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by

Dasel E. Hallmark
Hydraulic Engineer
Bureau of Public Roads
Washington, D. C.

and

George L. Smith
Hydraulic Engineer
Colorado State University
Fort Collins, Colorado

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STABILITY OF CHANNELS BY ARMORPLATING

ABSTRACT

This paper presents the results of experimental investigations of certain sediment characteristics found pertinent to the control of localized scour in alluvial channels. A relationship between fall velocity of the sediment particle, velocity at the beginning of sediment motion, and bed shear velocity is then developed in terms of the nominal diameter. All results are presented in the form of graphs.

STABILITY OF CHANNELS BY ARMORPLATING^a

By Dasel E. Hallmark¹, ASCE, and George L. Smith², M. ASCE

SYNOPSIS

In the design of stable alluvial channels the engineer must consider both the types of flow and their characteristics which cause erosion and the characteristics of the alluvial material which is scoured. Localized scour, an aspect of the erosion phenomena, is a result of the action of eddies, waves, jets and accelerated flow which are caused either by obstructions such as hydraulic structures in the channel or by changes in the channel boundary geometry. For control of localized scour for the case of non-cohesive material, experimental and theoretical studies were made of sedimentary materials consisting of uniform sand, uniform gravel, and graded sand-gravel mixture. The sediment characteristics found pertinent to the control of localized scour were: (a) particle size gradation, (b) shape of the sediment particle, (c) fall velocity of the sediment particle whose diameter is representative of the mean size of the material being scoured, and (d) size of the particle that will resist motion.

^a Presented at the May, 1962 ASCE Convention in Omaha, Nebraska.

¹ Hydraulic Engineer, Portland Cement Association, Chicago, Ill., formerly a Highway Research Engineer, Bureau of Public Roads, Washington, D. C.

² Assistant Civil Engineer, Civil Engineering Section, Colorado State University, Fort Collins, Colorado.

INTRODUCTION

Hydraulic structures constructed in alluvial channels disrupt normal regime flow patterns. This disruption is evidenced in the flow as eddies, waves, jets and accelerated flow either upstream or downstream of the structure. At the structure, the effect of the disrupted flow is to cause rapid and severe erosion of the alluvial bed and banks-- localized scour. In the design of stable alluvial channels near structures the engineer must consider the flow characteristics which cause localized scour and know those characteristics of sediment particles which will effect a control of the localized scour. Flow characteristics largely responsible for scour include shear drag and pressure drag. Sediment characteristics which are effective in controlling localized scour include (a) particle size gradation, (b) fall velocity of the sedimentary particle, (c) shape of the sedimentary particle defined in terms of a shape factor, and (d) size of particle that will resist motion.

Basically, control of localized scour means controlling those forces which produce scour. These forces are identified as the hydrodynamic lift and the shear drag or tractive force. The entrainment mechanism stems from these forces acting on the exposed layers of sediment particles and is a function of the fluctuation and surging of pressures resulting from variation in the flow characteristics. This fluctuation and surging of pressures, which causes sudden caving or sloughing of large masses of material, not only increases the size of the scouring basin but also provides a constant supply of raw material. This mass consisting largely of fine material is then acted upon by the main flow resulting in a sorting process and carrying away of the sediment particles. Thus, the estimation of velocity at the point of scour is an essential step in the design for control of localized scour which may occur at bends in channels; abrupt changes of channel cross sections; as well as around hydraulic structures. In many cases, this velocity can be assumed equal to the ambient velocity.

In the control of localized scour this paper will consider certain sediment characteristics--size gradation, shape, and fall velocity--and their relation to the beginning of sediment motion and tractive force concept used in stable channel design.

PARTICLE GRADATION--ARMORPLATE

Sedimentary materials consisting of uniform sand, uniform gravel, and a graded sand-gravel mixture were recently investigated (1, 2, 3) under conditions causing localized scour of the materials. The purpose of these investigations was two-fold: (a) to determine those characteristics of the sediment which would resist scouring, and (b) to determine the suitability of a graded sand-gravel mixture as an armorplate. (Hereinafter the term of armorplate refers to a graded sand-gravel mixture) material for scour control. Both the two-dimensional case--scour below a drop structure, and the three-dimensional case--scour below a cantilevered culvert outlet were studied.

