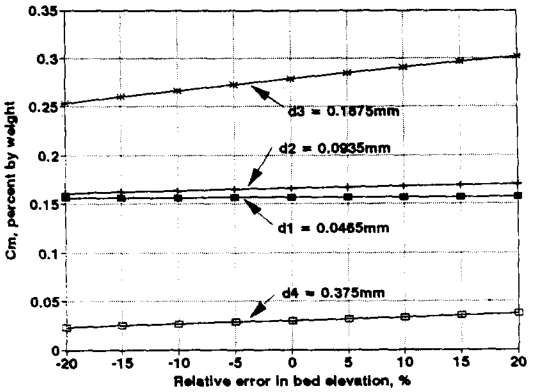

Fig. 9. Sensitivity to "best a" Error in Bed Elevation ($\beta = 1.0$, $\kappa = 0.4$)

A similar test of the concept of the best a is to ask, "what error results if the sample is actually taken unknowingly at a level other than the desired "best a"?" For this test the concentration distribution is basically unchanged, but is shifted because C_a as sampled is that of a higher or lower level. Fig. 8 shows the change in C_m for the several sizes as a function of the error in placing the sampler. For the finest fraction, the change in calculated concentration is negligible if the sampler is mislocated ± 0.3 meter from the best a/D of 0.41 in a stream depth of over 1.2 meters. For the coarsest fraction, the concentration error can be ±10% for a ±20% error in sampler location (about 0.3 meter). Clearly, precise sampler location becomes more important for coarse sediment. However, coarse sediment concentrations are absolutely small, and large relative errors in small values are still small. Whether or not the error is important depends on the problem.

Natural rivers seldom have uniform or steady flow patterns; the water-surface elevation changes with time, and the bed elevation and configuration are likely also to change with time. There will be errors in estimating sediment load due to not knowing the correct elevation of the water surface or the bed.

Another question to test the concept of "best a" is, "what will be the error generated by not knowing the correct elevation of the channel bed?" This error is similar to, but different from the error due to mislocation of the sampler. Results of analysis for this case are shown in Fig. 9 and are virtually identical to data in Fig. 8.

A similar test was made for the error generated by not knowing the correct elevation of the water surface. Especially during floods, discharge and water-surface elevations change more rapidly than bed elevations. As shown in Fig. 10, the effect is virtually the same as for error in sampler location (Fig. 8). The percent error in C_m decreases slightly, but for changes in water-surface elevation of -20% to +20% for the finest material (0.0465㎜) the error is less than ±1%. For the coarsest material (0.375 ㎜), C_m decreases from 0.07 to 0.025 for change in water-surface elevation of -20% to +20% with a value of 0.04 for the correct elevation of the water surface.

A question that probably cannot be resolved for some time is the matter of what exactly is happening in the near-bed region. This is the region where bed load is entrained into the flow,

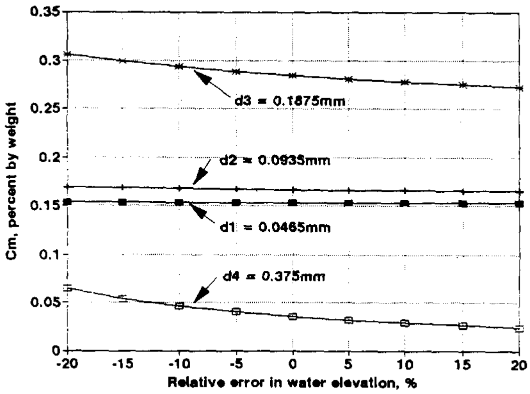

Fig. 10. Sensitivity of Average Suspended Sediment Concentration (C_m) to Error in Water-Surface Elevation ($\beta = 1.0$, $\kappa = 0.4$)

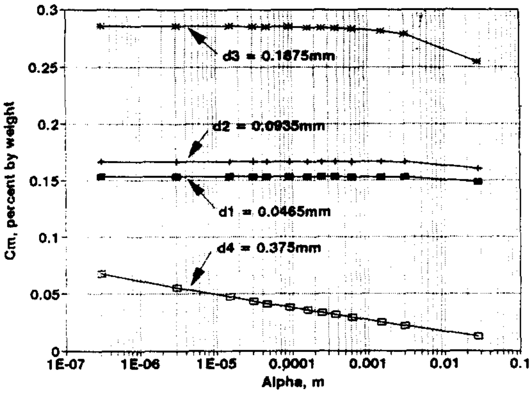

Fig. 11. Sensitivity of Average Suspended Sediment Concentration (C_m) to Lowest Sampling Limit (α) ($\beta = 1.0$, $\kappa = 0.4$)

where suspended load is returned at the bed, where the concentration distribution equations start to fail, where the velocity distribution is not well described, and where the bed level is not well defined (especially if there are dunes). Nevertheless, it is a region of interest.

