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SECTION 5

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RHEOLOGICAL MODEL FOR RING-SHEAR TYPE DEBRIS FLOWS

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ABSTRACT

Dry glass spheres of a uniform size, such as 3 mm in diameter, are used in a "ring-shear" apparatus to simulate debris flows and the corresponding rheological properties of simulated debris flows are evaluated. Velocity profiles, average shear and normal stresses on the shearing plane, and bulk volume change, if any, of the moving glass spheres in the sample ring are measured. A theoretical velocity profile of shearing glass spheres in the upper ring is derived from a simplified version of the generalized viscoplastic fluid (GVF) model in which the curvature terms are ignored. The method of least squares is used to fit measured velocity profiles to the theoretical ones in an attempt to evaluate the flow-behavior index and the consistency and cross-consistency indices of glass spheres. However, a regression analysis of the consistency index indicates that data on the solids volume fraction (or concentration) distribution of glass spheres in addition to the velocity profile are needed if all the indices are to be completely evaluated. Insufficiency of data is thus reflected in the indeterminacy of two of the regression coefficients in a binomial-type regression equation that describes the variation of the consistency index with the vertical coordinate. This and other critical issues in the evaluation of the rheological parameters with the ring-shear apparatus are addressed in this study.

INTRODUCTION

Bagnold (1954) pioneered rotating-drum experiments of neutrally buoyant spherical grains. Since then, numerous investigators, such as Savage and McKeown (1983), Savage and Sayed (1984), Hanes and Inman (1985), and Craig and others (1986, 1987a,b), have conducted similar experiments with an annular shear cell to relate the shear and normal stresses to the shear rate for rapidly flowing granular materials. Because the past technology in hydrometry did not readily permit the measurements of the velocity and concentration distributions of flowing granules in the shear cell, the previous investigators indiscriminately assumed a linear velocity distribution across the cell thickness as well as a bulk concentration for the entire cell. There has been no breakthrough in hydrometry. Although the rapidly advancing technology in high-speed video equipment in recent years has enabled us to measure the velocities of marked particles moving along a transparent side wall with a high degree of accuracy, a method has yet to be developed to measure the heavy concentrations of moving particles at various depths. Presented in this study are the various velocities of moving opaque (colored) glass spheres in the upper ring of the ring-shear apparatus, which were measued by an 8-mm high shutter-speed video camera.

Data on measured velocity profiles are needed in the evaluation of the rheological parameters, as defined in the generalized viscoplastic fluid (GVF) model (Chen, 1986, 1988a,b, 1989). Previously, a "conveyor-belt" flume was used to evaluate the rheological parameters by fitting measured velocity profiles to the theoretical ones, which are derived on the simplified assumption that the particle concentration is constant across the flow depth (Ling and Chen, 1989; Ling and others, 1990). This simplified assumption has frequently been used in the computation of sediment gravity flows without causing significant errors. However, if the curvature terms are excluded from the GVF model, satisfying the conservation of momentum for a simple shear flow in the upper ring requires that the concentration of glass spheres varies across the flow depth. Varying the concentration of glass spheres increases considerably the degree of complexity in the analytical treatment of the problem. It is possible that measured velocity profiles may fit the theoretical ones in a least-squares sense, yet the rheological parameters cannot be evaluated unless measured concentration distributions are also fitted to the theoretical ones. The purpose of this paper, therefore, is to determine whether or not both velocity and concentration data are needed in the evaluation of the rheological parameters for a simulated debris flow in the ring-shear apparatus.

THEORETICAL ANALYSIS

The GVF model as well as the equations of motion for flow of glass spheres in the sample ring, if expressed in cylindrical coordinates, contain the curvature terms, which are not amenable to analytical treatment. For simplicity, the curvature terms in the GVF model and in the equations of motion are ignored in the present analysis. This simplification physically implies that a steady simple (or unidirectional) shear flow of glass spheres in the sample ring is imaginarily transformed into a wall-driven flow of glass spheres between infinitely long parallel plates, as sketched in Figure 1. Exclusion of the curvature terms from the GVF model and the equations of motion may be justified for slow-shearing glass spheres in the ring-shear apparatus, but in case of fast-moving granules how such a simplification will affect the solution remains to be addressed in the future.

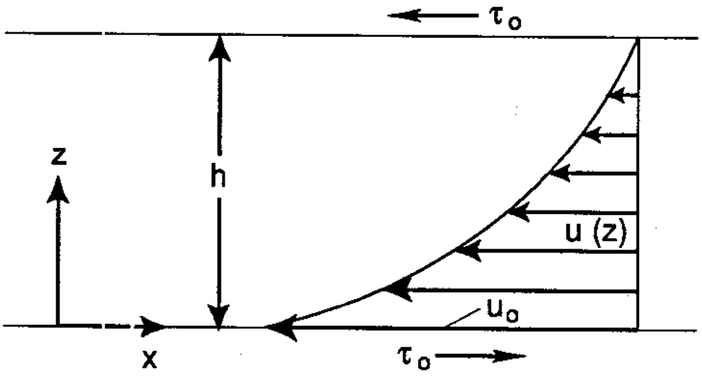

Figure 1.--Definition sketch of a simple shear flow.

A Simplified Version of the GVF Model

The total stresses for a steady simple shear flow of glass spheres between infinitely long parallel plates can be expressed from the GVF model as

$$T_{xz} = c \cos \phi + p \sin \phi + \mu_1 (du/dz)^{\eta} \tag{1}$$

$$T_{zz} = - p + \mu_2 (du/dz)^{\eta} \tag{2}$$

in which T_{xz} and T_{zz} = total shear and normal stresses, respectively; c = cohesion; ϕ = angle of internal friction; p = thermodynamic pressure given by the kinetic equation of state; μ_1 and μ_2 = consistency and cross-consistency indices, respectively; η = flow-behavior index; u = velocity component in the streamwise direction of flow; and x and z = horizontal and vertical (positive, upward) coordinates, respectively. The first two terms on the right-hand side of equation 1 may be referred to as the yield stress, s, which varies with the state of flow (Chen, 1988a). Rigorously speaking, the last term in equation 1 should be expressed as $\mu_1|du/dz|^{\eta-1}(du/dz)$ so that the expression can still hold in the case of the negative du/dz, but for simplicity the present study retains the expression of equation 1.

A simple shear flow between two horizontal parallel plates spaced a distance, h, apart, as shown in Figure 1, is induced by moving the lower plate with the velocity, u_b, thereby exerting a constant shear stress, τ_0, across h, including both upper and lower plates. The values of c and ϕ in equation 1 decrease from equilibrated values at limiting equilibrium to zero at the "viscous-fluid" state (Cowin, 1974). Both c and ϕ values may be ignored for flow at a fully dynamic state (Chen, 1988a), but they vary before such a fully dynamic state is reached. Although dry glass spheres are cohesionless (c = 0), their ϕ values range from the static angle of internal friction (ϕ_s) to zero. For lack of an independent description of ϕ as a function of flow states, it is assumed to be zero in this analysis. Therefore, if c and ϕ can be ignored, μ_1 in equation 1 (after setting $T_{xz} = \tau_0$) must vary with the concentration, C, which in turn varies with z in accordance with the variation of |du/dz|. The fact that |du/dz| on the lower slip boundary (z = 0) is much higher than |du/dz| on the upper no-slip boundary (z = h) may in effect establish a relation among μ_1, C, and z_* as

$$\mu_1 = A_1(1 - KC)^{-B/K} = a\ (z_* + b)^{\epsilon} \tag{3}$$

in which $A_1 = a_1\ \rho_s^{\eta-1}\ d^{2(\eta-1)}\ \mu_w^{2-\eta}\ C_m^{-B/K}$ = constant describing the lumped material properties of given granular materials (a_1 = numerical constant, ρ_s = grain density, d = grain diameter, μ_w = dynamic viscosity of interstitial fluid, and C_m = maximum concentration); B = 2.5 for rigid spheres, a gross factor describing the variation of particle size, shape, rheological properties, deformability, and orientation of the dispersed particles; K = $1/C_m$, a factor describing space-filling, solids volume, and self-crowding; $z_* = z/h$ = dimensionless vertical coordinate; and a and b = coefficients in the binomial function of z_* with ϵ as its exponent (or power). The quotient of B and K by itself represents a gross factor describing the interaction of colliding particles (Chen, 1988b). If one assumes the μ_1 versus z_* relation, as shown in the second part of equation 3, which is in turn equated to the first part of the equation to describe the monotonic increase of C with increasing z_* values, he may then find the least-squares estimates of a, b, and ϵ, thereby fitting measured velocity profiles to the theoretical ones.

Equations of Motion for Simple Shear Flow

The equations of motion for a steady simple shear flow of glass spheres with the varying C can be expressed in the differential form (Chen, 1988b) as

$$0 = (dp/dz)\ \sin\phi + A_1\ d[(1 - KC)^{-B/K}\ (du/dz)^{\eta}]/dz \tag{4}$$

$$\rho\ g = -\ dp/dz + A_2\ d[(1 - KC)^{-B/K}\ (du/dz)^{\eta}]/dz \tag{5}$$

in which ρ = mass density of solid-fluid mixture, g = gravitational acceleration, and A_2 is similarly defined as A_1 except that a_1 in A_1 is replaced by $-a_2$, another numerical constant. Solving equations 4 and 5 for dp/dz yields

$$dp/dz = -\rho\, g\, [1 + (A_2/A_1) \sin \phi]^{-1} \tag{6}$$

Equation 4 on substitution of equation 6, if expressed in a dimensionless form, yields

$$-(\rho_m\, g\, h^{\eta+1}/u_0^{\eta}) \sin \phi\, [1 + (A_2/A_1) \sin \phi]^{-1}\, \rho_* = A_1\, d[(1 - KC)^{-B/K} (du_*/dz_*)^{\eta}]/dz_* \tag{7}$$

in which ρ_m = maximum mass density of solid-fluid mixture; u_0 = velocity on the lower boundary; $\rho_* = \rho/\rho_m$; and $u_* = u/u_0$. Although C is related to ρ through $C = (\rho - \rho_w)/(\rho_s - \rho_w)$, in which ρ_w and ρ_s are the mass densities of interstitial fluid and solid grain, respectively, one cannot solve equation 7 alone for two unknowns, ρ_* and u_*, unless the kinetic equation of state can be developed to relate ρ to p and hence, to express ρ in terms of z (or ρ_* in terms of z_*). The equation of state postulated by Chen (1988b) is unfortunately not general enough to describe an actual trend of decreasing C with increasing p, with which shearing glass spheres behave in the upper ring. This trend appears to be opposite to that of gravity-induced granular flows. Above all, avoiding additional complicacy due to unknown ϕ in the analytical treatment of equation 7, one may simply assume $\phi = 0$ for the reason given earlier. Using this simplified assumption and then substituting equation 3 into equation 7, one can integrate the resultant expression once with respect to z_* to have

$$du_*/dz_* = (h/u_0)\, (\tau_0/a)^{1/\eta}\, (z_* + b)^{-\epsilon/\eta} \tag{8}$$

<u>Theoretical Velocity Profiles</u>

Two velocity profiles can be derived from equation 8: One is for $\eta = \epsilon$ and the other for $\eta \neq \epsilon$. The former may be called the logarithmic profile and the latter the power profile. For $\eta = \epsilon$, integrating equation 8 with respect to z_* with the aid of the no-slip boundary condition ($u_* = 0$) on the upper plate ($z_* = 1$) yields

$$u_* = (h/u_0)\, (\tau_0/a)^{1/\eta}\, \ln\, [(z_* + b)/(1 + b)] \tag{9}$$

whence the velocity, u_c, at the lower plate ($z_* = 0$) can be expressed upon substitution of $u_* = 1$ as

$$1 = (h/u_0)\, (\tau_0/a)^{1/\eta}\, \ln\, [b/(1 + b)] \tag{10}$$

Combining equations 9 and 10 yields

$$u_* = \ln\, [(z_* + b)/(1 + b)]/\ln\, [b/(1 + b)] \tag{11}$$

Likewise, for $\eta \neq \epsilon$, one obtains respectively

$$u_* = (h/u_0)\, (\tau_0/a)^{1/\eta}\, [\eta/(\eta - \epsilon)]\, [(z_* + b)^{(\eta-\epsilon)/\eta} - (1 + b)^{(\eta-\epsilon)/\eta}] \tag{12}$$

$$1 = (h/u_0)\, (\tau_0/a)^{1/\eta}\, [\eta/(\eta - \epsilon)]\, [b^{(\eta-\epsilon)/\eta} - (1 + b)^{(\eta-\epsilon)/\eta}] \tag{13}$$

$$u_* = [(z_* + b)^{(\eta-\epsilon)/\eta} - (1 + b)^{(\eta-\epsilon)/\eta}]/[b^{(\eta-\epsilon)/\eta} - (1 + b)^{(\eta-\epsilon)/\eta}] \qquad (14)$$

Equation 11 or 14 may be used as a regression equation for finding the least-squares estimates of the regression coefficients, a, b, ϵ, and perhaps, η or a combination of ϵ and η.

EXPERIMENTS AND DATA ANALYSIS

Ring-Shear Apparatus

The ring-shear apparatus (Sassa and others, 1984) is an annular shear cell with granular materials being sheared under controlled loading conditions. A sample container in the apparatus consists of the inner and outer rings of 30 and 48 cm in diameter, respectively, and 9 cm in height. The inner and outer rings are further divided equally into the upper and lower parts with interface between them acting as a shearing plane. The lower ring can be rotated at a desired linear speed between zero and 1 m/s at the mean radius of the inner and outer rings, while the upper ring remains stationary. During an experiment, a desired vertical load with capacity up to 7 kg/cm^2 is applied to the sample by pressuring air reservoirs above the loading plate, which in turn presses evenly across the top of the sample with pressure (i.e., the normal stress) measureable up to 0.4 kg/cm^2. The shear stress on the shearing plane is calculated from the torque measured by an armature system mounted on the upper lid and resting against a shear load cell at its end. Also measured in the ring-shear apparatus is the vertical displacement of the loading plate, from which one can calculate the change in the sample volume due to dilation or contraction of the moving glass spheres in the ring and hence, the change in the bulk concentration of glass spheres in the ring.

Experiments and Measurements

Experiments were conducted with 3 mm glass spheres. The following two sequences of loading and unloading are applied to the sample during an experiment. The first set of control is to increase gradually the vertical load to 6 kg/cm^2 and then decrease gradually back to nearly zero while the rotation speed of the lower ring is kept constant at 50 cm/s, repeating two cycles of loading and unloading. The second set of control is to increase gradually the rotation speed of the lower ring to 1 m/s and then decrease gradually back to nearly zero while the vertical load is kept constant at 3 kg/cm^2, repeating two cycles of varying speeds. A sequence of the normal and shear stresses as well as the volume changes of the moving glass spheres for a series of experiments under both sets of control were all measured, but only limited data on velocity profiles for the second set of control were collected for this study. Because of a limit in space, only measured velocity profiles are analyzed and presented herein.

Movement of marked glass spheres at various distances from the shearing plane was measured through the outer transparent wall with an 8-mm high shutter-speed video camera. Five velocity profiles so measured for five rotation speeds, u_b, as shown in Table 1, are plotted in Figures 2 and 3. For simplicity in illustration, the horizontal axis of the velocity profile is ticked in five overlapping scales, each corresponding to one of the five velocity profiles plotted. A data point marked in Figures 2 and 3 is the mean of measured velocities at that location, for which the 95% confidence interval is generally within 25% of the magnitude of the mean velocity itself. The bulk concentration of glass spheres measured for the five runs ranges from 0.610 to 0.621. Other measured data are given in Table 1.

Regression Analysis

Using the logarithmic velocity-profile equation (equation 11) as a regression equation of a measured velocity profile, one can determine the least-squares estimate of the regression coefficient, b, by fitting equation 11 to measured data in a least-squares sense, as shown in Figure 2. By the same token, one can determine the least-squares estimate of the regression coefficients, b and $(\eta - \epsilon)/\eta$, by fitting the power velocity-profile equation (equation 14) to the same measured data in a least-squares sense, as shown in Figure 3. The respective least-squares estimates of the regression coefficients so determined are listed in Table 1 for the five rotation speeds, u_b, tested. A comparison of Figures 2 and 3 indicates that the power velocity-profile equation with two regression coefficients apparently fits better to measured velocity profiles than the logarithmic velocity-profile equation with only one regression coefficient.

Table 1.--Experimental results and evaluation of regression coefficients.

Run	d (mm)	Measurements				Calculation		
		u_b (cm/s)	u_0 (cm/s)	h (cm)	τ_0 (kg/cm^2)	b (equation 11)	b (equation 14)	$(\eta-\epsilon)/\eta$ (equation 14)
1	3	-10	-4.42	4.05	0.0193	0.00202	0.331	-2.95
2	3	-30	-10.88	4.05	0.0205	0.00419	0.389	-2.92
3	3	-50	-18.89	4.05	0.0195	0.00546	0.435	-3.15
4	3	-70	-25.11	4.05	0.0193	0.00561	0.420	-3.00
5	3	-90	-34.43	4.05	0.0189	0.00374	0.391	-3.05

Note: The values of b and $(\eta - \epsilon)/\eta$ are the least-squares estimates.

An inspection of equations 9 through 11 for $\eta = \epsilon$ or equations 12 through 14 for $\eta \neq \epsilon$ reveals that there seems no way of finding the least-squares estimates of a, ϵ, and η unless the concentration distribution is additionally measured and fitted to

$$C = (1/K)\ [1 - (a/A_1)(z_* + b)^{\epsilon}]^{-K/B} \qquad (15)$$

which results from equation 3. The additional curve-fitting of measured concentration distributions by using equation 15 as a regression equation should be performed, of course, with the help of equation 10 in case of $\eta = \epsilon$ or equation 13 in case of $\eta \neq \epsilon$. For lack of such concentration data, further regression analysis cannot be undertaken in this study and thus, the least-squares estimates of a, ϵ, and η remain indeterminate.