The results of these investigations indicate:

- (1) A small amount of armorplate material results in a relatively large decrease in the rate of scour. As shown by figure 1, a protective 6 inch layer of 5 pounds per foot of width of graded armorplate

1. "Scour in a Gravel Bed," by R. K. Thomas, thesis presented to the Colorado Agricultural and Mechanical College in Fort Collins, Colorado, in 1953, in partial fulfillment of the requirements for the degree of Master of Science.

2. "Influence of Particle Size Gradation on Scour at Base of Free Overfall," by Dasel E. Hallmark, thesis presented to the Colorado Agricultural and Mechanical College in Fort Collins, Colorado, in 1955, in partial fulfillment of the requirements for the degree of Master of Science.

3. "Scour and Scour Control Below Cantilevered Culvert Outlets," by George L. Smith, prepared for Bureau of Public Roads, Colorado State University Research Foundation, Fort Collins, Colorado, CER61GLS14, May 1, 1961.

results in a 73 per cent reduction in the scour rate. Also shown by figure 1, a uniform size of aggregate slightly larger ($1/4'' - 1/2''$) than the largest particle size of the bed material reduces the scour more effectively than a larger uniform size aggregate ($1'' - 2''$).

(2) The thickness of the armorplate layer is approximately three times the maximum diameter of the armorplate material, or 6 inches for a material uniformly graded to 2-inch maximum diameter.

(3) A graded armorplate material decreases the rate of scour more effectively than a uniform size material.

(4) The effectiveness of armorplate depends not only upon its gradation but also upon its relation to the maximum size of aggregate of the bed material, that is the minimum size in the armorplate should be about the size of the maximum size of the bed material.

Graded armorplate is more effective in the control of localized scour than a uniformly graded material because the openings between the larger particle sizes are filled with progressively smaller sizes. This creates the "armorplating" effect, that is the filling of the interstices provides an interlocking of the particles which greatly retards or prevents the upward movement of the finer size bed material. At the same time this interlocking provides shear resistance to the flow of the fluid.

When a jet of flowing water impinges against the armorplate the large size particles break up the jet into smaller jets and the next smaller size particles cause the smaller jets to divide into still smaller jets. With each successive diffusion of the jet there is an increase in the small scale turbulence, which through viscous shear results in the eventual dissipation of the kinetic energy of the impinging jet. Thus, at some thickness of armorplate the jet loses its kinetic energy by this jet diffusion process; however, the pulsating pressure--pressure on the sediment particles varies

in accordance--pressure-velocity relationships varying in the energy equation--associated with this turbulent diffusion tends to draw the smaller size material up into the high velocity flow.

The gradation of armorplate provides two essential elements for control of localized scour; (a) it dissipates erosive energy by creating a large degree of small scale turbulence resulting in energy loss through viscous shear, and (b) it prevents or greatly retards the movement of finer size bed material up into the high velocity flow.

In the analysis of the scour phenomenon it has become evident that the relative motion between sediment particles and the surrounding fluid under various conditions of entrainment, transportation, and deposition appears to depend upon essentially the same factors as those which govern the velocity at which the particles would fall through the fluid under their own weight. Thus, it would seem that the terminal fall velocity of sediment particles represents a sediment characteristic of considerable importance in the control of localized scour by means of armorplate material.

FALL VELOCITY OF SEDIMENTARY PARTICLES

In the design for the control of localized scour the general procedure is to determine the maximum size of riprap on the basis of a velocity equated to terminal velocity of the sediment particle in a freely falling state of motion. This is analogous to the transport of sediment vertically as suspended load. However, in localized scour, sediment is also transported horizontally as bed load. Sediment movement in the horizontal direction is generally analyzed in terms of the velocity causing the beginning of sediment motion. For design purposes it is desirable to determine if there is a relation between the velocity causing the beginning of motion of the sediment particle and its terminal fall velocity. In order to arrive at such a relationship, those factors which govern the terminal fall velocity of a sediment

particle are considered first and, as a basis for the analysis use will be made of the results of studies made to date on these factors.