Samplers are finite in size and cannot sample in the near-bed region, and unless modified, they cannot be used to explore what occurs. Integratingrm $\bar{C}$udy down to various lower limits of α can be helpful in building confidence in single-point sampling. Fig. 11 shows that, for the finest fractions of suspended sediment, the lower limit α ceases to affect the relative mean concentration C_m/C_a at an α of 0.003 meters. For the coarsest fraction, there is an effect of increasing mean concentration with smaller α values because concentration of coarse material near the bed is much larger than in the body of the flow, and the increase in concentration overcomes the decrease in velocity. For coarse sediment, the near-bed conditions are theoretically very interesting although they may not be of any great importance in practice. Although these conclusions were not tested, they are probably true for any resonable concentration distribution. However, this does not say anything about relative composition; composition can be expected to change at lower levels of sampling.

5. Other Factors Examined in This Study

The fall velocity of a particle depends on such factors as shape, proximity of boundary, Reynolds number, concentration, and turbulence. Because all these factors act simultaneously in most problems, it is impossible to feel confident in determining the fall velocity of particles in the full complexity of alluvial-channel flow. The best that can be done is to use judgement, to explore how sensitive the result is to input, and to be careful and questioning about data.

At present, a common practice is to use the relation between sediment sieve diameter and fall velocity for quartz spheres of the same size falling alone in quiescent distilled water of infinite extent, as proposed by Rouse (1937). This can be improved by using the work of Schulz et al. (1954) who conducted extensive experiments and investigated the relation among nominal sediment diameter, sieve diameter, and fall velocity for naturally worn quartz particles (falling alone in quiescent distilled water of infinite extent). Theoretically, the fall velocity of spherical particles should be faster than the fall velocity of natural irregular particles having the same nominal diameter, since natural particles tend to fall with their maximum projected area perpendicular to the fall path. However, this simple explanation is not what Schulz et al. found for small particles. Their data, plotted in Fig. 12, indicate large natural particles fall slower than large spheres, but the opposite was reported for small natural particles and spheres. Why small platelets should fall faster than small spheres was not explained. Could it be that for fine sediment, a cloud of fine particles fell together in a mixture heavier than water?

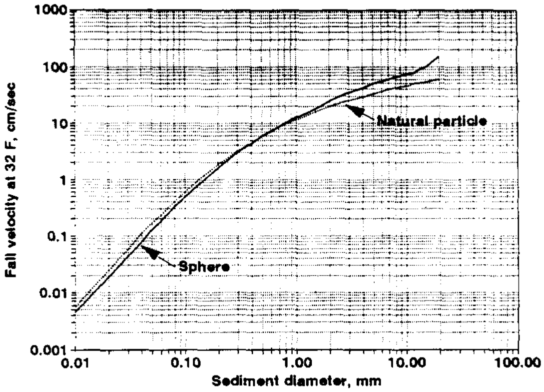

Fig. 12. Comparison of Fall Velocities for Spheres and Natural Particles at 32° F

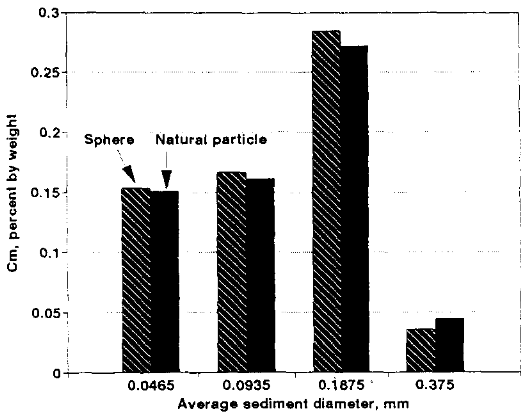

Fig. 13. Comparison of Average Suspended Sediment Concentration (C_m) Using Fall Velocity of Spheres and Natural Particles

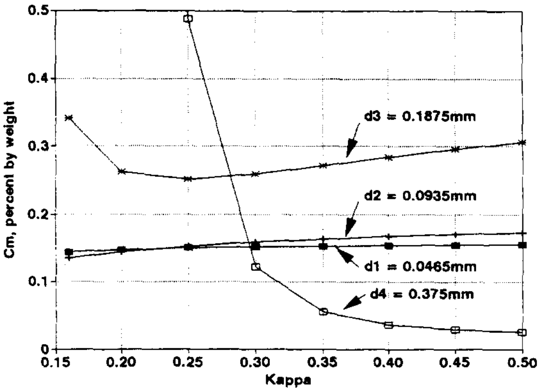

Fig. 14. Sensitivity of Average Suspended Sediment Concentration (C_m) to κ Values