CONCLUSIONS

It has been shown that measured velocity profiles of debris flows simulated in the upper ring can be fitted to the theoretical ones with a high degree

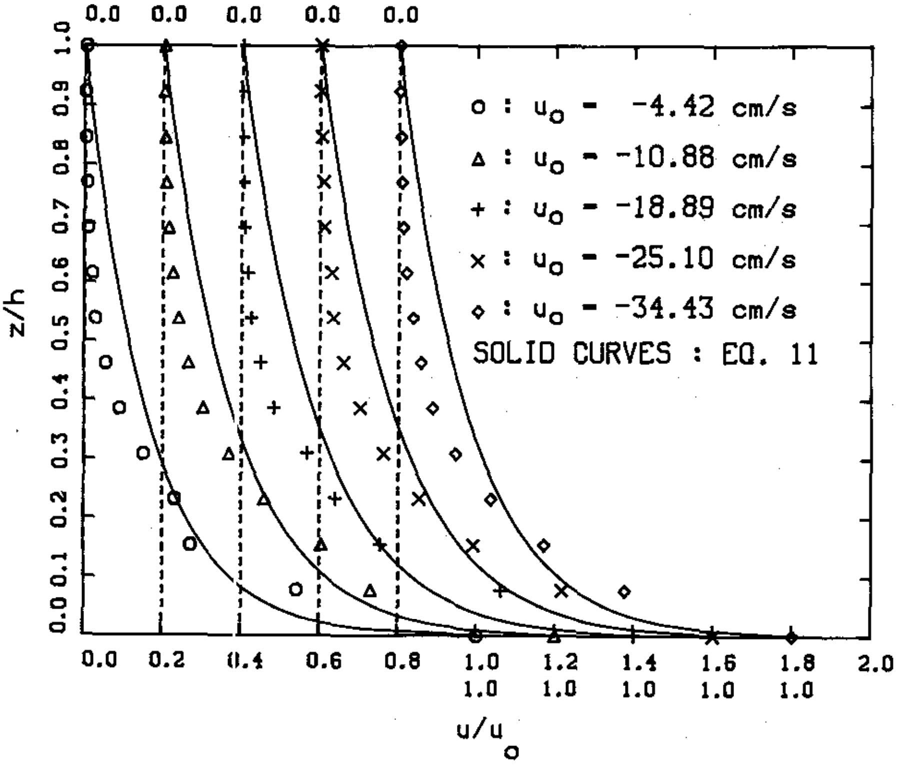

Figure 2.--Comparison of measured velocity profiles for 3 mm glass spheres to theoretical logarithmic profiles (equation 11).

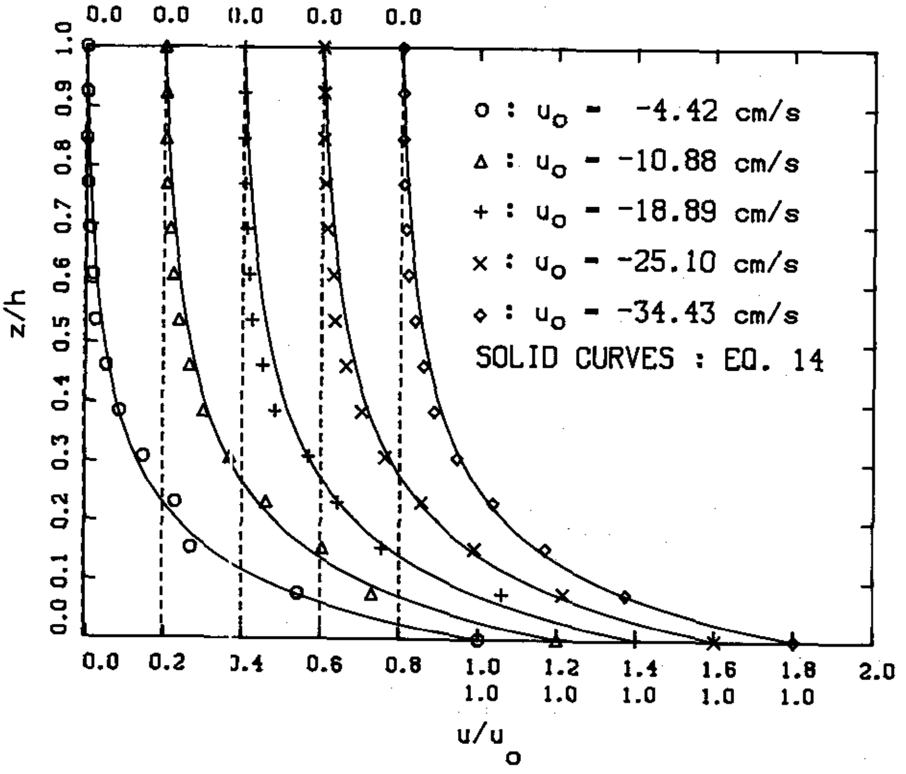

Figure 3.--Comparison of measured velocity profiles for 3 mm glass spheres to theoretical power profiles (equation 14).

of accuracy by assuming a binomial-type regression equation for the consistency index which appears to vary with the vertical coordinate. Although two of the three regression coefficients in such binomial-type regression equation cannot be determined by fitting the power velocity-profiles alone, this study reconfirms the variation of the consistency index with the concentration and hence, with the vertical coordinate, as described mathematically by equation 3, for a simple shear flow of glass spheres in the upper ring. Indeterminacy of some of the regression coefficients, including the flow-behavior index, indicates the need of additional data on concentration distributions, if they are all to be determined.

REFERENCES

Bagnold, R. A., 1954, Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proc., Royal Soc. of London, Ser. A, 225, 49-63.

Chen, C. L., 1986, Bingham plastic or Bagnold's dilatant fluid as a rheological model of debris flow? Proc. of Third Intl. Symp. on River Sedimentation, Jackson, Mississippi, 1924-1936.

Chen, C. L., 1988a, Generalized viscoplastic modeling of debris flow. J. Hydr. Engrg., Am. Soc. Civil Engrs. 114(3), 237-258.

Chen, C. L., 1988b, General solutions for viscoplastic debris flow. J. Hydr. Engrg., Am. Soc. Civil Engrs. 114(3), 259-282.

Chen, C. L., 1989, Issues in debris flow research: personal views. U.S. Geological Survey Water Supply Paper Series "Selected Papers in the Hydrologic Sciences" WSP 2340. (in press)

Cowin, S. C., 1974, A theory for the flow of granular materials. Powder Technology 9, 61-69.

Craig, K., Buckholtz, R. H., and Domoto, G., 1986, An experimental study of the rapid flow of dry cohesionless metal powders. J. Appl. Mech., Am. Soc. Mech. Engrs. 53, 935-942.

Craig, K., Buckholtz, R. H., and Domoto, G., 1987a, The effects of shear surface boundaries on stresses for the rapid shear of dry powers. J. Tribol., Am. Soc. Meh. Engrs. 109, 232-237.

Craig, K., Buckholtz, R. H., and Domoto, G., 1987b, Rapid shear flow of dry magnetic powder in an externally applied magnetic field: an experimental study. Phys. Fluids 30, 1993-1999.

Hanes, D. M., and Inman, D. L. , 1985, Observations of rapidly flowing granular fluid flow. J. Fluid Mech. 150, 357-380.

Ling, C. H., and Chen, C. L., 1989, Idealized debris flow in flume with bed driven by a conveyor belt. Proc. 1989 Hydr. Div. Natl. Conf. on Hydr. Engrg., Am. Soc. Civil Engrs., New Orleans, Louisiana, 1144-1149.

Ling, C. H., Chen, C. L., and Jan, C. D., 1990, Rheological properties of simulated debris flows in the laboratory environment. Proc. Intl. Symp. on Hydraul. and Hydrol. of Arid Lands, Am. Soc. Civil Engrs., San Diego, California, 218-224.

Sassa, K., Shima, M., Hiura, M., Nakagawa, A., and Suemine, A., 1984, Develoment of ring shear type debris flow apparatus. Report of Grant-in-Aid for Sci. Res. by Jap. Min. of Educ., Sci. and Cul. No. 57860028, Dis. Prev. Res. Inst., Kyoto University, Kyoto, Japan.

Savage, S. B., and McKeown, S., 1983, Shear stresses developed during rapid shear of concetrated suspensions of large spherical particles between concentric cylinders. J. Fluid Mech. 127, 453-472.

Savage, S. B., and Sayed, M., 1984, Stresses developed by dry cohensionless granular materials in an annular shear cell. J. Fluid Mech. 142, 391-430.

INTERACTION OF FINES WITH A GRAVEL BED

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ABSTRACT

The interaction of fine sediment with the bed material of a gravel stream was examined in the laboratory. Emphasis was given in reproducing several of the features that are typically encountered in natural gravel-bed streams, including the pavement and the pool-and-riffle structure. The present experiments indicated that the infiltrating fines created a seal within the top three layers of the bed material. The presence of the pool-and-riffle sequence resulted in spatial variation of the fines depositional pattern. Sediment motion is necessary to clean the bed from the fines below the pavement layer. The amount of fines settled in the subpavement is not influenced by flow parameters. However, the amount of fines deposited within the pavement are well correlated with the mean flow concentration.

INTRODUCTION

Natural gravel-bed rivers are characterized by a pool-and-riffle structure and the presence of a surface bed layer, called pavement, that is coarser than the subpavement material. Salmon and related species use these two features of gravel streams as tools for spawning. The pool-and-riffle sequence provides a considerable range of flow velocities and depths that is typically appropriate for spawning. The coarse surface layer is in place during floods, and therefore the eggs buried below the pavement are usually protected from scour.

The quality of the fish habitat depends, to a large extent, on the composition of the bed material. For the new generation of fry to be produced, the pavement must not be so coarse that it is impossible to construct a redd. In addition, the content of fines (material in the range of sand and finer) in the subpavement must not be so high as to a) crush the eggs in its interstices (Gibbons and Salo, 1973), b) reduce intergravel flow to the point that sufficient oxygen cannot be supplied to the eggs, or metabolic wastes cannot be removed (Iwamoto et al. 1978; Vaux, 1968) or c) entrap the fry as they try to escape upwards (Shea and Mathers, 1978).

Logging, road building, agriculture and other human activities can lead to excessive input of fine material into streams, which in turn can substantially increase the sedimentation of gravel beds (Megahan and Kid, 1972; Brown, 1974). In addition, stream regulation can result in unnecessary coarsening of the bed surface, and deprive the river of the peak flows that are capable of cleansing its bed from fine sediments.

The infiltration of fines into and their removal from a gravel-bed has been studied in the field (Milhous, 1973; Adams and Beschta, 1980; Frostick et al.

1984; Lisle, 1989; Alonso et al. 1988) and the laboratory (Einstein, 1968; Beschta and Jackson, 1977; Dhamotharan et al., 1980; Carling, 1984; O'Brien, 1987; and Jobson and Carey, 1989)

The importance of the pavement layer in the process of fines infiltration into and their release from the channel bed was emphasized by Milhous (1973, 1982), and Frostick et al. (1984). Field observations (Frostick et al., 1982; Lisle, 1989) suggest that typically the infiltrating fines create a seal near the top of the subpavement that restricts deeper intrusion of fine sediments. The amount of fines deposited within the channel bed varied both temporally and spatially (Frostick et al., 1982; Lisle, 1989). The first variation may be attributed to periodic, non-uniform flushing of fines. Within the same stream, higher amounts of fines tend to infiltrate along the channel thalweg, and in the pool areas.

Nearly all of the existing laboratory studies suffer from a rather simplistic modeling of natural gravel-bed streams. The process of the ingress of fines into the channel bed has been examined in the absence of a coarser surface bed layer, a pool-and-riffle structure, and bed load motion. Nevertheless, several useful observations have been made. It was found that the siltation rate was high even at flows of low sediment concentration (Carling, 1984). It was also ascertained that gravel mobilization is necessary to clean the bed from fines below the surface layer.

The objective of the present study was to remedy existing deficiencies in the modeling of gravel-bed streams in the laboratory. Two flumes were used to examine the infiltration of fines into and their cleaning from the channel bed, under conditions that are typical of natural gravel streams. The influence of the pavement and bedforms on the retention of fines in the bed was also explored. The interaction between suspended sediment and fines deposited within the pavement and subpavement layers is described based on the observations from the experiments.

EXPERIMENTAL LAYOUT AND PROCEDURE

The experiments were carried out in two flumes. The first flume was 16.75m long and 0.3m wide, and the second one was 12m long and 0.91m wide. They will be referred to as the long and the tilting flume, respectively. Six series of experiments were conducted in the long flume, which recirculated both sediment and water, and one series in the tilting flume, which operated as a feed system in both sediment and water. On the average, six experiments were performed for each series. The first experiment of each series was conducted in the absence of fine sediment. Its purpose was to reproduce in the laboratory the dominant features that are commonly encountered in natural gravel-bed streams. Poorly sorted sediment, with median grain size of 2.44mm and standard deviation of 2.75, was used as bed material. The water discharge could entrain even the coarsest particles of the bed material, and thus facilitated the development of a self-formed pavement. Sampling of the bed sediment clearly demonstrated the presence of a coarser surface bed layer during the present experiments. For the tilting flume case, a pool-and-riffle structure, representative of natural gravel streams (Lewin, 1976) was also present.

During the subsequent five experiments of each series, set amounts of fine material were introduced into the long flume to study the impregnation of fines into the gravel bed. Two sizes of silica flour were used as fines, one with D_{50}=0.08mm and the other with D_{50}=0.11mm, both being well sorted. The white color of the fines facilitated the observation of fines infiltration into the channel bed. The initial bed slope for the long flume ranged from 0.003 to 0.008, while for the tilting flume it was 0.012. The dimensionless design Shields stress varied from 0.10 to 0.15, based on the mean size of the original mixture.

INFILTRATION AND REMOVAL OF FINES

A designated amount of sediment was introduced at the downstream end of the long flume at the beginning of each experiment. The fines entered through the return pipeline, where they became well-mixed with the water before appearing at the channel entrance. The total amount of fines that was added into the long flume during a single series of experiments ranged from 19.5 to 27kgr.

In agreement with earlier observations (Carling, 1984), it was found that most of the fines deposited in the bed soon after they were introduced into the flume, resulting in suspended sediment concentrations that were close to zero. Only during the last two experiments of each series were appreciable amounts of fines retained in suspension after equilibrium was reached.

The fines added into the flow during the second experiment of each series created a clearly visible interface (seal) within the bed framework. This interface separated the bed material into two regions. No fines infiltrate in the region below the interface. Instead, it appears that the fine grains deposit in all levels above the interface, with the bulk of the filling progressing from the interface upwards to the gravel surface. The fines never penetrated deeper than the five top layers of the bed material. The average depth of the interface was $3D_{90}$ below the bed surface, where D_{90} is the grain size that is coarser than ninety percent of the bed material. This is close to the $2.6D_{90}$ average depth of fines infiltration that was determined by Lisle (1989) in a field study.

During the second, third, and fourth experiments in the tilting flume different fines feed rates were used to examine the depositional pattern of fines in a pool-and-riffle sequence with and without bed load motion. The ability and extent to which the stream could purge itself of the fines was tested during the last three experiments. The coarse and fine sediment feed rates, as well as the bed load transport rates for the tilting flume experiments are shown in Figure 1.

The amount of fines deposited in the bed during the tilting flume tests exhibited spatial variation, with higher quantities found in areas of relatively lower flow velocity, that is in the pool and the downstream end of the bar.

In the absence of fines infeed and boundary shear stress near the threshold of sediment motion, the flow was capable of cleaning most of the pavement layer

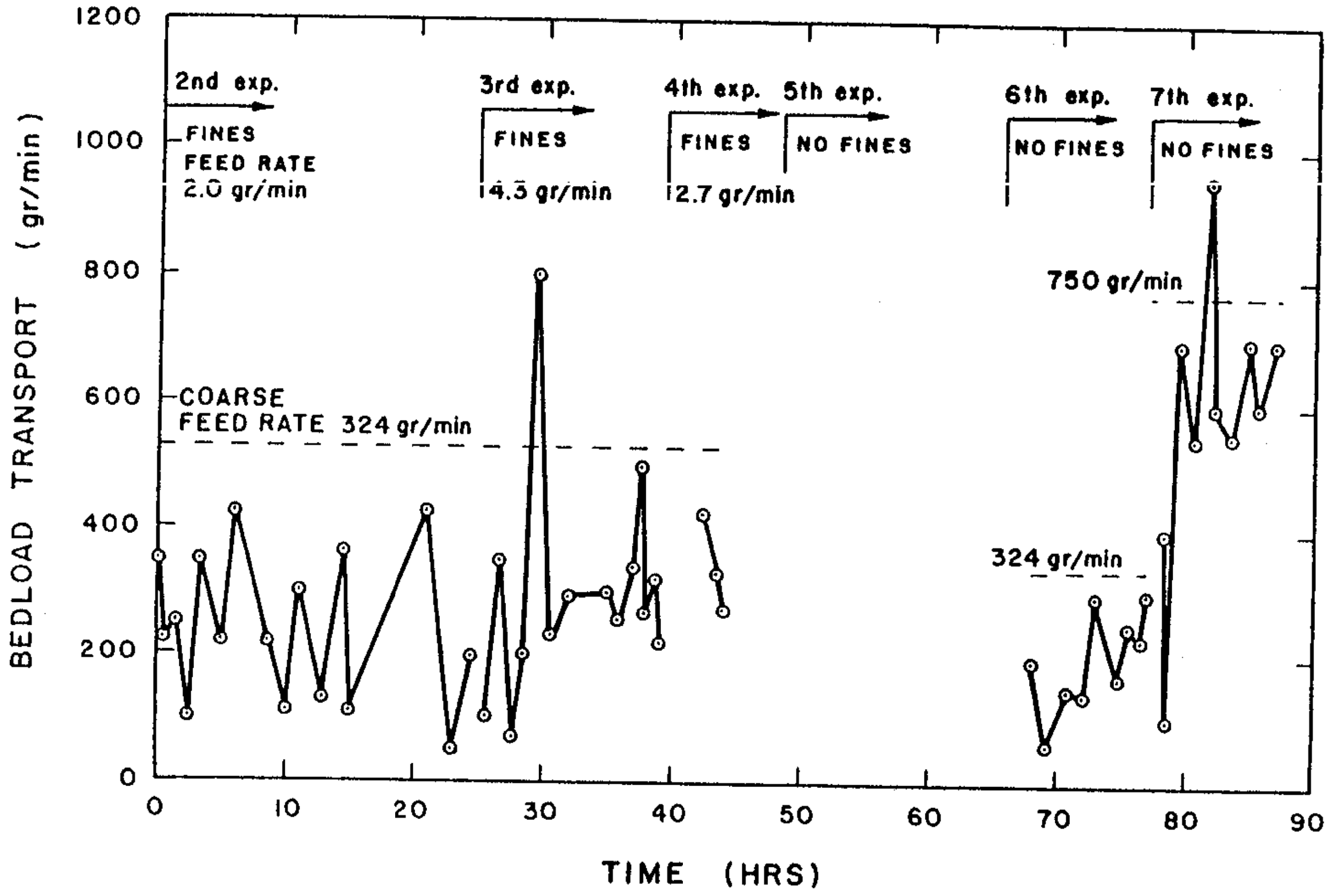

Figure 1. Pavement and subpavement at the end of the first experiment of the first series.

from the deposited fines. However, sediment motion was necessary to purge the bed from the fines below the pavement layer. During the last experiment the effects of a rather severe flood were simulated. At the end of the experiment the channel was devoid of bedforms and the bed material almost completely cleansed from the fines.