These studies include those of Rouse (4), who defined quite adequately the fall velocity W_o of spheres in terms of nominal diameter d_n ; those of Krumbein (5) who related the shape factor, s.f., to a sphericity parameter; those of Corey (6), Serr (7), McNown, and Malaika (8) who studied the effect of particle shape on the terminal fall velocity of the sedimentary particle. Albertson (9) made a more generalized study based on the equation

$$\phi_1(C_D, Re, s.f.) = 0 \quad (1)$$

in which C_D is the drag coefficient, Re is the Reynolds number and s.f. is the shape factor. The functional relationship of equation 1 is illustrated on figure 2, (10)

4. "Nomogram for the settling velocity of spheres": National Research Council, Report of the Committee on Sedimentation, by Hunter Rouse, May 1, 1937, Exhibit D, p. 57-64.

5. "Settling-Velocity and Flume-Behavior of Non-Spherical Particles;" by W. C. Krumbein, National Research Council, American Geophysical Union Transactions of 1942.

6. "Influence of shape on the fall velocity of sand grains," by A. T. Corey, thesis presented to the Colorado Agricultural and Mechanical College in Fort Collins, Colorado, in 1949, in partial fulfillment of the requirements for the degree of Master of Science.

7. "A comparison of the sedimentation diameter and the sieve diameter for various types of natural sands," by E. F. Serr, thesis presented to the Colorado Agricultural and Mechanical College in Fort Collins, Colorado, in 1948 in partial fulfillment of the requirements for the degree of Master of Science.

8. "Effects of Particle Shape on Settling Velocity at Low Reynolds Numbers," by John S. McNown and Jamil Malaika. Transactions, American Geophysical Union, Vol. 31, No. 1, February 1950.

9. "Effect of Shape on the Fall Velocity of Gravel Particles," by Maurice L. Albertson, Proceedings of the Fifth Hydraulics Conference, State University of Iowa, Iowa City, Iowa, June 9-11, 1952.

10. "Measurement and Analysis of Sediment Loads in Streams, Some Fundamentals of Particle Size Analysis," IACWR Report No. 12, U.S. Government Printing Office, Washington 25, D.C., 1957.

It is significant that sedimentary materials found in streams and stream deposits which could be used as armorplate, have a shape factor of approximately 0.7. Crushed stones or synthetic riprap also have a shape factor approximating 0.7. In order to extend the fall velocity data for particles into the full range of armorplate usage, it will be necessary to analyze the relationship between fall velocity and particle size and shape for different conditions of flow. And then, by using the results of this analysis, establish a relationship between fall velocity and those forces causing scour.

Consider a falling spherical particle with diameter d_n and density ρ_s falling for a given time t in an infinite pool of water of density ρ_w , dynamic viscosity μ and kinematic viscosity ν . If the fall velocity W is in the range of small Reynolds number Re where Stokes law is valid, the motion of the falling particle^{a/} can be expressed by

$$(M + 1/2 m) \frac{dW}{dt} = (M - m) g - 3\pi\mu d_n W \quad (2)$$

in which

$$M = \frac{\pi}{6} d_n^3 \rho_s$$

$$m = \frac{\pi}{6} d_n^3 \rho_w$$

In equation 2, the terms on the left side of the equation relate to the inertia forces. The first term on the right side of the equation is an expression of the gravity and buoyancy forces. The second term on the right side is the resistance due to viscosity.

Integrating equation 2 with the initial condition that $W = 0$ when $t = 0$ obtain

$$\frac{W}{W_o} = 1 - e^{-\xi t} \quad (3)$$

^{a/} Equation 2 was derived from "Hydrodynamics" by Sir Horace Lamb, Sixth Edition, N. Y.

in which

$$W_o = \frac{1}{18} \left(\frac{\rho_s}{\rho_w} - 1 \right) \frac{g}{\nu} d_n^2 \quad (4)$$

and

$$\xi = \frac{\frac{36 \nu}{d_n^2}}{\left(2 \frac{\rho_s}{\rho_w} + 1 \right)} \quad (5)$$

W_o is the terminal fall velocity and is generally referred to as the fall velocity of the sediment particle.

The equation of motion of a sediment particle derived on the assumption that the flow resistance is proportional to the square of the velocity is given by

$$M \frac{dW}{dt} = (M-m) g - \frac{1}{2} m \frac{dW}{dt} - \frac{1}{8} \rho_w \pi d_n^2 C_D W^2 \quad (6)$$

in which C_D is the so-called drag coefficient.