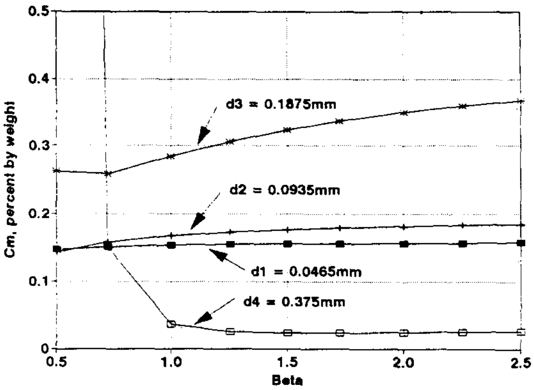

Fig. 15. Sensitivity of Average Suspended Sediment Concentration (C_m) to β Values

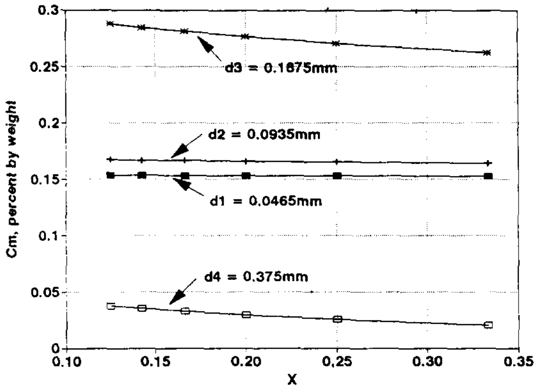

Fig. 16. Sensitivity of Average Suspended Sediment Concentration (C_m) to Exponent, (X) of Power Velocity Distribution Equation

When the natural particle fall velocity of Schulz et al. (1954) was used in the calculation procedure, the total suspended sediment concentration was usually less than 10% different than when assuming spherical particles (Fig. 13). The concentration of fine particles was slightly less; of the coarsest, slightly more.

The relationship between the von Karman constant and sediment concentration is shown in Fig. 14. When the von Karman constant in creases from 0.25 to 0.50, there is a small increase in concentration for small particles. For larger particles, the error may well be a problem when the value of is less than 0.35.

The effects of α, β and X factors also were examined, as shown in Fig. 11, 15, and 16. There is little evidence to suggest β values of less than unity, and possible variation of β should not be of great concern.

6. Discussion of Results

Before examining possible errors, computations were made to find the "best a", defined as the sampler location where $C_a=C_m$. Intuitively, it was felt that if the reference concentration is equal to the mean concentration in the vertical, errors would tend to be minimized. All the parameters in the integral of Cudy have some effect on the value of the "best a", but the most important parameter is the Rouse number z which is the exponent in the concentration distribution equation. Because κ and β are relatively constant, z varies primarily with the ratio of fall velocity to total shear velocity $w/\sqrt{gDS}$. For any specific gaging station, that velocity ratio will vary primarily with sediment size. The best a/D values for sediment of various sizes are shown in Fig. 5. For fine sediment, the best value of a/D is about 0.4, a little lower than mid-depth. For coarse sediment, the best value of a/D is much closer to the stream bed, with the a/D equal to about 0.1 when the fall velocity/shear velocity ratio equals 0.5, and near zero when the fall velocity/shear velocity ratio equals 1.0. The shear velocity is a substitute for the vertical component of the turbulence. When the fall velocity is equal to the root-mean-square of v', ($\sqrt{\overline{v'^2}}$), the mass of fluid surrounding the particle seldom rises faster than the particle is falling.

Unfortunately, the notion of a "best a" where $C_a=C_m$ is not very useful for the natural mixed sediment found in the field. Although there is a level where $C_a=C_m$, the composition of the sample will not be the composition of total suspended sediment load. Usually this overall best a will be close to that of the finer size fractions of the sample. If the primary sediment problem is the useful life of a reservoir, this would probably be the best level at which to sample. However, at this level the concentration of the coarse size fraction will be very small and prone to error. If the primary sediment problem is stream behavior such as aggradation or degradation, it is the coarser fraction that is most important, and the sampling level should be chosen to best sample that fraction.

As can be seen in data for the finest suspended sediment in Figs. 7, 8, 9, 10, and 11, errors z value, sampler location, bed elevation, water-surface elevation, and lowest sampling elevation have to be quite large to result in significant error in the concentration. This is simply because the concentration in the vertical is relatively uniform except near the bed. For the coarsest suspended sediment, the opposite is true; errors in concentration can be large for locational errors that can be expected. During a flood the water surface rises and then falls, the bed scours and fills if there is a contraction of the cross section (or fills and scours if there is an expansion). For acceptably accurate measurement of the coarse fraction, everything must be kept track of at all times.