INTERACTION BETWEEN TRANSPORTED AND DEPOSITED FINES

The long flume experiments indicated that the deposition of suspended sediment is independent of the flume bed conditions. However, the entrainment depends on not only the influence of the boundary forces, but also on the presence of suspendible material in the bed. The question that arises here is at what point the fines in the bed can be entrained by the flow. The bed load transport rate is expected to influence this process. Nevertheless, during the present experiments it was observed that unless the suspendible material appeared in the surface bed layer, the entrainment rate was very small. This observation does not contradict with the cleaning process that took place in the last three experiments in the tilting flume. During these experiments the incoming water was completely free of fines, and the cleaning of a rather small amount of fines hidden inside the bed is possible even with very small entrainment rates, given the lengthy duration of the experiments. Therefore, regardless of the bed load motion most of the fines removed from the flow deposit within the channel bed as long as no fines are present in the pavement layer. This implies that the fines do not interact significantly with the flow until they have almost saturated the subpavement layer.

It is therefore suggested here, that even at flows of low sediment concentration the subpavement will be eventually filled with fines. It is expected that the amount of fines deposited in the pavement layer will depend on the mean flow concentration C, the fall velocity of the fines v_s, and parameters describing the fluid flow and the bed stability (Diplas and Parker, 1990). From dimensional analysis the following functional relation is obtained

$$C_f = g\left(C, \frac{U*}{V_s}, \tau*_{50}, R_p, \frac{d}{D_{p50}}\right) \qquad (1)$$

where C_f is the percentage of fines in the pavement by weight, C is the vertically averaged volumetric concentration of the flow, d is the flow depth, D_{p50} the median size of the pavement material, $\tau*_{50}$ the dimensionless Shields parameter based on the median size of the bed material, U* is the shear velocity, and R_p is the particle Reynolds number. The limited number of data obtained during the present study do not permit a complete delineation of Eq. 1. It seems that only the measurements of the mean flow concentration and percentage of fines in the pavement provided a sufficiently wide range of values, and therefore they are the only variables of Eq. 1 that can possibly be correlated based on the data of the present study.

In the long flume experiments, where fines were present only in the subpavement, the measured mean flow concentration did not exceed 50 mgl^{-1}, and they did not exhibit any consistent correlation with the amount of fines in the subpavement. The mean flow concentrations measured during experiments with fines in the pavement layer are plotted in Figure 2. as a function of the percentage of fines found in this layer. A semilogarithmic linear regression of the data points results in the following relation

$$C_f = 10.1 \log \left[8.6 \times 10^{-3} C \right] \qquad (2)$$

with a correlation coefficient of $r = 0.89$. As is shown in Figure 2, the minimum mean flow concentration required for the appearance of fines in the pavement is about 200 mgl^{-1}. This agrees with the absence of fines in the pavement layer during the second experiment in the tilting flume, where the fines feed rate was 156mgl^{-1}. It was also found that when the pavement consisted of about 25 percent of fines, the surface layer was almost completely covered with fines. In this case, the corresponding mean flow concentration for given flow conditions and fines grain size should be close to the capacity of the flow to carry this material in suspension.

CONCLUSIONS

The present experiments demonstrate the importance of the pavement layer and the pool-and-riffle sequence in the deposition of fines into and their removal from a gravel-bed stream. The fines tend to collect within the top three bed layers. The depth of infiltration depends on the difference in size between the penetrating grains and the coarser bed material and the boundary Shields stress. The channel bedforms influence the spatial depositional pattern of fines, by promoting higher accumulations in the pool and the downstream end of the bar. For entraining the fines from the pavement layer no bed load motion is required. Purging, however, the subpavement from fines requires mobilization of the channel bed.

The fines that settle within the subpavement do not interact significantly with the flow. The amount present in the pavement layer is, however, influenced by the mean flow concentration, and parameters describing the fluid flow and the bed stability of the channel. The present experiments suggest that at equilibrium conditions the percentage of fines in the pavement layer is related to the mean flow concentration through a semilogarithmic expression.

ACKNOWLEDGEMENTS

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REFERENCES

Adams, J. N. and Beschta, R. L. (1980), Gravel bed composition in oregon coastal streams. Can. J. Fish. Aquati. Sci., 37(10), 1514-1521.

Alonso, C. V., Theurer, F. D. and Zachmann, D. W. (1988), Tucannon river offsite study: sediment intrusion and dissolved-oxygen transport model. U.S. Dept. of Agriculture, Agricultural Research Service, Hydro-Ecosystems Research Group, Fort Collins, Colorado, U.S.A.

Beschta, R. L. and Jackson, W. L. (1979), The intrusion of fine sediments into a stable gravel bed. J. Fish Res. Board Can., 36, 204-210.

Brown, G.W., 1974, Forestry and water quality. Report, School of Forestry, Oregon State University, Corvallis, OR.

Carling, D. A. (1984), Deposition of fine and coarse sand in an open-work gravel bed. Can. J. Fish. Aquat. Sci., 41, 263-270.

Dhamotharan, S., Wood, A., Parker, G. and Stefan, H. (1980), Bedload transport in a model gravel stream. Proj. Rep. No. 190, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MI., U.S.A.

Diplas, P. and Parker, G., Fines retention in gravel in a recirculating configuration. In preparation for submission for publication.

Einstein, H. A. (1968), Deposition of suspended particles in a gravel bed. J. Hydraul. Div., Am. Soc. Civ. Eng., 94(5), 1197-1205.

Frostick, L. E., Lucas, P. M. and Reid, I. (1984), The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for statigraphical interpretation. J. Geol. Soc. London, 141(6), 955-965.

Gibbons, D. R. and Salo, E. O. (1973), Annotated bibliography of the effects of logging on fish of the western united states and canada. USDA For. Serv., Gen. Tech. Rep., PNW-10, 145 .

Iwamoto, R. N., Salo, E. O., Madej, M. A. and McComas, R. L. (1978), Sediment and water quality: a review of the literature including a suggested approach for water quality criteria. Report, U.S. Environmental Protection Agency Region X, Seattle, WA.

Lewin, J. (1976), Initiation of bed forms and meanders in coarse-grained sediment. Geol. Soc. of America Bulletin, 87, 281-285.

Jobson, H.E. and Carey, W.P., 1989, Interaction of fine sediment with alluvial streambed. Wat. Resour. Res., 25(1), 135-140.

Lisle, T. E. (1989), Sediment transport and resulting deposition in spawning gravels, north coastal california. Water Resour. Res., 25(6), 1303-1319.

Megahan, W.R. and Kid, W.J., 1972, Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. Forestry, 70(3), 136-142.

Milhous, R. T. (1973), Sediment transport in a gravel bottomed stream. Ph.D. Thesis, Oregon State University, Corvallis, OR, U.S.A.

Milhous, R. T. (1982), "Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers. In Gravel-Bed Rivers, Hey, R.D., Bathurst, T.C. and Thorne, C.R. (eds). Wiley, London, 819-841.

O'Brien, J. S. (1987), A case study of minimum streamflow for fishery habitat in the yampa river. In Sediment Transport in Gravel-Bed Rivers, Thorne, C.R., Bathurst, J.C. and Hey, R.D., Wiley, New York.

Shea, M. and Mathers, J. S. (1978), An annotated biblography on the effects of roads on aquatic systems. Report, Ontario Ministry of Natural Resources, Canada.

Vaux, W. G. (1968), Intragravel flow and interchange of water in a stream bed". Bulletin, U.S. Fisheries and Wildlife Service, 66(3), 479-489.

Walling, D. E. and Webb, B. M. (1987), Suspended load in gravel-bed rivers: uk experience. In Sediment Transport in Gravel-Bed Rivers, Thorne, C.R., Bathurst, J.C. and Hey, R.D., Wiley, New York.

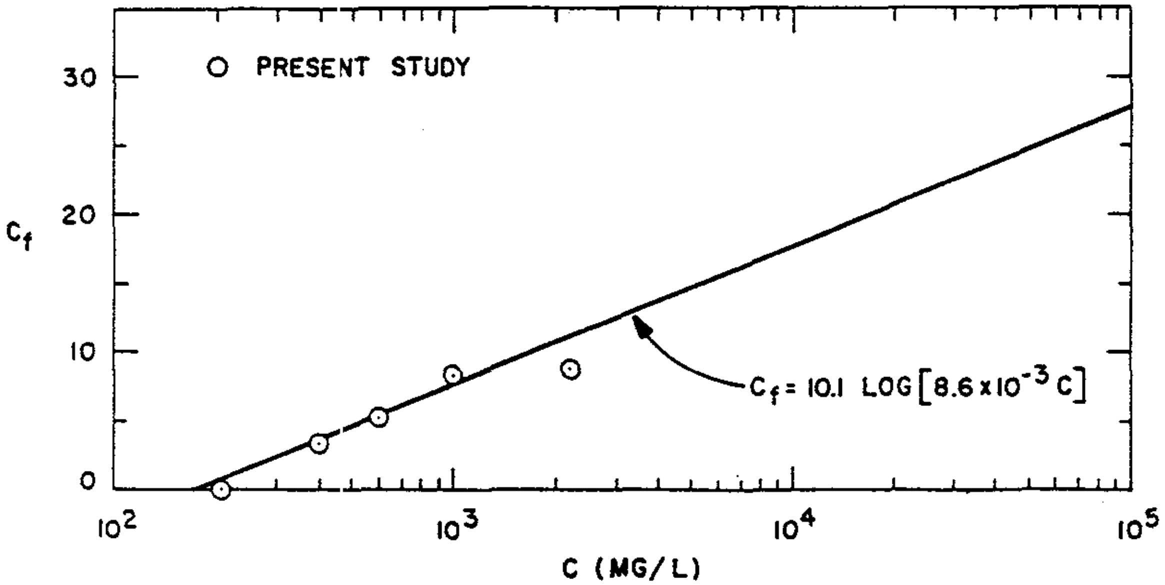

Figure 2. Mean flow concentration of fines, C, versus percent of fines in the pavement by weight, C_f.

MISSISSIPPI RIVER SEDIMENT SIZE CHANGES, 1932 TO 1989

By

B.S. QUEEN[1], R.E. RENTSCHLER[2], and C.F. NORDIN[3]

ABSTRACT

During the low flow seasons of 1932 and 1934, personnel from the U.S. Army Corps of Engineers collected bed sediment samples from the thalweg along a reach of the Mississippi River between Cairo, Illinois, and the Gulf of Mexico. The results of these investigations were published in Paper 17 of the U.S. Waterways Experiment Station (WES, 1935). The systematic reduction in particle sizes along the 1,070 mile reach between Cairo and Head of Passes is considered a classic example of the downstream decrease in bed particle sizes that occurs in most rivers.

During September, 1989, we collected thalweg samples along the same reach, using the same sampling equipment and techniques and approximately the same spacing between samples. The main purpose of the sampling was to determine if there have been any appreciable changes in the bed sediment size distributions since 1932.

The Mississippi River has changed appreciably since 1932. The river has been shortened by cutoffs, the mid-to-low flow channel has been narrowed by spur dikes and river training works. Bank erosion has been greatly reduced by bank protection works, and the incoming suspended sediment load has been reduced by reservoirs on the tributaries, especially on the Missouri River. We postulated that, as a result of these changes, the bed sediments should be coarser today then they were in 1932.

Sample analyses are not completed, but a few conclusions can be drawn, as follows:

1. The samples are composed mostly of medium sand with small quantities of fine and medium gravel.
2. Gravel was found at about the same locations in 1989 as in 1932.
3. Not all samples are analyzed, but the evidence to date shows that the thalweg bed sediments in 1989 were finer than the bed sediments in 1932, at least for the reach upstream of RM 300. This is counter to our expectations, and we have not yet arrived at a satisfactory explanation of this phenomenon.

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INTRODUCTION

In 1932, the Chief of Engineers, U.S. Army, directed that studies be undertaken to determine the force of flowing water required to move materials composing the bed of the Lower Mississippi River (WES, 1935). The studies were initiated that same year and were carried out in two parts. The first part consisted of a series of flume studies of materials moved by hydraulic traction. The second part consisted of systematic sampling and analyses of bed sediments from the Mississippi River channel thalweg along a 1,070-mile reach between Cairo, Illinois, and Head of Passes (572 samples in all) and some additional sampling in major tributaries and in the passes to the Gulf, 1091 miles downstream of Cairo. The results of these investigations were published in 1935 in Waterways Experiment Station Paper Number 17, "Studies of River Bed Material and Their Movement, with Special Reference to the Lower Mississippi River". The field data were to become, and are still, the classic example of bed sediment size reduction along a river. Leopold, Wolman, and Miller (1964), in their book "Fluvial Processes in Geomorphology", stated "The changes in grain size in the Mississippi River...are as well documented as in any large river of the world." and "Few, if any, sets of data extant are as consistent and voluminous".

Many changes have taken place on the Mississippi River since 1932. The river has been shortened by cutoffs and channel realignment. Bank revetments and protection works have substantially eliminated bank erosion as a source of sediments. In addition, dams on the Missouri River, the largest contributor of sediment to the system, have reduced the sediment contributions from that river to a fraction of their historic values. Sediment discharges to the Gulf of Mexico by the Mississippi River today are less than one-half of what they were prior to 1952 (Meade and Parker, 1985). In view of these changes, one would expect the bed sediments of the Mississippi to be coarser today than they were in 1932. However, until now, data to confirm this were not available, and in fact, the results of recent fairly extensive sampling programs in the Vicksburg District suggested that the bed may be finer (Robbins, 1977). However, the procedures in sampling were not the same so the results are not directly comparable, as pointed out by Robbins (1977, p. 14). Many of Robbins' values were averages of 4 to 12 samples across a section, and because some of the samples may contain finer bed sediments in regions of low velocities, the average size distribution values are not directly comparable to the size distributions of the thalweg samples of 1932. In order to make comparisons, samples needed to be collected from the thalweg during the low flow season, August-October, in the same way that they were collected in 1932.

In 1989, the Corps of Engineers contracted Colorado State University to undertake a sampling program to duplicate as closely as possible the program carried out in 1932. The purposes of the study were (1) to determine if the size distributions of bed sediments in the river thalweg have changed since 1932, and (2) to provide baseline information against which future changes can be monitored. This report presents our initial findings.

APPROACH

All samples in 1932 and 1934 were collected with the WES drag sampler, Figure 1. The sampler is a 4-inch I.D. steel pipe, 4 ft. long, welded shut at one end and flared to about 8 inches at the opening. A 1.25 inch diameter rope was attached to the bail. In sampling, the boat was allowed to drift with the current, the sampler was lowered to the bed, and several hundred feet of line were played out before dragging the sampler in the downstream direction. After the sample was retrieved, it was split, placed in a container and labeled, and transported to the WES Soils Laboratory for sieving. If the sample contained appreciable silts and clays, the size distributions of these finer sediments were determined by hydrometer analyses.

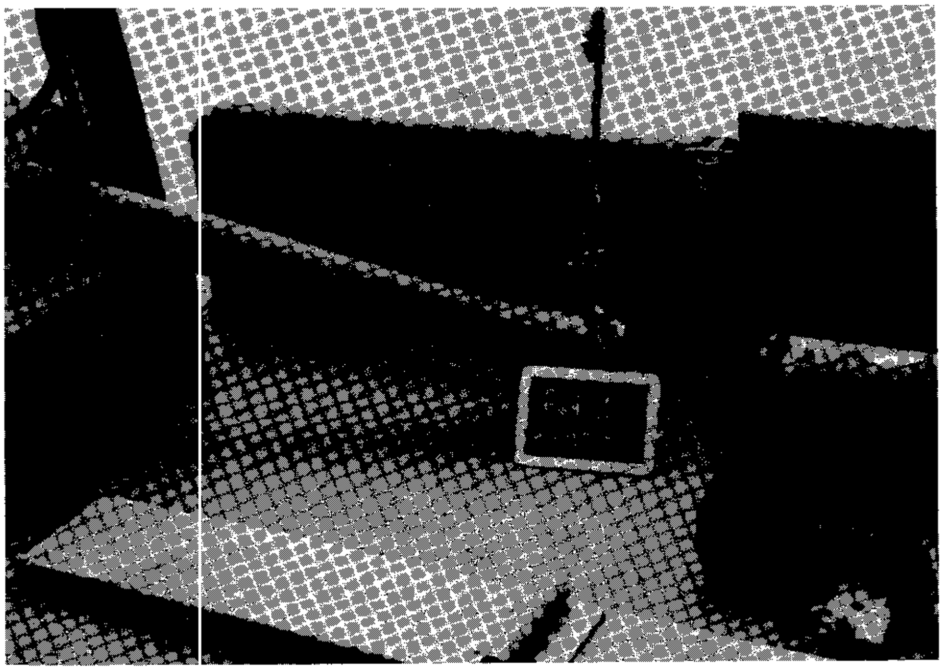

Figure 1. The WES drag sampler.

In 1989, we used an identical procedure, except the sampler was attached to the steel cable of a hydraulically operated winch. We obtained a profile of the bed with a sonic sounder over the length of channel the boat drifted, and held the research vessel stationary while the sampler was being retrieved so that the sampler was dragged along the same reach that was sounded. The sounding record was monitored carefully to avoid dragging into snags, bank revetment, or bedrock and clay outcrops.

At a number of locations we collected additional samples with the U.S. BM-54 bed material sampler and with shorter 4-inch and 8-inch diameter drag samplers to compare results with the WES sampler. In all, 505 samples were collected at 416 locations. Our sieving followed standard procedures, but we are analyzing silts and clays using both hydrometer and pipet methods. The sieving is completed, but about 30 pipet and hydrometer analyses still have to be run. The pipet method is the accepted method today for particle size analysis of fine sediments. The results are more accurate and more easily reproduced than results of the hydrometer method.

The sampling was carried out during September, 1989, from the research vessel "Acadiana" operated by Louisiana Universities Marine Consortium. The Acadiana can accommodate a scientific crew of four and ship's crew of three.

RESULTS

Matching 1932 Locations to 1989 Locations

In 1932, sample locations were identified by river miles downstream of Cairo, Illinois. Cairo was River Mile (RM) 0 and the Head of Passes was RM 1069.5. Since 1932, many changes have taken place along the Mississippi River. In the late 1930's and early 1940's, many of the large meander bends were cut off, shortening the overall channel length by 160 miles. In 1962, the delineation of river mileage was changed, with river miles beginning at 0 at the Head of Passes and increasing upstream. Cairo is at RM 954.6.