Integrating equation 6 for the initial conditions that $W = 0$ when $t = 0$ gives

$$\frac{W}{W_o} = \tanh(\xi t) \quad (7)$$

in which

$$W_o = \left\{ \frac{4}{3} \left(\frac{\rho_s}{\rho_w} - 1 \right) \frac{g}{C_D} d_n \right\}^{1/2} \quad (8)$$

and

$$\xi = \frac{\left(\frac{\rho_s}{\rho_w} - 1 \right)}{\left\{ \left(\frac{\rho_s}{\rho_w} + \frac{1}{2} \right) W_o \right\}} \quad (9)$$

As shown by equation 3 and equation 7, the time required to reach the terminal fall velocity is theoretically infinite, but from a practical viewpoint

it is sufficient to consider the time required for the value of W/W_o to become approximately one. If W_o is large, that is to say, if ξ and ζ are small, then the time is large.

Equation 8, a general equation for terminal fall velocity shows that C_D is variable, that is, W_o is determined for different values of C_D only. Furthermore, since C_D is a function of $Re = W_o d_n / \nu$, it is not possible to determine W_o for a given value of d_n or to determine d_n from a given value of W_o .

In order to obtain a single valued relationship between d_n and W_o for armorplate selection of sediment particles having a shape factor approximating 0.7, rewrite equation 8 as

$$W_o^2 = \frac{4}{3} \left(\frac{\rho_s}{\rho_w} - 1 \right) \frac{g d_n}{C_D}$$

and let

$$R^* = \frac{\left(\frac{\rho_s}{\rho_w} - 1 \right)^{1/2} g^{1/2} d_n^{3/2}}{\nu} \quad (10)$$

Substituting equation 10 into the Reynolds number obtain

$$Re = \left(\frac{4}{3} \right)^{1/2} \left(\frac{1}{C_D} \right)^{1/2} R^* \quad (11)$$

Similarly let

$$R_{W_o}^* = \frac{W_o^{3/2}}{\left(\frac{\rho_s}{\rho_w} - 1 \right)^{1/2} g^{1/2} \nu} \quad (12)$$

and by substituting into the Reynolds number obtain

$$Re = \frac{3}{4} C_D (R_{W_o}^*)^2 \quad (13)$$

The effect of viscosity decreases with an increase in Reynolds number; therefore, for conditions of scour which occur at large Reynolds numbers $Re > 2 \times 10^3$ obtain the relationship

$$R^*_w = \left(\frac{4}{3}\right)^{3/4} \left(\frac{1}{C_D}\right)^{3/4} (R^*)^{1/2} \quad (14)$$

Therefore from figure 2 and assumed large Reynolds numbers equation 14 becomes

$$R^*_w = 1.24 (R^*)^{1/2} \quad \text{for s.f.} = 0.7 \text{ and } C_D = 1.0 \quad (15a)$$

$$R^*_w = 0.80 (R^*)^{1/2} \quad \text{for s.f.} = 0.5 \text{ and } C_D = 1.8 \quad (15b)$$

$$R^*_w = 2.38 (R^*)^{1/2} \quad \text{for s.f.} = 1.0 \text{ (spheres) and } C_D = 0.42 \quad (15c)$$

Equation 14 plotted on figure 3, shows that fall velocity is directly proportional to the square root of d_n as C_D approaches some constant value for $Re > 10^3$. The data points on figure 3 were computed from the mean curve of figure 2 for the respective particle shape factors. The fit of the data for $Re > 10^3$ to equations 15 verifies that fall velocity is proportional to square root of d_n .

Substituting equations 10 and 12 into equation 14, and by means of equation 15a, obtain the relation

$$W_o = (1.24)^{2/3} \left(\frac{\rho_s}{\rho_w} - 1\right)^{1/2} g^{1/2} d_n^{1/2} \quad (16)$$

which for the conditions $g = 980 \text{ cm per sec}^2$ and $(\rho_s/\rho_w - 1) = 1.65$ reduces to

$$W_o = 14.7 d_n^{1/2} \quad \text{for s.f.} = 0.7 \quad (17)$$

In a similar manner, but using equation 15b and 15c, respectively, obtain the relations

$$W_o = 10.9 d_n^{1/2} \quad \text{for s.f.} = 0.5 \quad (18)$$

and

$$W_o = 22.7 d_n^{1/2} \quad \text{for spheres} \quad (19)$$

The data of W_o versus d_n and shape factor, $\text{s.f.} = 0.65 < 0.7 < 0.75$ is plotted on figure 4.