Knowing where the water surface, bed, and sampler are is a solvable problem; not necessarily easy, but reasonably straightforward. The other primary source of error is in evaluation of the exponent z, the Rouse number. It is a parameter made up of the fall velocity w, total shear velocity $\sqrt{gDS}$, mixing length coefficient κ, and mixing ratio β of the sediment and momentum mixing coefficients. None of these variables is understood well enough. The shear velocity is the best understood and easiest measured, but the slope S is not as simple as it might seem – and is really a substitute for the real thing, the vertical turbulent velocity. The universal constant κ varies at least between 0.4 and 0.3, being largely dependent on boundary roughness. (Note that it can also depend on the particular definition equation used.) The mixing ratio coefficient β, if needed, probably varies between unity and about 1.5.

The most uncertain step in the computational procedure presented is related to the value of the Rouse number ($\beta K \sqrt{\tau_0/\rho}$). Variables in this parameter are not yet completely understood. The fall velocity value needed in the computation procedure is the fall velocity of a natural sediment particle in turbulent flow and in the presence of many other particles. The κ needed is for flow in a natural channel with complex planform and complex (and variable) roughness elements. The β factor needed is a measure of the difference between the mixing of momentum and sediment in suspension over and above the correlation coefficient used in the derivations presented in this study. The scant evidence cited here suggests that the restricted β might have a value of about one, and that any variation would be small.

That leaves the fall velocity w as the variable most likely to result in error. The fall velocity which should be used is that of the oddly-shaped natural particle in the presence of other particles, larger and smaller, in natural water, and in a turbulent field of flow. Schulz et al. (1954) made measurements of the fall velocity of natural sand particles, but they were not in a turbulent field of flow and not in a mixture of larger and smaller particles. Thus, the correct fall velocity is still a question that needs a better answer.

7. Conclusions

Errors in the final estimate of suspended sediment load can be the result of errors in different parts of the total process:

1. Errors in sampler placement and in measurement of stream geometry. The effects of such errors have been studied. For fine material, the effect on the estimate of mean concentration and composition is small; for coarse material, the effect can be significant in percent error in absolute values of that part of the suspended sediment load. Because coarse material is generally a small fraction of total suspended load, the resulting error in total load is usually small. Therefore, the error is significant for some types of problems and not for others. Measurements made for the purpose of specific site evaluation should show whether the stream bed scours and fills, whether the flow pattern is similar for different discharges, and whether the stream characteristics are predictable for a given discharge.

2. Errors in the descriptive distribution equations and in their usage. This type of possible error has been studied here. Such errors should seldom be so large as to be a problem, although again the effects are greater for coarse sediment particles than for fine sediment particles. The possible final errors should be minimized if detailed surveys of flow and suspension are made to adjust "theoretical" relationships to reality. Research on this topic could reduce the complexity of trying to unravel the individual, independent variables of the Rouse number. Such research would be difficult, but could be fruitful. For now, the overall adjustments, based on site specific measurements, must be relied upon and should yield sufficient reliability and

accuracy.

3. Errors in the sampling procedure or errors in measuring the concentration and composition of the sample. This problem has not been examined here.

Notation

The following symbols are used in this paper:

a : reference level above the bed or best a" in a vertical of a channel cross section

C : time-averaged sediment concentration at level y

C_a : point sediment concentration or reference sediment concentration at level a

C_m : average sediment concentration in percent by weight

D : flow depth

d : average sediment diameter for a size fraction

d_{50} : mean sediment size

J : = x + 1=5/4 ~ 8/7

q_s : suspended sediment load per unit width

q : water discharge per unit width

Q : water discharge

S : slope of the channel

$\bar{u}$: time-averaged flow velocity at a distance y above the channel bed

$\bar{U}$: average flow velocity in the vertical of a channel cross-section

v' : mean normal component of turbulent fluctuation

$\sqrt{\overline{v'^2}}$: root-mean-square (rms) values, measures of intensity of turbulence in y direction

w : fall velocity

x : exponent in power velocity distribution equation

y : vertical distance above the bed

z : exponent in Rouse concentration distribution equation

α : lower limit of suspended sediment sampling zone slightly above the streambed

β : proportionality factor, $\in_s/\in_m$

κ : von Karman "universal" mixing length coefficient, 0.4

κ_0 : total tractive force or shear force at the boundary

η : unit coefficient

γ : specific weight of liquid

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