To make a useful comparison between the 1932 data and the 1989 data, it was necessary to obtain the current river mileages for the 1932 sample locations and identify samples taken in parts of the river which were later cut off. Using the descriptions of sample locations in Paper No. 17 (WES, 1935) and a set of navigation maps of the Mississippi River dated 1938, it was possible to identify most of the 1932 sample locations. These locations were then transferred to the 1988 navigation charts using latitude and longitude lines for reference.

As can be expected for a river as dynamic as the Mississippi, the current channel does not occupy the same alignment as it did in 1932. Cutoffs and lateral migration have resulted in significant changes in channel location. Because of these changes, many of the 1932 sample locations are no longer in the river channel, complicating the comparison between 1932 and 1989. In choosing samples for the comparison, the following procedure was used. Where the channel simply migrated laterally, the river mileage for the 1932 sample location was chosen such that a line perpendicular to the river channel would intersect the 1932 sample location. If the 1932 samples were located in a part of the river that has since been cut off, they were eliminated from the comparison. Only the 1989 samples obtained with the WES sampler were used for the comparison.

Comparison of Median Grain Diameters

The median grain diameter, d_{50}, is the diameter such that half of the sample by weight is smaller, and half is larger. For the 1989 data, the median diameters were determined from the results of the sieve analysis. The median grain diameters for the 1932 samples were provided in Paper No. 17 (WES, 1935).

Figure 2 shows the median grain diameters for the 1932 and 1989 samples, averaged over 25 mile reaches. A similar plot is shown in WES (1935), however, the mean grain diameter was used rather than the median. The mean grain diameter is a weighted average diameter, and is always larger than the median diameter. The median diameter was chosen for this report because the current trend is to utilize the median rather than the mean diameter.

As shown in Figure 2, the bed material sampled in 1989 is generally finer than in 1932. For the reach from Cairo to Old River Control Structure, downstream of RM 300, the median diameters are about the same for the two sets of data. This comparison may be skewed by the difference in frequency of sampling in 1932 and 1989. In 1989, samples were collected approximately every 2 miles, regardless of the bed material. In 1932, when gravel was obtained in the sample, further samples were taken at much smaller increments (as little as 0.125 miles). This procedure resulted in a higher concentration of gravel-bearing samples in the 1932 samples than the 1989 samples.

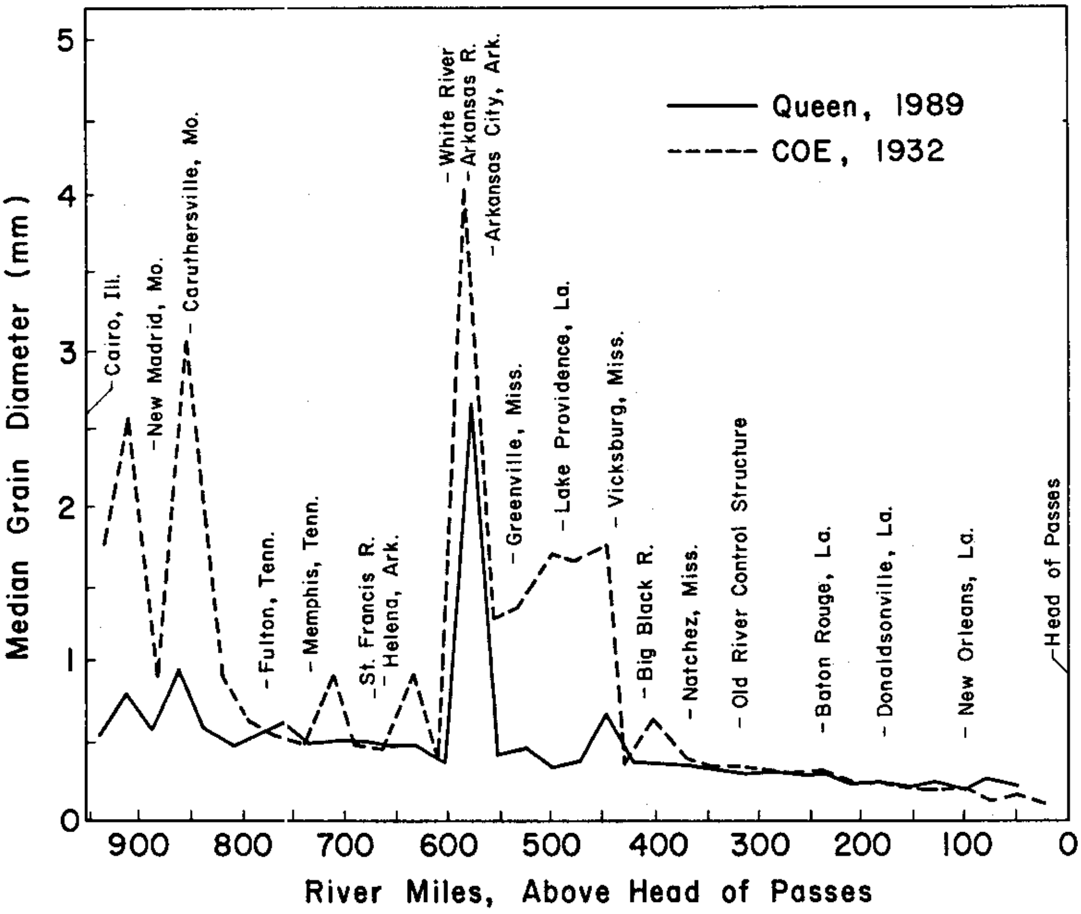

Figure 2. Variation in median grain diameters averaged over 25-mile reaches for 1932 and 1989 samples.

Both bedrock and gravel outcrops occur along the reach between Cairo and about RM 550, and these outcrops may influence the low-water profile. Figure 3 shows a typical example of the gravel obtained during the 1989 field trip. While gravel was obtained in approximately the same locations in both sampling periods, indicated by the nested high points in Figure 2, the gravel obtained in 1989 was not as coarse as that sampled in 1932.

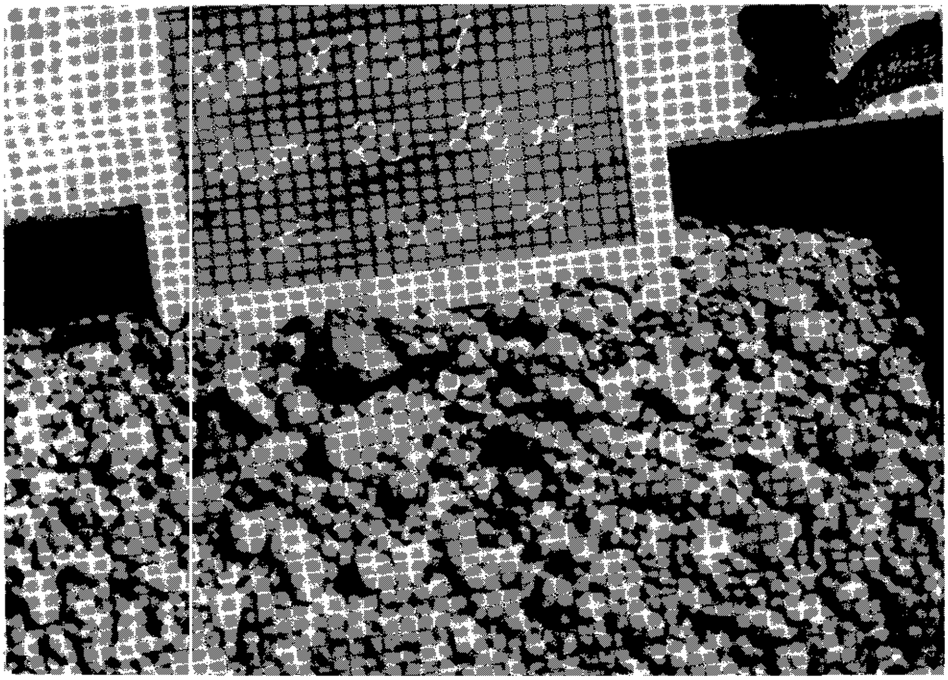

Figure 3. Gravel sample obtained in 1989.

In particular, in the reach between Arkansas City and Vicksburg, the 1989 bed material was much finer than it was in 1932, as shown in Figure 2. In this reach in 1989, the samples consisted mostly of medium sand, with a few samples containing fine gravel. In 1932, 43 samples containing medium gravel were collected from this reach. There is a similar trend, though not as dramatic, in the reach between Cairo, Illinois and Memphis, Tennessee.

Downstream of Natchez, Mississippi, the bed materials from the two sampling periods are nearly identical. However, the samples obtained in 1989 which contain mostly clay have not yet been analyzed. Once these are analyzed and averaged in with the other samples, the median diameters for 1989 could be reduced, making the 1989 bed material finer in this reach as well.

Comparison of the Composition of Bed Material

The variation in the composition of the samples collected in 1989 is shown in Figure 4. In this figure, as in Figure 2, the data are averaged over 25 mile reaches. The figure shows that the bed material becomes progressively finer in the downstream direction.

In Paper No. 17 (WES, 1935), a similar plot was produced. Unfortunately, the two cannot be directly compared since the WES used a different grade scale to identify the classes of material. Additionally, the changes in river mileage (described in the previous section) complicate the comparison. However, using the WES figure, some of the current grade scale breakdowns (0.125, 0.25, 0.5, 1.0, and 2.0 mm) were located by linear interpolation. From this conversion, it is possible to make a few comparisons at known sites (i.e. Memphis, Vicksburg, etc.).

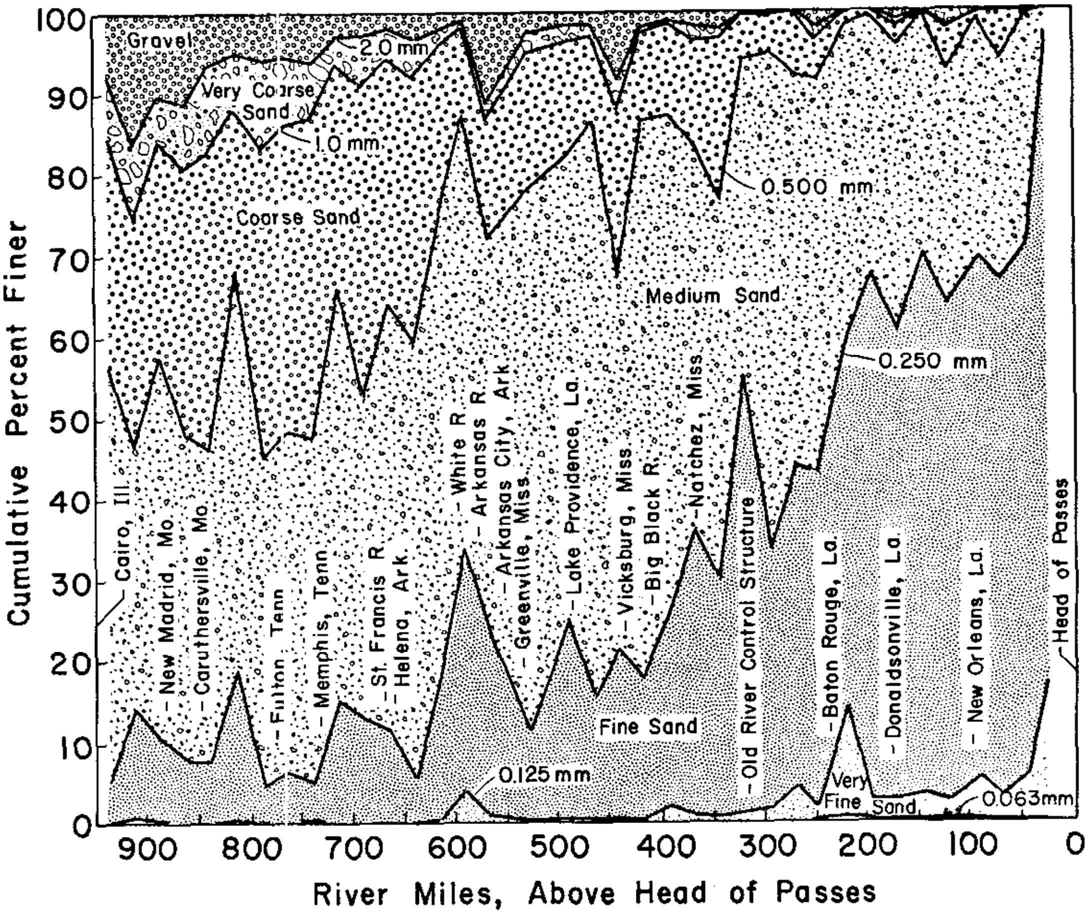

Figure 4. Variation in composition averaged by 25-mile reaches.

The comparison reveals that the bed material sampled in 1932 was more uniformly distributed over the size range than that sampled in 1989, having larger percentages of both coarse and fine material. The 1989 samples contained mostly medium sand with small percentages of coarser and finer material. Considering the entire study reach, the average amount of gravel in samples was approximately 8% in 1932 and 5% in 1989, the average amount of medium sand was 33% in 1932 and 42% in 1989, and the average amount of very fine sand and finer material was approximately 13% in 1932 and 3% in 1989. It is expected that the proportion of very fine sand and finer materials will increase for the 1989 study when the samples containing silts and clays are analyzed.

This comparison indicates that although the bed material is finer in 1989 than 1932 (as shown in Figure 2), there is possibly less very fine material in 1989 than in 1932. The increase in proportion of medium sand from 1932 to 1989 is the reason for the decrease in median grain diameter.

CONCLUSIONS

1. Most of the samples are composed of sand with small quantities of fine and medium gravel. The bed sediments become finer in the downstream direction.

2. Gravel was found at about the same locations in 1989 as in 1932.

3. Contrary to our expectations, the samples of thalweg bed sediments in 1989 were generally finer than samples collected in 1932 upstream of RM 300. They contained a larger fraction of medium sand, a smaller percentage of gravel, and very fine sand.

REFERENCES

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial processes in geomorphology: W.H. Freeman and Co., San Francisco, 522 p.

Meade, R.H., and Parker, R.S., 1985, Sediment in rivers of the United States: U.S. Geological Survey Water-Supply Paper 2275, p. 49-60.

Robbins, L.G., 1977, Suspended sediment and bed material studies on the Lower Mississippi River: Potamology Investigations Report 300-1, U.S. Army Engineer District, Vicksburg, Corps of Engineers.

Waterways Experiment Station, 1935, Studies of river bed materials and their movement with special reference to the Lower Mississippi River: U.S. Waterways Experiment Station Paper No. 17, Mississippi River Commission, 161 p.

STUDY OF BASIC CHARACTERISTICS OF A BINGHAMIAN FLUID

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ABSTRACT

The Yellow River in China is characterized by so high sediment concentration that its water-sediment mixture in the flood season should rehologically be regarded as a Binghamian fluid. Its basic characteristics, such as its yield stress and rigidity coefficient are strongly associated with its mineralogical composition. The silt at Huayuankou Beach on the the Yellow River was used as the sediment sample and was separated into several components with a variety of size gradations for the mineralogical analyses, and the relation of their grain size distribution to the content of clay minerals was definitely determined. The view on the microstructure of the water-sedement mixture with hyperconcentration of fine sediment led to the suggestion of the critical sediment concentration under which the mixture would be transformed into a Binghamian fluid and the effective sediment concentration which can effectively contribute its share to the yield stress by writers. Based on the above basic concepts, the rehological experiments with heavily concentrated suspensions, and the theoretical analyses prompted writers to propose the relationships of the basic characteristics to the sediment concentration and the size grain distribution. All relationships provided by writers were quite well verified by experimental data from various investigators.

INTRODUCTION

The water-sediment mixture can be transformed from Newtonian fluid into Binghamian one, when its sedinemt concentration exceeds a definite critical value. The rheological equation of a Binghamian fluid can be expressed as:

$$\tau = \tau_b + \eta \frac{du}{dy} \qquad (1)$$

where τ_b is the yield stress, η is the rigidity coefficient and du/dy is the gradient of velocity. The parametrs τ_b and η are representative for a Binghamian fluid and according to experimental data they are mainly related to its sediment concentration and grain size distribution.

The silt at Huayuankou Beach on the Yellow River was separated into several components of uniform gradations with the gravity-fallen sorting. The mineralogical composition of each component was determined with its diffraction pattern provided by a x-ray difractometer. The analyses of difraction patterns show that the content of clay minerals in a unit volume of sediments is related directly with the quantity of fine sediments contained in the component. So the relation of parameters τ_b and η to the sediment concentration and size distribution can be reduced to the relation to the content of clay minerals.

As well known, the clay minerals are of multilevel structure. So they are easy to be cleaved and to be broken down into flakes with very large specific surface areas. Because of the effect of isomorphic replacements the surfaces of clay flakes are negatively charged and are surrouded by the cations in solvent to form the positive double layers. The edges of clay flakes have a positive capability of adsorption and the anions in solvent are adsorbed around them to form negative double layers. With the quantity of clay flakes increasing, the double layers would be attracted or overlapped each other and the net-framelike texture would be developed and filled to the capacity. The net-framelike texture is capable of resisting the shear deformation due to the external forces applied to it. So the yield stress τ_b and the rigidity η can be regarded as the measures of the capability.

In order to identify the relationship of parameters τ_b and η to the content of clay minerals, the rehological experiments have been conducted with the slurries prepared from the silts containing the different content of clay minerals. Introduced the concept of effective sediment concentration and identified the dependence of maximum concentration on the content of clay minerals, *the formulas of* τ_b *and* η *can be derived and verified* rather well by experimental data from different investigators.

Relation of the unit content of the clay minerals to the size distribution.