Equations 17 and 19 applied to the data of figure 4 shows a good fit of the data to the curves for $d_n > 1 \text{ mm}$. However at large Reynolds number for spheres the drag coefficient abruptly changes due to a sudden shift in the boundary layer and the linear equation is no longer valid. On the other hand, most natural particles and broken stone used for armorplate are not spherical, and this may not be important.

In order to apply the fall velocity of a sediment particle to bank stability protective works, a study was made first of competent velocity, that is, velocity at beginning of sediment motion. Data were obtained from several sources (11, 12, 13) in which one of the objectives of the studies was to obtain a correlation between competent velocity and sediment size. From an analysis of these data, a correlation between fall velocity and velocity for the beginning of motion - incipient scour - will be sought.

11. "The Transportation of Detritus by Flowing Water - I," by F. Theodore Mavis, Chitty Ho, and Yun-Cheng Tu, University of Iowa Studies, Iowa City, Iowa, Bulletin 5, March 1, 1935.

12. "The Transportation of Detritus by Flowing Water - II," by F. T. Mavis, Te-yun Liu, and Edward Soucek, University of Iowa Studies, Iowa City, Iowa, Bulletin 11, September 1, 1937.

13. "Formulas for Bed Transport," by Meyer-Peter and Muller, IASHR 2nd meeting, Stockholm, Sweden, 1943 - p. 32.

Beginning of Motion of a Sediment Particle

INCIPIENT SCOUR

The force necessary for incipient scour of the bed material can be expressed by

$$F_M = C_D \frac{\pi}{4} d_n^2 \rho_w \frac{V^2}{2} \quad (20)$$

in which C_D , d_n , and ρ_w are as previously defined and V is the velocity of flow causing the beginning of motion of the sediment particle.

The force opposing motion is given by

$$F_R = C_1 \frac{\pi}{4} d_n^2 \rho_w \frac{W_o^2}{2} \quad (21)$$

in which C_1 not previously defined is a function related to gradation, compaction and particle shape. When considering the total particle mass instead of the individual sediment particles C_1 is also a measure of the interlocking of the particles.

By assuming for the condition of incipient scour that kinetic viscosity is accounted for in C_1 , C_D and W_o , it is permissible to write

$$F_M = F_R$$

or

$$C_D \frac{\pi}{4} d_n^2 \rho_w \frac{V^2}{2} = C_1 \frac{\pi}{4} d_n^2 \rho_w \frac{W_o^2}{2} \quad (22)$$

and obtain the relationship between V and the nominal diameter

$$V = C_2 \left(\frac{\rho_s}{\rho_w} - 1 \right)^{1/2} d_n^{1/2} \quad (23)$$

in which

$$C_2 = \left[C_1^{1/2} \left(\frac{4}{3} \right)^{1/2} g^{1/2} \right] .$$

In equation 23, V is the velocity causing the particle to move. Also, C_2 has the same limitations that are inherent in defining C_1 adequately. However by assuming the same fluid transport system the velocity for motion becomes a function of the square root of the sediment size and is inversely proportional to the drag coefficient, which in turn involves some of the characteristics assigned to the function C_1 .

The equations for fall velocity were superimposed on the beginning of motion data in figure 5. The equation for spheres results in a very good fit for the beginning of motion data; whereas, the equation of fall velocity for particles of $s.f. = 0.7$ falls below the beginning of motion data for d_n less than 10 mm, but tend to fit for particles with d_n greater than 10 mm. The variation between the fall velocity equations and competent velocity can be attributed to the function C_2 . However, curves for W_o for various shape factors indicated on the graph demonstrate that these equations are applicable for selecting the size of armorplate that will resist scour.

In case of the relation between full velocity and the critical bed shear velocity use is made of the results of the study by Liu (14). In this study, for values of $U^* d_n / \nu > 100$, it was found that bed shear velocity (U^*) was constant and expressed as

$$U^* = 0.13 W_o \quad (24)$$

14. "Mechanics of Sediment Ripple Formation," by H. L. Liu, Paper 1197, ASCE Journal HY 2, Vol. 83, April 1957.