The silt at Huayuankou Beach was separated into five components of a uniform gradation with the gravity-fallen sorting (Hu, 1989). The mineralogical composition was determined and the unit content of clay minerals (the quantity of clay minerals in a *unit volume of sediments) was measured with the* x-ray diffractometer. The measured results indicate that the silt at Huayuankou Beach consists mainly of clay minerals (Illite, Montmorillonite and Kaolinite, etc.) and original minerals (Quartz, Orthoclase, etc.) and the unit contents of clay minerals *are listed in Tab.1. It is pointed out from Tab.1 that with* the medium diameter, D_{50} finner or the quantity of fine sediments

Table 1 the unit content of the clay minerals

No:		1	2	3	4	5
D_{50}	μm	0.42	1.42	3.26	7.66	17.5
unit contednt	%	85	62	44	29	19

larger the unit content of clay minerals is greater. Suppose the representative diameter for the i-th component in a sand mixture is Di and its unit content of clay minerals is Pi. It is considerable reasonably that differential of Pi with respect the (1/Di) is conversely propotional to the (1/Di), i.e.

$$\frac{d(P_i)}{d(1/D_i)} = \frac{\alpha_i}{(1/D_i)} \qquad (2)$$

Integrating equation (2), the unit content of clay minerals for the i-th component, Pi can be expressed as:

$$P_i = \alpha_i \ \ln\frac{\alpha_i}{D_i} \qquad (3)$$

where α_1 and α_2 are the coefficients determined as 0.181 and 43.2 by experiments, respectively. Suppose Ti is the fraction of the i-th component in a sand mixture, its total unit content of clay minerals, P can be expressed by the summary of Pi :

$$P = \sum_i Ti \cdot Pi = 0.181 \sum_i Ti \cdot \ln\frac{43.2}{D_i} \qquad (4)$$

The representative diameter Di for each component in formula (4) is measured in microns (μm). The comparison of formula (4) with authors' data sets is given in Fig.1 and shows that the agreement of formula (4) with experimental data sets is rather good. It can be calculated from formula (4) that the unit content of clay minerals in the sediments with diameters greater than 40 μm may be negligible, while that in the sediments with diameters less than 0.20 μm is nearly 100%. So the sediments with diameters finner than 0.20 μm consist mainly of clay minerals. The clay minerals are two-dimensionally superimposed of crystallolayers each of which is composed of one sheet of silica and two sheets of alumina with oxygen atoms shared. So the clay minerals are of multilevel structure and are easy to be cleaved as flakes.

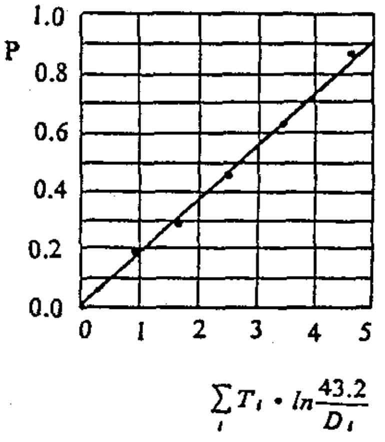

Fig.1 The Comparison of Equation (4) with Experimental Data sets.

It is natural that very fine sediments consist mainly of clay minerals as shown by formula (4). The original mineral is of granular structure and is hard to be cleaved or to be broken down. So it is also natural that the coarse sediments consist mainly of originnal minerals.

Association of clay flakes and the critical sediment concentration

The surface and edge of a clay flake are adsorbed by cations and anions in the solvent, respectively, due to the isomorphic replacement and activation (Olphen Van., H., 1977).
Around a clay flake are two kinds of double layers, i.e. negative double layer and positive double layer. Under the influence of Brownian or nonuniform fallen movement, the double layers of clay flakes can be attracted or overlapped each other. So some of flakes are associated as a floccus even though in the water-sediment mixture of a dilute concentration. According to the analysis by Olphen Van., H., the flocci can be divided into three fundamental modes of associations, i.e. edge to edge, edge to surface and surface to surface shown in Fig.2.
As pointed out by Partheniades H., when the sediment concentration is increasing, the individual flocci can be connected further as the floccus aggregates (Partheniades E, 1986). When the sediment concentration is further increasing the aggregates can further be connected each other as aggregate networks. When the sediment concentration is so high that the quantity of clay flakes in a unit volume of the water-sediment mixture is large enough to make it possible that the aggregate networks can be solidified into a net-framelike texture filled to the capacity. So the net-framelike texture is characterized by two main properties: (1) the critical quantity of clay flakes in a unit volume of the mixture for developing such a net-framelike texture may be considered as a constant, and (2) the water-sediment mixture is of a capacity to resist the shear deformation. Both of them indicate that the mixrure is transformed from Newtonian fluid into Binghamian fluid. The critical quantity of clay flakes is mainly depends on the volmumetric sediment concentration, Cv and the unit content of clay minerals, P. Suppose the critical concentration at which the water-sediment mixture is transformed into the Binghamian fluid is Cv_0, we can establish the following relationship:

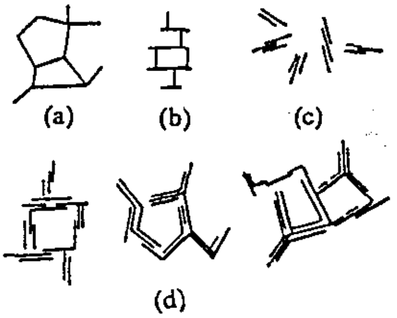

Fig.2
The Modes of flake Associations
(a) - edge to edge
(b) - edge to surface
(c) - surface to surface
(d) - mixed

$$C_{v_0} P^{\alpha_3} = \alpha_4 = \text{constant} \tag{5}$$

where α_3 and α_4 are coefficients to be determined by experiments. According to the experimental data by some investigators (Fei, 1983; Qian, 1980; Wan and Hu, 1989) α_3 and α_4 equal 0.68 and 0.05, respectively, i.e.

$$C_{v_0} = 0.05\ P^{-0.68} \tag{6}$$

The comparison of formula (6) with the experimental data from some investigators is shown in Fig.3.

The effective concentration and yield stress

Based on formulas (5) and (6), we can define the effective concentration, (Cv)e as

$$(Cv)e = Cv\ P^{0.68} - 0.05 \tag{7}$$

which may be explained as the one effective for developing the yield stress τ_b. The rehological experiments were performed by authors with the slurries prepared from the component silts of a variety of size gradations or the unit contents of clay minerals. The experimental data show that the relation of yield stress τ_b to the effective concentration, (Cv)e can be expressed by the exponential form as follows:

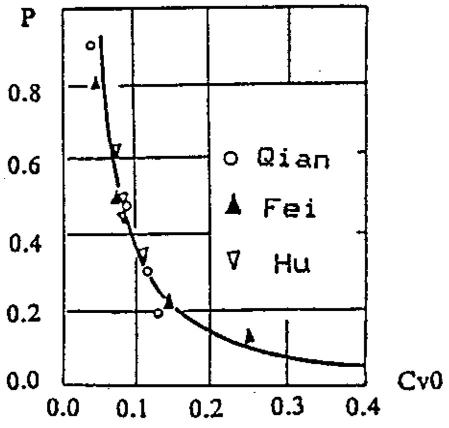

Fig.3 The Comparison of Formula (6) with Experimental Data Sets

$$\tau_b = (\tau_b)_0\ e^{\alpha_5 (C_v)_e} \tag{8}$$

where coefficients $(\tau_b)_0$ and α_5 were experimentally determined as 5.0 and 46.2 from Fei, Qian and authors' data sets. Substituting Equation (7) into Equation (8) yields

$$\tau_b = 5.0\ e^{46.2\ (\ Cv\ P^{0.68} - 0.05\ )} \tag{9}$$

were e is the datum of the natural logarithm and the yield stress is measured in (dyn/cm^2).

Fig.4 shows the comparison of formula (9) with the experimental data sets by Fei, Qian and authors. When the difficulties of accurately measuring the rehological parameters would be taken into account, the scater from the predicted relation is not excessive.

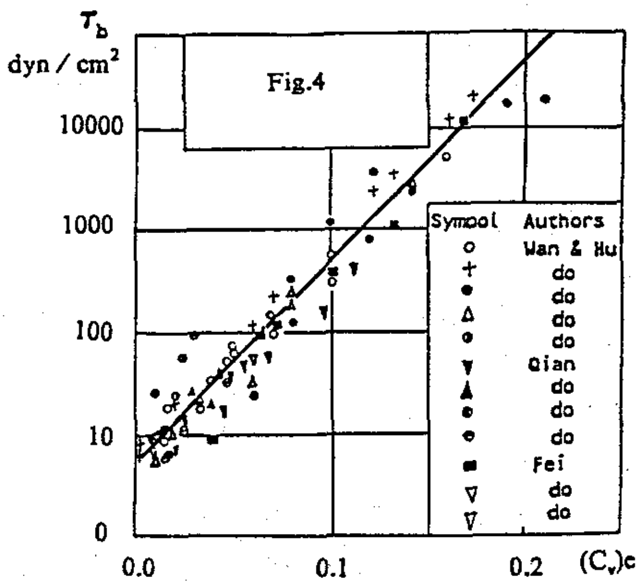

Fig.4 The Comparison of Equation (9) with the Experimental Data by Some Investigations.

The rigidity η and maximum concentration

The rigidity coefficient η is the second basic characteristic for a Binghamian fluid and represents the viscosity of the water-sediment mixture. The rehological experiments indicate that the dimensionless rigidity (η / μ), where μ is the viscosity of water at the same temperature, is mainly depended on the relative sediment concentration (Cv / Cm), where Cm is called as the maximum volumetric sediment concentration.

The maximum volumetric sediment concentration for a water-sediment mixture is corresponding to the closely paved condition. As above mentioned, the transition of a Newtonian fluid into a Binghamian fluid results from the formutation of the net-framelike texture in the water-sediment mixture which can provide the resistance preventing the clay flakes from closely approaching. Thus, the mixture with a higher content of clay minerals is characterized by a less maximum volumetric sediment concentration, Cm. The experimental data show that the relation of the maximum volumetric sediment concentration, Cm, to the unit content of clay minerals, P can be expressed by a exponential form as follows:

$$C_m = 0.271\ P^{-0.47} \qquad (10)$$

Chu J., D. theoretically derived at the universal formula expressing the relation of the dimensionless rigidity (η/μ) to the relative sediment concentration (Cv / Cm) as follows:

$$\eta_r = \eta / \mu = \left(1 - \frac{C_v}{C_m}\right)^{-2.5} \qquad (11)$$

When the formulas (4), (10) and (11) would be taken into account, the relative rigidity (η/μ) can be written as

$$\eta_r = (1 - K\ Cv)^{-2.5} \qquad (12)$$

where coefficient K is dependent on the unit content of clay minerals and can be expressed as:

$$K = 1.65 \left(\sum_i T_i \cdot \ln \frac{43.2}{D_i}\right)^{0.47} \qquad (13)$$

Fig.5 shows the comparison of formula (12) with data sets provided by Qian's experiments. It is clear that the predicted values check well with the experimental data sets.

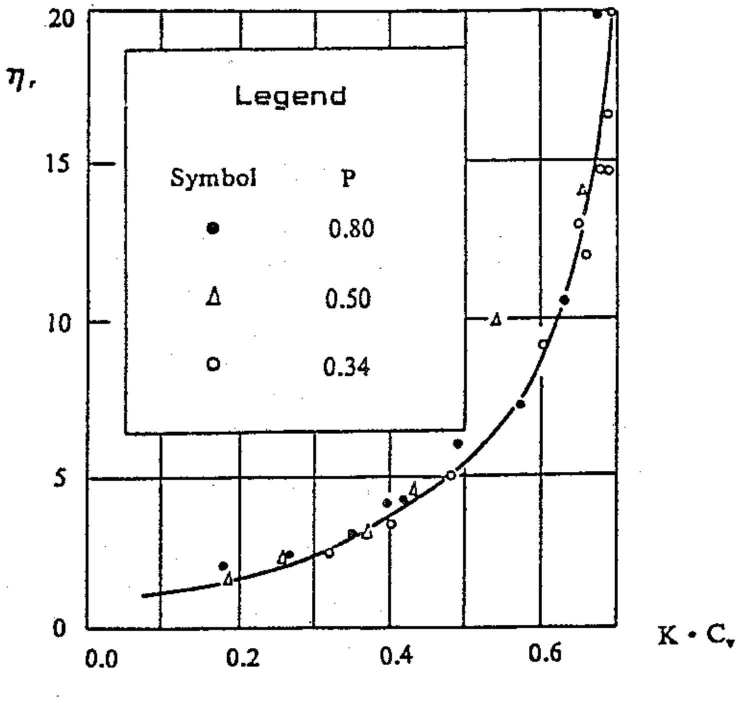

Fig.5 The Comparison of Equation (12) with Qian's Experimental Data Sets.

Conclusions

1. The transition of a Newtonian fluid into a Binghamian one results from the formulation of the net-framelike texture in a water-sediment mixture. The net-framelike texture can resist the shear deformation and the approaching of the clay flakes, thus provide the yield stress and much greater rigidity.

2. The association of clay flakes is the primary motivation for developing the net-framelike texture. It can be divided into four main modes of the association, i.e., floccus, flccus agrregates, aggregate networks, and the net-framelike texture.

3. The representative parameters τ_b and η for a Binghamian fluid are the measures of the capability for the net-framelike texture to resist deformations aroused from the external forces.

4. The parameters τ_b and η can be expressed as the relationships to the unit content of clay minerals and sediment concentration which are quite well verified by the experimental data by various investigators.

References

Hu, Z., H., 1989, An Investigation on the Mineralogical Composition and Size Fraction of Silt at Huayuankou Beach on the Yellow River, Research Report of Nanjing Hydraulic Res. Inst., pp.3-10.

Olphen, Van. H., 1977, An Introduction to the Clay Collid Chemistry", A Wilcy-Interscience Publication, Second Edition.

Partheniades, E., 1986, The Present State of Knowledge and Needs for Future Research on Cohesive Sediment Dynamics, Proceedings of the Third International Symposium on River Sedimentation, School of Engineering, the University of Mississippi, University, Mississippi, U. S. A.

Fei, X., J., 1983, Grain Composition and Flow Properties of Heavily Concentrated Suspensions, Proceedings of the Second International Symposium on River Sedimentation, Water Resources and Electric Power Press, pp.296-306.

Qian, Y., Y., 1980, Basic Characteristics of Flow with Hyperconcentration of Sediment, Proceedings of the International Symposium on River Sedimentation, Guanghua Press, Beijing China, B 3-1 - B 3-8.

Wan, S., G., and Hu, Z., H., 1989, An Investigation on the Yield Stress of Slurries, Research Report of Nanjing Hydraulic Res. Inst. pp. 10-20.

LONG-TERM ^{137}CS AND SOIL LOSS FROM FIELD PLOTS

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ABSTRACT

^{137}Cs, a nuclear fallout product, has been used to quantify soil erosion but few studies have measured both ^{137}Cs loss and soil loss because of time and expense involved. The purpose of our study was to measure ^{137}Cs loss from field plots where long term soil loss records were available so the relationship between long term ^{137}Cs loss and soil loss could be examined for low erosion rates. Six field plots at the Midwest Claypan Experiment Station in central Missouri were sampled to determine ^{137}Cs loss from 1954 to 1987. A linear relationship with a correlation coefficient of 0.97 was found between ^{137}Cs loss and soil loss from the plots. The average relationship was 2.7 Mg/ha soil loss to 1% ^{137}Cs loss. These results indicate considerable enrichment of ^{137}Cs in eroded material. Comparisons with other published data indicated that a single relationship between ^{137}Cs and soil loss may not be generally applicable.

INTRODUCTION

Quantification of erosion to determine its severity and the success of erosion abatement practices is labor intensive and expensive. Since the beginning of the nuclear age, radioisotopes have been released as fallout into the environment. The released radioactive elements have the potential to reduce the cost of erosion studies. One of the relatively long lived and abundant fallout radioisotopes, cesium-137, which attaches to soil particles, has been used to estimate soil erosion (Ritchie and McHenry, 1990). It was first investigated as a soil contaminant in 1964 by Rogowski and Tamura (1965) at Oak Ridge, Tennessee. They found a logarithmic relationship between ^{137}Cs loss and soil loss from small field plots sprayed with a ^{137}Cs solution (Rogowski and Tamura, 1970). Ritchie and co-workers (1974) determined ^{137}Cs loss from eroded sites by comparing ^{137}Cs levels between eroded and adjacent uneroded sites. They then estimated soil loss from their eroded sites with the Universal Soil Loss Equation (USLE) (Wischmeier et al., 1958). Ritchie et al. (1974) combined their data with the data of Rogowski and Tamura (1970) and some ^{90}Sr loss data (Menzel, 1960; Graham, 1963), and determined a logarithmic equation for the relationship between radioisotope loss and estimated soil loss.

A number of studies have measured ^{137}Cs and then estimated soil erosion (McHenry and Ritchie, 1977; Brown et al., 1981; Wilkin and Hebel, 1982; DeJong et al., 1986; Martz and DeJong, 1987). There are, however, very few studies which have measured both ^{137}Cs and soil loss that could be used to form the basis of a general relationship. Elliott and co-workers

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(1984) measured soil loss for three and one-half years from five small plots in Australia. They found that high percentages of ^{137}Cs were lost at low erosion rates from their uncultivated plots. Lance et al. (1986) measured ^{137}Cs on adjacent cultivated and grassed watersheds in Oklahoma. The cultivated watershed was found to have lost 11% of the ^{137}Cs in eight years compared to the grassed watershed which did not have appreciable erosion. Measured soil loss from the cultivated watershed was 17.8 Mg/ha for the eight year study period. Kachanoski (1987) measured ^{137}Cs loss over an 11 year period from ten runoff plots at Guelph, Ontario. The plots had high erosion rates and he found soil loss directly proportional to ^{137}Cs loss. The amount of ^{137}Cs loss per unit of total soil loss was appreciably less than that reported by Lance et al. (1986). These studies vary in the range of erosion rates investigated and reported relationships. More data are necessary in order to fully describe ^{137}Cs and soil loss over a wide range of conditions and to determine the appropriateness of a general ^{137}Cs to soil loss relationship. Knowledge of the relationship between ^{137}Cs loss and soil loss on cultivated land would mean soil erosion on a field could be evaluated with one sampling.

The purpose of this study was to examine the relationship between long-term ^{137}Cs loss and soil loss for cultivated land over a range of erosion rates lower than that reported by Kachanoski (1987). In this study, we will also examine the appropriateness of a general relationship between ^{137}Cs and soil loss.

METHODS

Six field plots were investigated in the Central Claypan Soils resource area at the Midwest Claypan Experiment Station located in central Missouri near Kingdom City. Plots were 3.2 m wide and 27.4 m long with a slope of 3% except for one plot with a slope of 3.5%. The plots were divided by sheet metal borders and had multislot divisor flumes (Cochocton type) and collection tanks for runoff. Soil loss data has been measured from the plots since 1941 (Kramer and Alberts, 1986). The dominant soil type is a Mexico silt loam (fine, montmorillonitic, mesic, Udollic Ochraqualf).

Predominant crops grown on the plots are shown in Table 1. All plots received conventional tillage through 1982, which mixed the soil to a depth of 15 cm. In 1983, three of the plots were converted to no-till plots. Fallow plots were periodically cultivated to prevent weed growth.

A bucket auger which collected a 10 cm diameter soil sample was used to sample the plots in June 1987. Three equidistant rows were laid out transversing the length of each plot and six 20 cm deep samples were collected 4 m apart along each row. In order to determine total deposited ^{137}Cs fallout at the site a soil sample was collected in the middle of a level 0.25 ha permanent grassed area at the top of the plots. The sample was taken in 2 cm depth increments to a depth of 20 cm in a 30.5 by 30.5 cm frame.

Table 1. Predominant crops grown on the six study field plots, 1954-1987.

	Time by Decades			
Plot	1950's	1960's	1970's	1980's
3	Corn	Corn	Soybean	Corn[1]
5	Hay	Hay	Corn	Soybeans[1]
7	Hay	Hay	Corn	Fallow
13	Hay	Hay	Corn	Fallow
14	Hay	Hay	Corn	Soybeans[1]
31	Corn	Corn	Corn	Fallow

[1] No-till beginning in 1983.

Soil samples were dried at 50 C for 24 hours, crushed, and then passed through a 6 mm mesh screen. Cesium-137 activity was determined with a multi-channel analyzer and germanium lithium-drifted solid state crystal detector. Each sample was analyzed twice for a period of 4,000 sec and the average ^{137}Cs activity was used in subsequent analysis.

An independent measure of ^{137}Cs input to the study site was determined from radioactive fallout records at Columbia, Missouri (Larsen, 1985; Health and Safety laboratory, 1977). Fallout data for Columbia, Missouri were supplemented with data from Argonne, Illinois, Tulsa, Oklahoma and New York City, New York to account for missing data (Larsen, 1985, Health and Safety Laboratory, 1977). Data from Argonne and Tulsa were used directly since they had similar precipitation and ^{137}Cs fallout to Columbia. New York City data were proportioned to account for differences in precipitation.

RESULTS AND DISCUSSION

^{137}Cs in the grassed area was found to be in the top 15 cm of soil with an activity level of 2647 Bq/m^2. This was only a little higher than the 2585 Bq/m^2 determined as the total accumulated input of ^{137}Cs fallout (decay corrected) in 1987 at Columbia, Missouri. The close agreement between the ^{137}Cs level of the grassed area and fallout input confirmed that the grassed area had not eroded and was a good indicator of total ^{137}Cs input to the site. The average ^{137}Cs level of the cultivated plots was compared to the value of the grassed area to determine percentages of ^{137}Cs lost (Table 2).

Table 2. Measured ^{137}Cs and soil loss (1954-1987) from field plots near Kingdom City, Missouri.

Plot	Slope	^{137}Cs Mean	^{137}Cs Std	Loss	Soil Loss
	%	----Bq/m^2---		%	Mg/ha
3	3.0	2213	860	16	28
5	3.0	2487	682	6	25
7	3.0	1740	574	34	70
13	3.0	2274	516	14	67
14	3.0	2477	535	14	33
31	3.5	1077	279	59	169

We found a highly correlated (r of 0.97) linear relationship between ^{137}Cs loss and soil loss (Figure 1). The computed linear equation for the relationship is:

$$Y = 2.7 \times (X)$$

where Y = total soil loss in Mg/ha and X = ^{137}Cs loss as a percentage of input (input corrected for decay). The relationship was made to go through the origin because without soil loss there should be negligible ^{137}Cs loss except for decay which was taken into account. Rogowski and Tamura (1970) found that less than 1% of the ^{137}Cs lost in runoff was not associated with soil particles which supports our assumption. An analysis of variance (F-test) indicated the regression to be significant at the .001 level of probability.

These results generally differ from those reported in other studies. Although the erosion rates in Elliot et al. (1984) were low as in this study, the high rates of ^{137}Cs loss reported were probably due to the fact that the plots were not cultivated; hence most of the ^{137}Cs would be very close to the surface where it would erode faster than if mixed throughout the plow layer. Our data indicated much less soil loss per percentage of ^{137}Cs loss than Kachanoski (1987) found. The average relationship in our study was 2.7 Mg/ha soil lost to 1% ^{137}Cs lost while Kachanoski (1987) reported 24.9 Mg/ha soil lost to 1% ^{137}Cs lost. We compared soil loss as a percentage loss of the plow layer to percentage ^{137}Cs loss in order to make comparisons on a relative basis. Overall, we found that 0.15% of the plow layer was lost when 1% of the ^{137}Cs was lost. In contrast, Kachanoski (1987) reported 1.28% of the plow layer was lost when 1% of the ^{137}Cs was lost (Figure 2). Depth of the plow layer in both studies was considered to be 15 cm. The average bulk density for the plow layer at our site was 1.2 Mg/m^3 (unpublished) while Kachanoski (1987) reported his to be 1.3 Mg/m^3.

The greater ^{137}Cs loss per unit of soil loss in our study is indicative of considerable enrichment of ^{137}Cs in eroded material. ^{137}Cs is known to be associated more closely with the clay and finer soil particles (Ritchie et al., 1975). At low erosion rates proportionally greater amounts of clay and finer soil particles could erode taking proportionally more ^{137}Cs with them. In addition the present study measured ^{137}Cs loss over the entire time it was accumulating in the soil. Precipitation deposits ^{137}Cs on the soil surface where it remains until the field is plowed or cultivated. If a sequence of runoff events occurs between plowings a greater amount of ^{137}Cs would be lost per unit of soil than if it were mixed throughout the plow layer. The Guelph study differed from ours in that it started at the end of the major accumulation period (1962-1965), which allowed much of the ^{137}Cs to be incorporated into the profile before the study began.

CONCLUSIONS

With low erosion rates, there is greater ^{137}Cs loss per unit of soil loss which indicates greater enrichment of ^{137}Cs in eroded material. Our findings indicate we need more information about the processes involved in the loss of ^{137}Cs in relationship to total soil loss to accurately predict and develop a general model of soil loss using ^{137}Cs.

ACKNOWLEDGEMENTS

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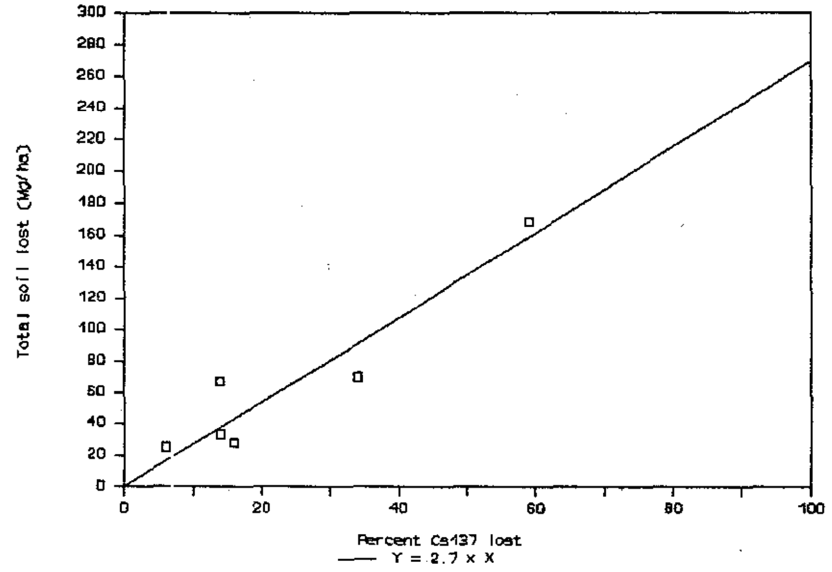

Figure 1. Graph of ^{137}Cs loss to soil loss from field plots near Kingdom City, Missouri.

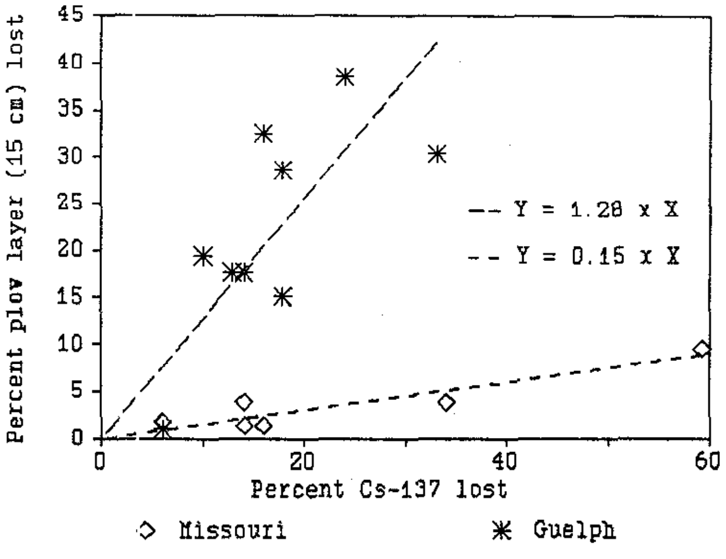

Figure 2 Measured and predicted percent loss of ^{137}Cs vs percent loss of plow layer for Kingdom City, Missouri and Guelph, Ontario.

REFERENCES

Brown, R. B., Kling, G. F., and Cutshall, N. H., 1981, Agricultural erosion indicated by ^{137}Cs redistribution: II. Estimates of erosion rates. Soil Sci. Soc. Am. J. 45:1191-1197.

DeJong, E., Wang, C., and Rees, H. W., 1986, Soil redistribution on three cultivated New Brunswick hillslopes calculated from 137-Cs measurements, solum data and USLE. Can. J. of Soil Sci. 66:721-730.

Elliott, G. L., Campbell, B., and Loughran, R. J., 1984, Correlation of erosion and erodibility assessments using Cesium-137. J. Soil Conservation (New South Wales) 40:24-29.

Graham, E. R., 1963, Factors affecting Sr-85 and I-131 removal by runoff water. Water and Sewage Works 110:407-410.

Health and Safety Laboratory, 1977, Final tabulation of monthly ^{90}Sr Fallout Data: 1954-1976. U.S. Energy and Development Admin. Rep. HASL-329.

Kachanoski, R. G., 1987, Comparison of measured soil 137-cesium losses and erosion rates. Can. J. of Soil Sci. 67:199-203.

Kramer, L. A., and Alberts, E. E., 1986, C factor for corn under changing management. Trans. Am. Soc. Agri. Eng. 29(6):1590-1596.

Lance, J. C., McIntyre, S. C., Naney, J. W., and S. S. Rousseva, 1986, Measuring sediment movement at low erosion rates using cesium-137. Soil Sci. Soc. Am. J. 50:1303-1309.

Larsen, R. J., 1985, Worldwide deposition of ^{90}Sr through 1983. Environmental Measurements Laboratory; U.S. Dept. of Energy, Rep. EML-444.

Martz, L. W., and De Jong. E., 1987, Using cesium-137 to assess the variability of net soil erosion and its association with topography in a Canadian prairie landscape. Catena 14:439-451.

McHenry, J. R., and Ritchie, J. C., 1977, Estimating field erosion losses from fallout cesium-137 measurements. IASH-AISH Publ. No. 122, pp. 26-33.

Menzel, R. G., 1960, Transport of strontium-90 in runoff. Science 131:499-500.

Ritchie, J. C., Hawks, P. H., and McHenry, J. R., 1975, Deposition rates in valleys determined using fallout Cesium-137. Geol. Soc. Am. Bull. 86:1128-1130.

Ritchie, J. C., and McHenry, J. R., 1990, Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. J. Environ. Qual. 19(2):215-233.

Ritchie, J. C., Spraberry, J. A., and McHenry, J. R., 1974, Estimating soil erosion from the redistribution of fallout ^{137}Cs. Soil Sci. Soc. Am. Proc. 38:137-139.

Rogowski, A. S., and Tamura, T., 1965, Movement of ^{137}Cs by runoff, erosion and infiltration on the alluvial Captina silt loam. Health Phys. 11:1333-1340.

Rogowski, A. S., and Tamura, T., 1970, Erosional behavior of cesium-137. Health Phys. 18:467-477.

Wilkin, D. C., and Hebel, S. J., 1982, Erosion, redeposition, and delivery of sediment to Midwestern streams. Water Resour. Res. 18:1278-1282.

Wischmeier, W. H., Smith, D. D., and Uhland, R. E., 1958, Evaluation of factors in the soil loss equation. Agric. Eng. 39:458-474.

SYNTHETIC SEDIMENTS: A TOOL FOR RESEARCH

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ABSTRACT

Formulation of synthetic sediments for use in ecological and toxicity testing is described. Results of toxicity tests with complex effluents in synthetic sediments that contained various concentrations of organic matter are compared with results from hydroponic tests. It is shown that the sediment system affects toxicity of complex effluents and it is suggested that both sediment and hydroponic tests be performed for rigorous risk assessment.

INTRODUCTION

Laboratory testing with sediments often requires rigorous control of physical and chemical characteristics such as particle size distribution, pH, Eh, cation exchange capacity, etc. Although natural sediments contain all of the constituents of natural systems, they have some disadvantages in research areas such as aquatic ecology and toxicity testing. They cannot be formulated to specific experimental requirements, there is inconsistent composition among samples collected at different times (Stemmer et al., 1990), they undergo chemical and physical changes when stored, and they may be contaminated with chemicals or undesired organisms (Bradshaw, 1989; Walsh et al., in press a).

Synthetic sediments offer an alternative to natural sediments when physical and chemical conditions must be carefully controlled. They can be formulated as desired with commercially available sand, clay, silt, and dissolved and particulate organic matter, and they support survival and growth of submersed, wetland, and terrestrial plants as well as freshwater and estuarine animals (Walsh et al., in press b). In addition, they can be prepared as needed, with little difference among lots, are not contaminated, can be stored dry at room temperature, and do not contain undesirable organisms.

This report describes formulation and use of synthetic sediments in toxicity tests with wetland plants and complex effluents.

Responses to effluents in sand and in sediments of different organic contents are compared with responses in hydroponic culture to demonstrate effects of sediment systems on toxicity.

MATERIALS AND METHODS

Synthetic Sediments

Preparation of synthetic sediments has been described in detail (Walsh et al., in press a, b). Their compositions are given in Table 1. They were prepared by mixing 135 g of the dry constituents (Table 1) into 42 ml of plant nutrient solution (Hoagland and Arnon, 1950) or effluent that contained the same nutrients. Some characteristics of this wet sediment are given in Table 2.

Effluents

Effluents tested were from chemical and sewage treatment plants. After collection by grab sampling, they were packed in ice and shipped in insulated chests to the U.S. Environmental Protection Agency, Gulf Breeze, Florida. Upon receipt within 24 h, they were checked for pH, salinity, color, suspended solids, and odor. They were stored in darkness at 4 C and used in toxicity tests the day after receipt.

Test Species

The test species was Echinochloa crusgalli (L.) Beauv. var crusgalli. Echinochloa crusgalli is a monocot widely distributed in freshwater wetlands and terrestrial habitats of the U.S. Seeds were obtained from Wildlife Nurseries, Oshkosh, WI.

Hydroponic Survival and Growth Test

The hydroponic test was conducted to establish toxicity of effluents in direct contact with roots in liquid. Five days before the test began, seeds were planted in coarse sand wetted with deionized water and incubated at 25 ± 1 C under 110 $\mu E/m^2/s$ cool white fluorescent light. On the day of the test, seedlings were harvested, their bases wrapped with cotton, and the roots immersed in nutrient solution prepared with deionized water (control) or effluent dilutions, to which nutrients were added in a 125 ml Erlenmeyer flask. The cotton plug prevented the seedling from falling into the medium and suppressed evaporation of medium. Six seedlings were exposed to control and effluent media under the same temperature and lighting conditions as above. Seedlings were harvested after a total of two weeks exposure. At harvest, the seedlings were divided into roots and shoots, dried for 24 h at 103 C, and weighed.

Table 1. Compositions of synthetic sediments used in toxicity tests with *Echinochloa crusgalli*. 0.01 g of humic acids was added to each synthetic sediment.

	Composition, % by Weight			
Components	3% Organic	5% Organic	7.5% Organic	10% Organic
Sand	82.8	81.1	76.7	72.5
Clay and silt	14.6	14.3	13.6	12.8
Dolomite	0.5	0.5	0.5	0.4
Sphagnum moss	2.1	2.1	2.0	1.9
Cow manure/compost	-	2.0	7.2	12.4

Suppliers

Medium sand:	Mystic White No. 45, New England Silica, Inc. South Windsor, CN
Clay and silt:	ASP 400, Englehard Corp., Edison, NJ
Dolomite:	Southern Agri-Minerals Corp., Hartford, AL
Sphagnum moss:	Hyde Park Products, Inc., Mamroneck, NY
Cow manure/compost:	Hyponox Corp., Atlanta, GA
Humic acids:	Aldrich Chemical Co., Milwaukee, WI

Table 2. Characteristics of synthetic sediments used in toxicity tests with wetland plants.

	Percent						
Substratum (% organic)	Sand (mm)					Silt (mm)	Clay (mm)
	1-2	.5-1	.25-.5	.1-.25	.05-.1	.002-.05	<.002
3	0	13.4	63.8	5.6	0.6	12.1	4.5
5	0	13.8	62.0	5.4	0.6	13.2	5.0
7.5	0.2	13.8	58.0	5.8	0.6	16.1	5.5
10	0	12.8	56.0	6.6	0.8	20.0	3.8

Substratum (% organic)	Extract. bases (meq/100g)	Extract. acids (meq/100g)	pH	Eh	CEC (meq/100g)	Cond. (mmho/cm)
3	4.86	0.16	6.4	462	5.1	0.17
5	7.77	0.52	6.8	412	8.3	0.37
7.5	17.16	1.74	6.9	373	18.9	0.83
10	25.96	2.07	7.2	347	28.0	1.33

Sediment Survival and Growth Test

Sediment toxicity tests were conducted to evaluate any effect sediment may have on toxicity of the effluents, compared to effect in liquid medium. Ten seedlings, grown as above, were planted in each of three styrofoam cups, 5.5 cm high x 7.5 cm diameter, that contained sediment prepared as above. Similar cups were prepared with washed medium sand as a control. The seedlings were grown for 2 weeks under the conditions described. At harvest, shoots and roots were dried, and weighed as above.

Statistical Analysis

Differences between treatment means were evaluated by analysis of variance (SAS 1989). Treatment means were compared with the control by Duncan's multiple range procedure when F values were significant ($P = 0.05$; SAS, 1989).

RESULTS AND DISCUSSION

Chemical Plant Effluent

There was no effect of chemical plant effluent on survival of *E. crusgalli* in the hydroponic or sediment tests.

Hydroponic test, growth. Seedling weights were affected by chemical plant effluent (Fig. 1). Although not statistically significant, there appears to be a trend toward greater average shoot and entire seedling (root and shoot) weights in 1, 10, and 25% effluent when compared with the control. (See the "sediment" section below, where weights of seedlings treated with effluent in sand were greater than those of untreated seedlings.) Conversely, in 50 and 100% effluent, average weights of roots ($P = 0.0014$), shoots ($P = 0.0003$), and entire seedlings ($P = 0.0002$) were significantly lower than average weights of the controls.