From figure 4, $W_o = 22.7 d_n^{1/2}$, and
by substitution into equation 24,

$$U^* = 0.13 \times 22.7 d_n^{1/2} = 2.94 d_n^{1/2} \quad (25)$$

By assuming that competent bed velocity is a function of the bed shear velocity, a correlation between force and particle size is possible for $U^*/W_o = 0.13$ and $U^* d_n / \nu > 100$, since

$$\frac{U^*}{W_o} = \frac{\left(\frac{\gamma DS}{\rho_w} \right)^{1/2}}{\frac{4}{3} \frac{1}{C_D} \left(\frac{\rho_s}{\rho_w} - 1 \right) g d_n^{1/2}} = 0.13$$

Defining tractive force as $\tau = \gamma DS$ in which γ is unit weight of water, D is depth of flow in feet and S is energy slope. Solving for tractive force results in

$$\tau = 0.0169 \rho_w W_o^2 \quad (26)$$

or

$$\tau = 0.0169 \rho_w \left\{ \frac{4}{3} \frac{1}{C_D} \left(\frac{\rho_s}{\rho_w} - 1 \right) g d_n \right\}$$

and for

$$\left(\frac{\rho_s}{\rho_w} - 1 \right) = 1.65$$

$$\tau = 2.31 \frac{d_n}{C_D} \quad (27)$$

Substituting equation 17, units converted to feet, into equation 26 gives

$$\tau = 0.0169 \rho_w 8.44^2 d_n$$

or

$$\tau = 2.32 d_n \text{ (lbs per ft}^2\text{)} \quad (28)$$

an equation very similar to equation 27 when $C_D \approx 1.0$. It must be pointed out that this condition exists for (1) high particle Reynolds number resulting in near constant drag coefficient and, (2) high bed Reynolds number resulting in near constant relation of bed shear velocity to fall velocity. Also, C_D must be a function of bed resistance to flow and necessarily varies with particle size and other boundary properties of the flow.

The USBR data on figure 6 indicates the influence of gradation on stability. In analysis of these data based on tractive force concept, Lane (15) used the particle size at which 25% was larger. On figure 6 this size analysis would shift the tractive force ordinate upwards indicating that only a small percentage of large size material is necessary to increase the erosion resistance of the bed material. Data based on Lane's tractive force theory tend to lie above the data for the beginning of motion based on uniform size bed material, another indication of gradation influencing the bed stability.

On figure 6 (16) are plotted data for various ranges of hydraulic conditions of stable channels. The channels are considered stable because neither excessive scouring nor silting can be detected in the canal reaches. However most of these canals have appreciable sediment load moving through the system.

15. "Design of Stable Channels," by Emory W. Lane, ASCE Transactions, Vol. 120, 1955, Paper No. 2776, p. 1234.

16. "Theory and Design of Stable Channels in Alluvial Materials," by D. B. Simons, Colorado State University, Fort Collins, Colorado, May 1957, CER No. 57, DBS 17.

Figure 6 illustrates the degree of fit for the various equations on actual stable channel data. The data consist of a wide range of variables including sediment transport. The most important factor of this development is the consistency of all approaches for $d_n > 10$ mm. Because of the consistency in the three approaches in determining sediment size to resist scour, a safer projection can be made to particle sizes greater than 100 mm diameter for armorplate selection.

SUMMARY

The effect of particle gradation increases the effectiveness of an armorplate layer as shown on figure 1. The gradation effect on the beginning of motion studies is difficult to determine in that the first particles to move would be the smaller size particles of the exposed surface. The armorplate could have some particle movement and remain stable for even higher velocities than recorded.

Since there is such good agreement in the large particle sizes among fall velocity, velocity at beginning of sediment motion and tractive force concept it is feasible to extend the relation of fall velocity and sediment size above the range of presented data for armorplate selection. Of course there may be an upper limit on particle size in which the resistant forces are considerably modified and no longer act as interlocking particles but as interlocking structural members of a wall. This hypothesis is partially verified by the present engineering practice for large size hand placed armorplate (riprap). The practice is to reduce the size stone and thickness of the layer for hand placed riprap compared to dumped riprap. Riprap is used here instead of armorplate material because of the definite distinction of size gradation for armorplate compared to normal riprap criteria which usually gives the outer size rock and some filter criteria for bedding.

However for bank stability of canals and many natural streams at bends or near hydraulic structures the selection of proper armorplate and its placement will involve stones of less than two foot diameter and not considered as being hand placed.