Sediment test, growth. The effluent caused significant increase in average weights of shoots ($P = 0.0021$) and entire seedlings ($P = 0.0094$) in sand (Fig 2). Here average weight of shoots exposed to the effluent was 56.1% greater than that of the control group; average weight of entire seedlings exposed to the effluent in sand was 50.0% greater than that of the control. These data, with the apparent trend toward enhanced growth of seedlings treated with low concentrations of effluent in the hydroponic test, suggest that plant nutrients were present in the sample tested. Although the effluent was toxic in the hydroponic test, it was not in the sediment test.

Sewage Treatment Plant Effluent

Sewage treatment plant effluent did not affect survival of *E. crusgalli* in the hydroponic and sediment tests.

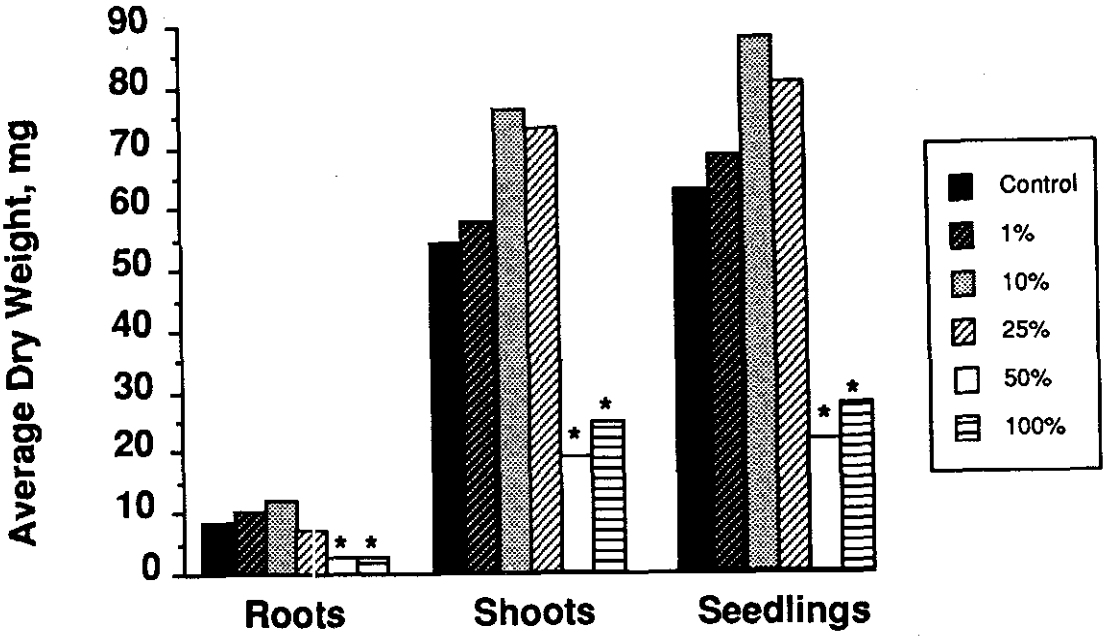

Fig. 1. Average dry weights of roots, shoots, and entire seedlings of Echinochloa crusgalli exposed to chemical plant effluent in the hydroponic test. * = significantly lower than control, P = 0.05.

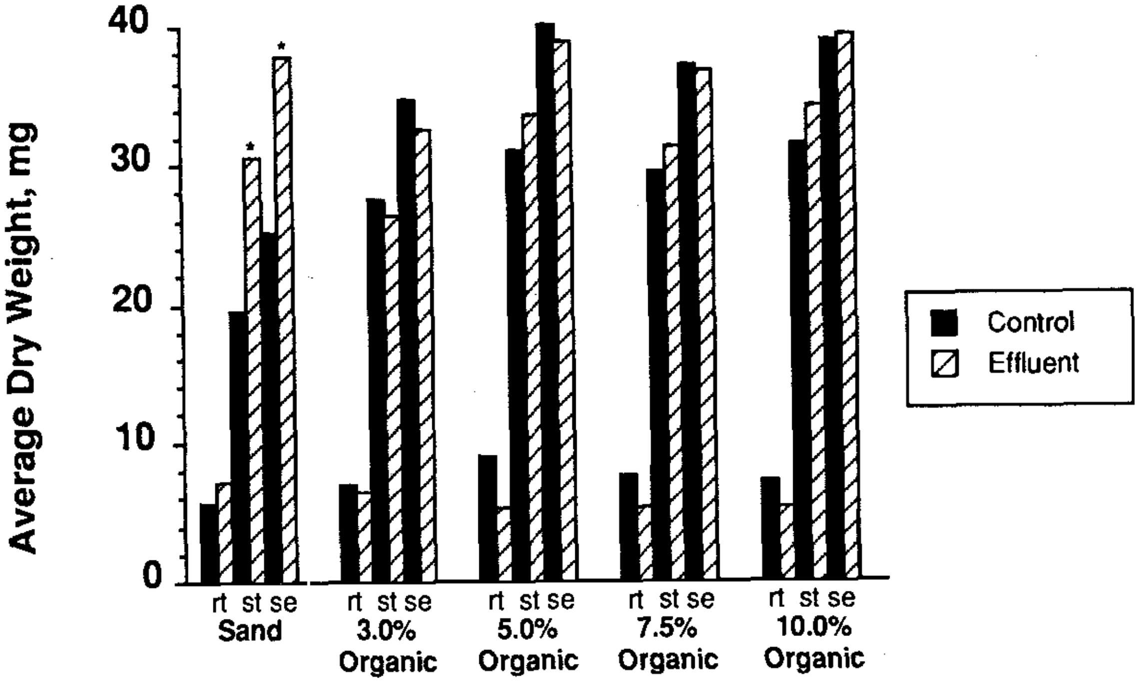

Fig. 2. Average dry weights of roots (rt), shoots (st), and entire seedlings (se) of Echinochloa crusgalli exposed to chemical plant effluent in sand and synthetic organic sediments. * = significantly greater than control, P = 0.05.

Hydroponic test, growth. The effluent inhibited growth of E. crusgalli in the hydroponic test (Fig. 3). Average root weight was significantly lower than that of the control in concentrations of 10% effluent and greater (P = 0.0001), and average shoot (P = 0.001) and average entire seedling (P = 0.0001) weights were significantly lower than the controls at 25% and above effluent.

Sediment test, growth. The effluent significantly inhibited growth of E. crusgalli in sand, but not in the synthetic sediments (Fig. 4). In sand, average weight of treated roots was 20.3% of the control (P = 0.0098), average weight of treated shoots was 38.7% of the control (P = 0.0005) and average weight of entire seedlings was 32.8% of the control (P = 0.0066).

These results demonstrate that sediment can reduce toxicity of complex effluents to wetland plants. Both effluents were toxic to E. crusgalli in the hydroponic test but not in sediments that contained as little as 3% organic matter. Stimulation of growth by chemical plant effluent as in the hydroponic test and sand did not occur in the organic sediments.

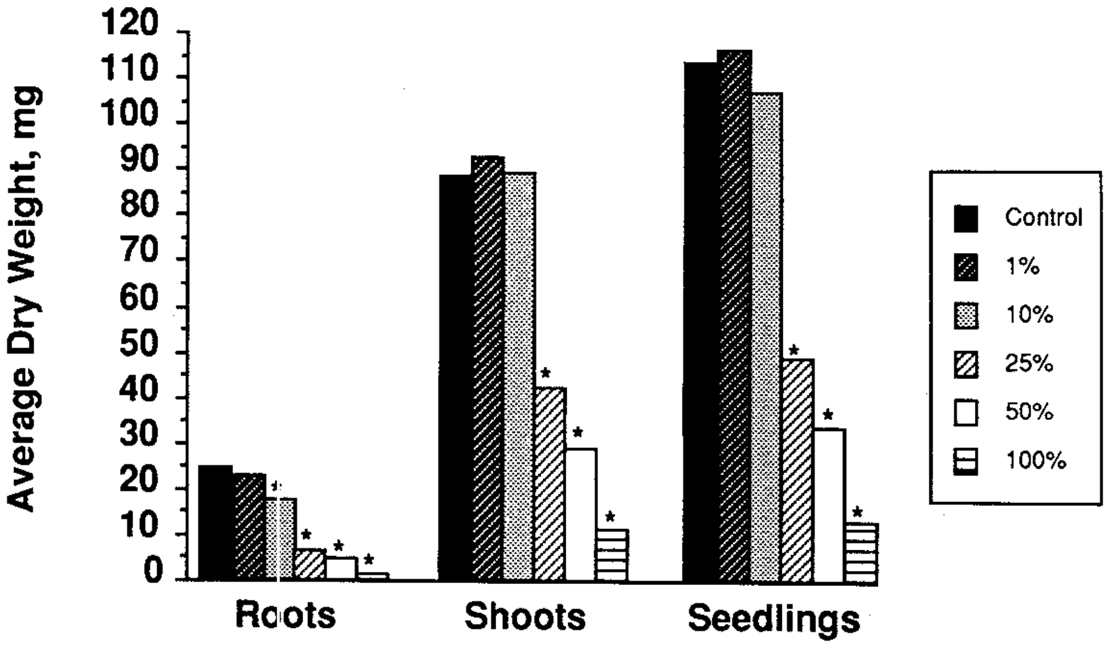

Fig. 3. Average dry weights of roots, shoots, and entire seedlings of Echinochloa crusgalli exposed to sewage treatment plant effluent in the hydroponic test. * = significantly lower than control, P = 0.05.

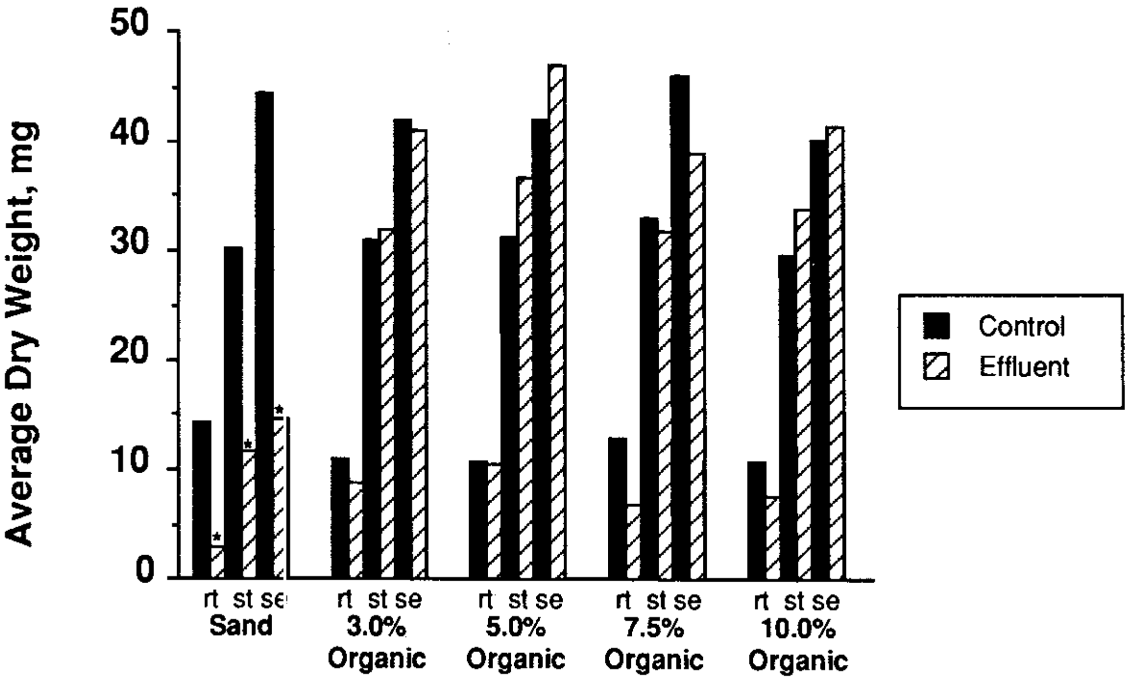

Fig. 4. Average dry weights of roots (rt), shoots (st), and entire seedlings (se) of Echinochloa crusgalli exposed to sewage treatment plant effluent in sand and synthetic organic sediments. * = significantly lower than control, P = 0.05.

CONCLUSION

It is concluded that hydroponic tests can identify phytotoxic effluents but sediments may affect toxicity of some effluents to plants. For a complete risk assessment, it is suggested that hydroponic and sediment tests be performed, one to show potential effects of the untreated effluent, and the other to provide a more realistic estimate of possible effects in the field.

LITERATURE CITED

Bradshaw, A.D. 1989. The quality of topsoil. Soil Use Mgmt. 5: 101-108.

Hoagland, D.R. and D.I. Arnon. 1950. The Water Culture Method for Growing Plants Without Soil. California Agricultural Experiment Station, Circular 347, Berkeley, CA.

SAS Institute, Inc. 1989. SAS/STAT User's Guide. Version 6, 4th ed., Vol. 1, SAS Institute, Inc., Cary NC.

Stemmer, B.L., G.A. Burton, Jr., and G. Sasson-Brickson. 1990. Effect of sediment spacial variance and collection method on cladoceran toxicity and indigenous microbial activity determinations. Environ. Toxicol. Chem. 9:1035-1044.

Walsh, G.E., D.E. Weber, T.L. Simon, and L.K. Brashers. Toxicity tests of effluents with marsh plants in water and sediment. in.: J. Gorsuch and W. Wang, eds. Use of Plants for Toxicity Assessment, STP 1091, American Society for Testing and Materials, Philadelphia, PA. in press a.

Walsh, G.E., D.E. Weber, L.K. Esry, M.T. Nguyen, J. Noles, and B. Albrecht. Synthetic substrata for propagation and testing of soil and sediment organisms. Biol. Fertil. Soils. in press b.

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VARIATION OF BED COMPOSITION IN LOWER YELLOW RIVER

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ABSTRACT

Lower reaches of the Yellow and the Weihe River are composed of fine sand. During floods, local water surface slope, river morphology as well as surface bed material composition subject to great changes. Percentage greater than 50 micron in the bed material may vary in ranges more than 40 %. This paper describes the drastic change of the bed material composition based on the analysis of observed data which could provide basis for stucying the influence of the variations of the surface bed material on the sediment transport capacity of the river.

PREFACE

Alluvial river will adjust its conveyance and transport capacity in compatible with the oncoming flow and sediment load. The surface bed material in middle and lower reaches of the Yellow River below Longmen is composed mainly of find sand with some silt. Study of the variations of bed material composition at surface of the river bed will be of great asistance to a better understanding of the variation of the sediment transport capacity. Self-adjustment of the alluvial river can best be illustrated by the adjustment in its slope, bed material composition, bed morphology as well as conveyance capacity of the main channel and its flood plain. For the Yellow River, it would be necessary to study how the adjustment is carried out. The paper describes basically the variatior of the surface bed material by analysis of available field data.

ANNUAL VARIATION OF SURFACE BED MATERIAL COMPOSITION OVER SPECIFIC CROSS SECTION AT GAGING STATIONS

Sampling and size analysis of bed material over the cross section of a gaging station on the alluvial reaches of the lower Yellow River and its tributary Weihe River was done simultaneously with the measurement of sediment discharge over the section. Frequency of sampling varies according to circumstances. Size gradation of the bed material at each cross section published in the year book is the average value over the cross section during the period while measurement of sediment discharge was undertaken.

If the percentage finer than 50 micron (P50) or median diameter (D50) of the bed material is used to indicate variations of the bed material composition and is compared with the hydrograph of the sediment discharge, it is discovered that, under most circumstances, the bed material composition varies obviously in accordance with the variation of the sediment discharge which is usually measured more frequently during the flood seasor and in couple of months before and after the flood season. But, the bed material is usually less frequently sampled in the nonflood season. It would be difficult to describe systematically the variation of bed material composition in a whole year due to insufficient data. Data shown in figure 1 was selected from the published data in which the number of observations was barely enough to illustrate the process of variation of the bed material size.

It can be seen from the figure that the bed material composition varies greatly in a year., becoming coarsened or finer in response closely to the variation of the sediment concentration or sediment discharge. The composition varies also in response to the erosion and sedimentation of the cross section during a flood process. A tendency of the variation may also be detected if accumulative erosion or deposition takes place. Station BQ is located on the topset of the delta in the backwater area of the Guanting Reservoir on the Yongding River. It can be seen from figure 2 that the bed material composition became obviously coarsened in response to an erosion of approximately one meter in the mid August 1963. The data also indicated that the bed material became finer corresponding to a rise of bed elevation of about 2 meters after August 1964. The tendency was clear if fluctuations of the observed data were not considered.

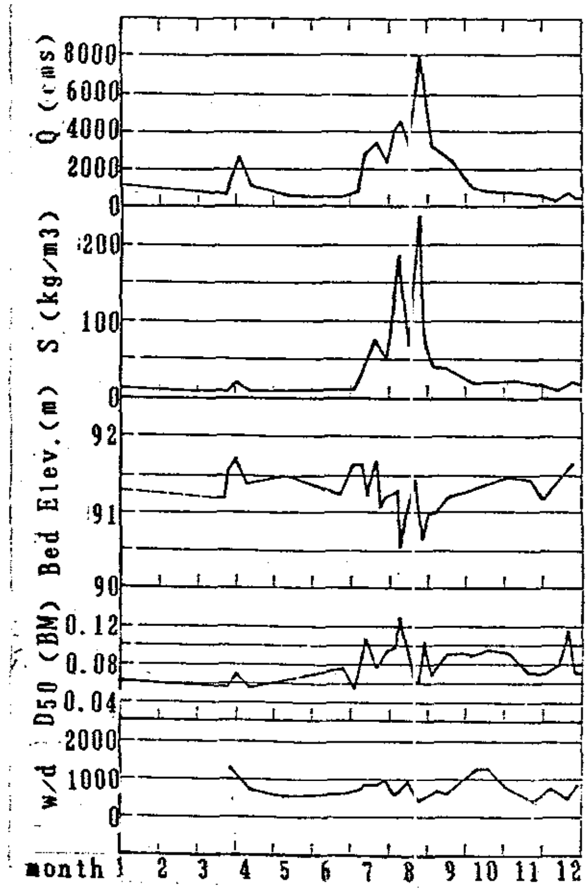

Fig.1 Hydrograph (Huayuankou 1959)

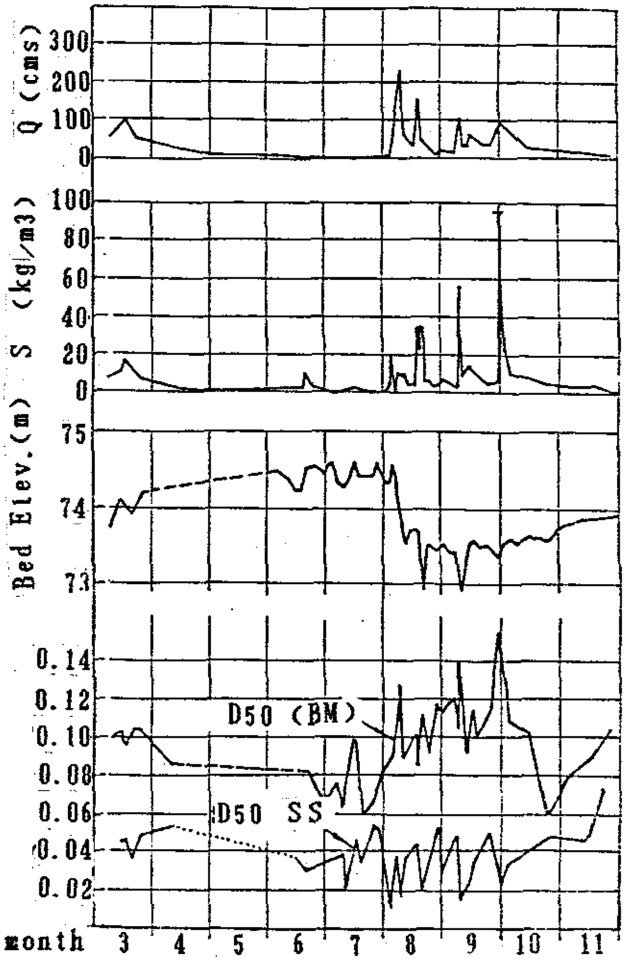

Fig.2 Hydrograph (sta BQ 1963)

Measurement of suspended sediment concentration as well as its size gradation were carried out all year round at major gaging stations on the main and tributaries of the Yellow River. After data processing, monthly and yearly average size gradation of the suspended sediment were obtained and published in the year book. A rough analysis of the variation of the suspended sediemnt composition was made, which may be compared with the variation of the bed material composition in a year, although the data of the latter might be insufficient to describe the complete process of the flow. Variation of both the suspended sediment and the bed material composition in a year at the gaging station BQ periodically influenced by the backwater of the reservoir can also be seen in the figure 2. To illustrate the variations of the suspended sediment composition in a year, figure 3 is drawn, which represents the variations of the suspended sediment composition above and below the Sanmenxia Reservoir which is operated in a mode of storing water during the nonflood season from November to June in the next year and operating at low head with essentially no impoundment during the flood season from July to October. It can be seen from the figure:

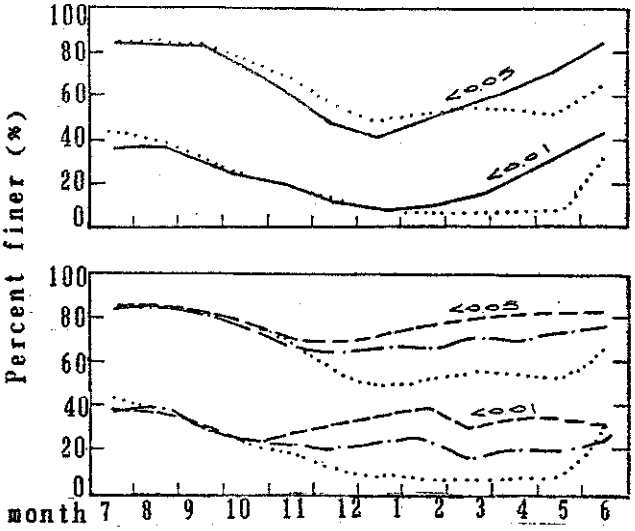

Fig.3 Variation of suspended sediment size along lower Yellow River 1975--1984

1. Suspended sediment composition is in general fine in the flood season and becomes coarser in the nonflood season. Percentage greater than 50 micron varies greatly in a year, from 12-20 % in July through September to 54-58 % in December through February at the Tongguan Station which is located at the headwater of the Sanmenxia Reservoir, about 113 km upstream from the damsite.

2. After regulation of the reservoir, the suspended sediment composition at gaging stations downstream from the dam differs greatly from the natural condition. This part of sediment originated mainly from erosion of the river bed taken place during the release of clear water from the reservoir in the nonflood season including also the bank erosion.

3. As an average, the composition does not change very much during the flood season as a result of no impoundment in the reservoir.

For a reach on the lower Yellow River, the sediment load and its size gradation of the upstream gaging station represents the condition of the oncoming flow. The sediment load and its size gradation observed at downstream gaging station represents the result of adjustment in the studied reach. The adjustment can be reflected in the erosion and sedimentation of the river reach and in the variation of the bed material composition. It is clear that appreciable amount of wash load is contained in the suspension and its proportion depends on the sediment yield from the watershed, with little correlation with the hydraulic properties in the river reach, therefore, it would not be appropriate to expect that the bed material composition and the suspended sediment composition echo each other very closely. However, due to the self-adjustment of the alluvial channel, variation of the bed material composition can be reflected to some extent by the variation of the suspended sediment composition.

During floods, discharge and sediment concentration of the oncoming flow vary greatly. Generally speaking, the river bed would be scoured during the rising period of a flood and be filled back during recession. During a flood with hyperconcentration of sediment, width of the river would greatly be narrowed down by deposition on one or both sides. Phenomena of this kind would propagate gradually downstream during the flood process. It is clear that an exchange of bed material actually takes place in a flood process not in a dimension of several centimeters but rather, in several decimeters or even in meters. Or, in other words, the bed material after the flood has been replaced by the newly deposited material with a certain thickness. The flood duration is usually not very long, in consequence, exchange of the bed material can be accomplished in a short time. This phenomena of exchange of bed materials during the flood process could not be easily noticed if not enough bed material samples were taken during the floods. However, the drastic variation of the suspended sediment composition could be a good indication.

VARIATION OF BED MATERIAL COMPOSITION IN MANY YEARS

Variation of bed material composition in a long period reflects the adjustment of the alluvial river reach in conformity with the variation of the oncoming flow and sediment load. Sanmenxia Reservoir is situated at the lower part of the middle Yellow River and commenced its impoundment in September 1960. In March 1962, it was decided to change its mode of operation to detention of flood only during the flood season, that is, the outflow was not controlled at all. Due to limited outlet capacity, however, in a wet year such as 1964, the reservoir stage was still very high and serious deposition took place in the reservoir. Reconstruction for enlargement of the outlet capacity was decided at the end of 1964 and the reconstructed outlets were gradually put into operation from June 1966 through 1973. During this period, the reservoir occasionally stored some water in the nonflood season for ice-flood prevention and was operated only to detain large floods. Since 1974, after the completion of the reconstruction work, the reservoir has been used to store relatively clear water in the nonflood season for ice flood control, industrial and municipal water supply and providing additional surface water for irrigation in Spring. The reservoir was drawn down and kept at low heads during the flood season to facilitate the disposal of floodwater and flushing of the reservoir deposits occured during the previous nonflood season.

Operation of the Sanmenxia Reservoir greatly modified the oncoming flow and sediment condition for the lower Yellow River. Figure 4 illustrates the variation of bed material size in a reach 70-120 km upstream from the dam. Only the average bed material size obtained during reservoir survey was plotted on the graph which didnot reflect the variation of size during floods. It is clearly shown that in the early stage of impoundment,the bed material size was very fine and became coarser after the change of the operation mode. The sawtooth shaped variation in latter years reflects the influence of deposition in the nonflood season and scour in flood season corresponding to the operational scheme adapted in the latter years. This kind of variation may be considered representative for reservoirs operated to store clear water only in the nonflood season.

Weihe River is a major tributary confluenced in the vicinity of Tongguan into the main Yellow River. Lower reaches of the Weihe River was influenced by the upstream extension of the backwater deposits in the early stages of operation of the Sanmenxia Reservoir. Adjustment of this alluvial reach was studied by Zhang and Long (Zhang and Long 1978). Figure 5 shows the variation of accumulative amount of deposition, water surface slope and median diameter of the bed material in a reach of 15.6 km on the Weihe River, 120 km upstream from the confluence point and 230 km from the dam. The graph was drawn based on the reservoir survey data obtained every year prior and after the flood season.

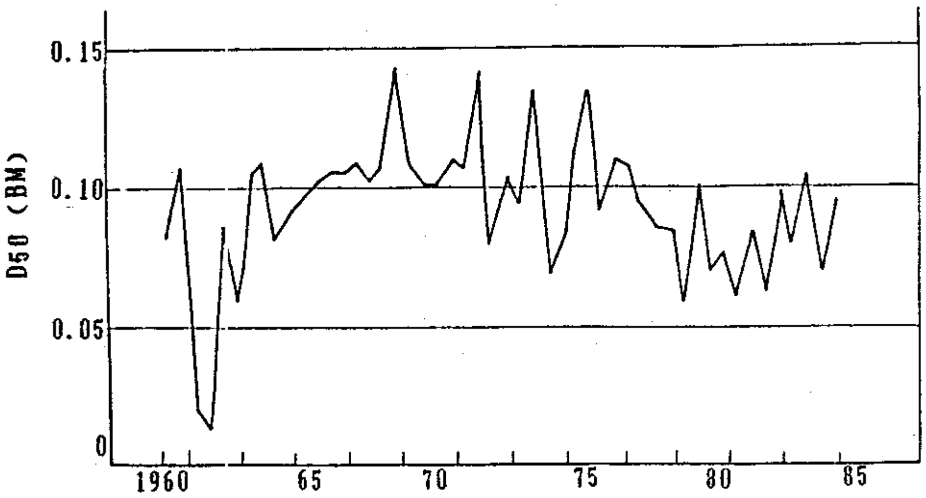

Fig.4 Variation of bed material size

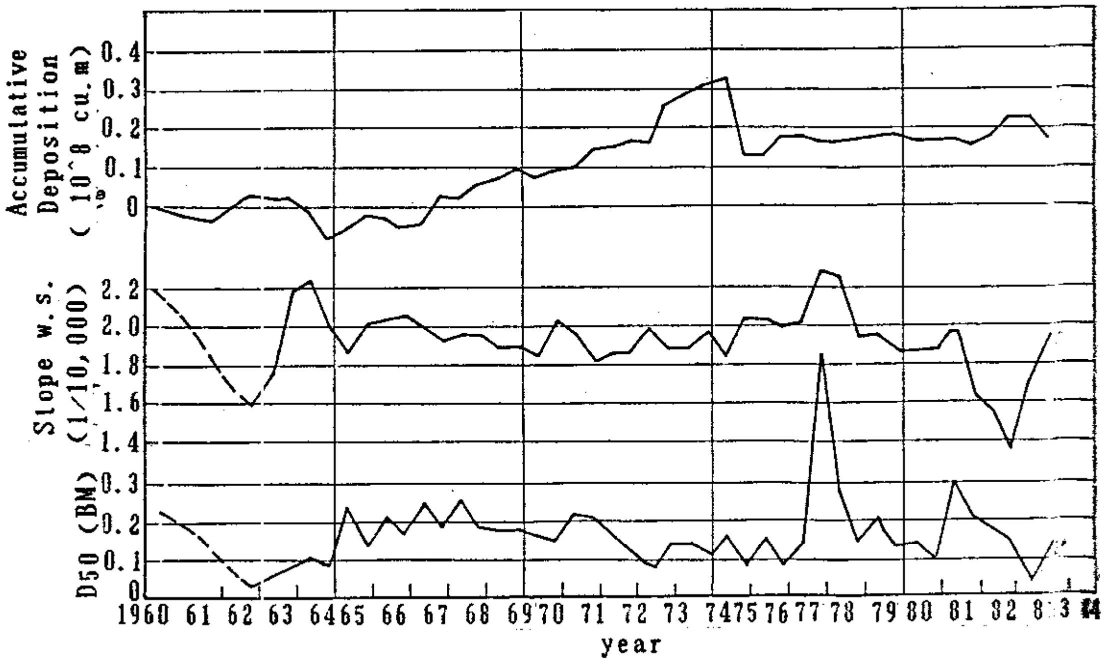

Fig.5 Process of accumulative deposition, bed material size in reach 18-21 of Weihe River

It can be seen from the figure that from 1967 through 1974, there was accumulative deposition in the reach and, correspondingly, the bed material size tended to be finer. Very intensive erosion took place during two floods with hyperconcentration of sediment in 1977 which accounted for the sudden coarsening of the bed material size in that year. This reach was located in the backwater zone of the reservoir during the period of impoundment. After the change of the operational mode, the studied reach has been free from direct backwater effect, yet the channel morphology, slope, bed material composition, flood stage as well as the relative difference in elevation of the main channel and the flood plain still underwent adjustment due to the influence of deposition occured in the previous stage. For the oncoming flow and sediment condition which has been experienced up to now, the river channel becomes stabilized and resumes its natural process of erosion and sedimentation.

Since the operation of the Sanmenxia Reservoir, the lower Yellow River has also experienced adjustment under different conditions of the oncoming flow and sediment. The adjustment may be reflected in the variation of channel geometry as well as the relative difference in elevation of the main channel and the and the floodplain, however, variation of the bed material size is one of the prominent elements subject to adjustment. Coarsening along the course of lower Yellow River of the bed material size (Li 1980) indicates that adjustment of the bed material size could be completed in relatively short distance and required not very long period of time. In 1961, clear water was released from the reservoir,median diameter of the bed material in a reach above Huayuankou change from 0.08 to 0.12 mm in the process of erosion and in a period of two months after the reservoir drawdown in later October of 1964, the median diameter of bed material varies from 0.18 to 0.07 mm,which illustrates that the river adjust its bed material size rather rapidly in the process of erosion or sedimentation. In twenty years from 1965 through 1984, variation of the bed material size corresponding to the deposition in river reaches 620 km downstream from the Sanmenxia Reservoir is shown in Figure 6. The variation denotes only the change prior or after the flood season. It is seen that the median diameter of the bed material has a tendency of becoming finer in course of aggradation.

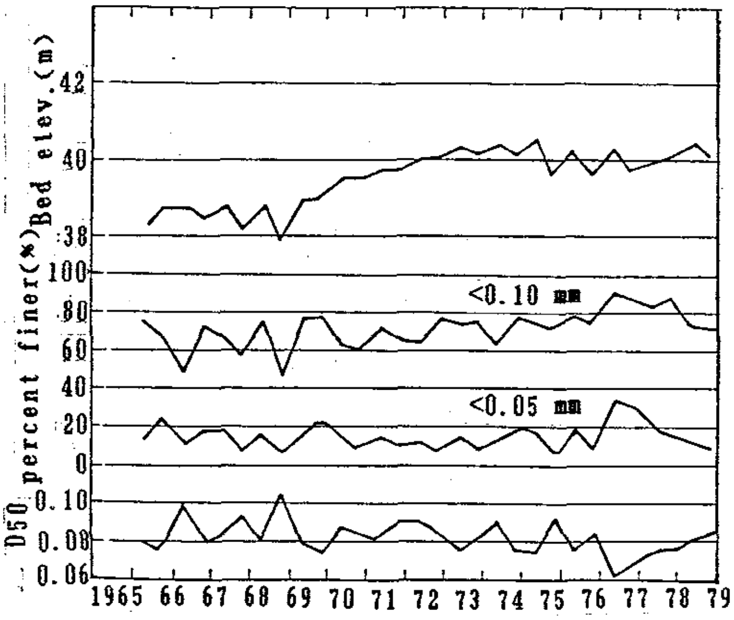

Fig.6 Variation of bed material size at Aishan section

INFLUENCE ON TRANSPORT CAPACITY DUE TO VARIATION OF BED MATERIAL SIZE

In order to study the influence of bed material composition on the sediment transport capacity of the lower Yellow River, observed data were compiled into a database in which, discharge, width, depth, water surface slope, temperature, suspended sediment concentration, suspended sediment and bed material composition are tabulated for use in the analysis. Several dimensionless parameters were selected from the available observed data to establish an empirical relationship between the transport capacity and the hydraulic parameters in a form as follows :

$$C = k\,(J^2/gd)^a * (U/w)^b *(d/D65)^c$$

In this expression, C represents concentration of the total sediment load in units of kg/ m^3, U and d represent velocity and depth of flow in units of m/s and m respectively, w represents the fall velocity of sediment in motion also in m/s, D65 represents the characteristic grain size of the bed material which is 65 % finer in the composition in units of mm, k, a, b, c, are either coefficientg or exponents which may be deducted by regression analysis. In the regression analysis, sediment concentration of the total load is used, which is obtained by applying the Modified Einstein Procedure, slightly modified to be applicable to our condition, to the measured suspended sediment discharge. For 1018 data sets, obtained by field measurement from 1980 - 1988 at seven gaging stations along the lower Yellow River, the coefficient and exponents are as follows :

$$k = 0.0257 \quad a = 0.80 \quad b = 0.48 \quad c = 0.44$$

and the coefficient of correlation is equal to 0.87. If the ratio of computed value to the measured value is expressed by r, 88.1 % data points are within $0.5< r <2$. Obviously the relationship should be considered fairly good if probable error in the field measurement also the nonequilibrium between the transport rate and the transport capacity were taken into consideration. From this expression, influence of the variation of bed material size on the transport capacity can be directly perceived.

REMARKS

Self-adjustment of the alluvial river in conformity with the oncoming flow and sediment load is a natural law of sediment transport in rivers. For a sediment laden river such as the Yellow River and its major tributaries, abundant sediment supply is available from the watershed which meets the requirement of adjustment. It has been found from field observation that adjustment of bed material size and channel geometry can be accomplished in a relatively short period, or, in other words, the adjustment is rapidly carried out. However, due to the stochastic and periodic properties of hydrological events, the river would further adjust itself once a less frequently occured water and sediment flow which had not occured in the previous period were to take place. Although the river has already adjust itself in previous stage in compatible with the ordinary oncoming flow. The river would be stable only in a relatively long time span.

REFERENCES

Zhang Qishun, Long Yuqian, 1980, Sediment Problems of the Sanmenxia Reservoir, Proc. Intern. Symp. on River Sedimentation, IRTCES, Beijing

Li Baoru et al, 1980, Changes of River Channel Downstream of Sanmenxia Reservoir during Silt Detention Period, Proc. Intern. Symposium on River Sedimentation, Guanghua Press, Beijing

Lin Bingwen, Liang Guoting, 1989, Influence of Variation of Bed Material Composition on Sediment Transport Capacity, Research Report 88-063 IHR Yellow River Conservancy Commission