For simplicity of armorplate selection figure 4 or figure 6 provides an engineering basis. Rocks of mass density equal to 2.65 can be selected directly from the fall velocity curve for spheres. Under design conditions that require the ultimate in protection, the fall velocity curve for natural particles of s.f. = 0.7 should be used. In cases where the relation of mass density is other than $(\rho_s/\rho_w - 1) = 1.65$. The use of equation 16 provides a ready solution. For example, a change of $(\rho_s/\rho_w - 1)$ to unity would change the fall velocity equation for spheres to $W_o = 11.5 d_n^{1/2}$.

The effect of a change in density also relates to kinematic viscosity. Since kinematic viscosity changes with density, a change in the fluid density by addition of material that remains in suspension such as bentonite would change the kinematic viscosity. This apparent change in kinematic viscosity therefore would change the fall velocity similarly to the mass density change discussed previously. However the total change of kinematic viscosity is not all attributable to density. When a clay or sediment is in suspension there also is the possibility of a chemical change which effects the kinematic viscosity as well. The chemical effects can account for tremendous differences in kinematic viscosity.

Another factor not presented here is the effect of side slope. It is assumed that side slope effects will be handled in a manner similar to Lane's theory for Stable Channel Design.

The armorplate placement can usually be accomplished by dumping from a truck and some form of power equipment for spreading. There are two points of caution in placing armorplate. One, make certain that the

aggregate remains well mixed while dumping and spreading and, two, make certain the armorplate extends beyond the local scour area to prevent undermining of the structure.

Loose armorplate tends to self heal when one part is damaged. The armorplating shifts with the flow jet causing erosion. In some tests by Hallmark a varying discharge shifted the armorplate so that the top layer of larger particles always developed under the greatest jet force. This shifting was rather rapid and where the entire striking zone of the jet was not protected slight additional erosion existed before the bed again became protected. The maximum thickness of armorplate tended to be three times the larger particle size material of the armorplate at the point of jet impingement.

APPLICATION OF RESULTS

One of the problems the designer and practicing engineer faces is the stabilization of the channel bed just downstream of the end sill of a drop or similar structure. As an example, assume a chute drop placed in a canal. Assume for this example the canal as designed will withstand velocities of 1.5 feet per second but that the mean outflow velocity at the end sill is about 6 feet per second. At this velocity the canal bed could be expected to scour and to control scour armorplate is needed. The mean size of armorplate can be selected from either figure 4 or 6 by entering with the mean velocity on the velocity scale and reading the diameter of the mean size material. In this case using figure 6 read $d_n = 0.2$ feet or about 3 inches for material of $(\rho_s / \rho_w - 1) = 1.65$ from the curve $W_o = 22.7 d_n^{1/2}$.

The next step is to determine an approximate gradation and thickness of the armorplate layer. From the studies discussed in this paper it appears

that the maximum particle size necessary is about twice the mean size material. For this problem then the upper size range necessary would be about 6 inches. The minimum size range should be nearly equal to the maximum size of the alluvial bed material. For other than alluvial bed material the smallest size armorplate material should conform to the Terzaghi-Vicksburg filter requirements on minimum size to prevent upward movement of the fine material and graded to the larger size previously determined. Attention to the smaller size selection also is needed when seepage into the canal occurs. As a guide in determining the amount of material, the thickness of the armorplate, as determined from laboratory observations, should be about 3 times the maximum size material. For this example the maximum material is about 6 inches, therefore, the material should be sufficient to cover the expected scour zone to a depth of 18 inches.

CONCLUSIONS

To protect hydraulic structures built in alluvial channels from localized scour, it is important to consider both the type of flow and their characteristics and certain sediment characteristics. Sediment characteristics which are pertinent to the design of the control of localized scour include:

- a. Particle size gradation - armorplate;
- b. Fall velocity of the sediment particle at large Reynolds number as influenced by its nominal diameter and shape; and
- c. The size of particle that will resist incipient scour.

From an analysis of the studies of these characteristics it is evident that:

1. Particle gradation provides two significant functions in local scour control by armorplate. (a) It dissipates erosive energy by creating a large degree of small scale turbulence resulting in energy loss

through viscous shear. (b) Gradation prevents movement of fine materials through the armorplate and this in turn prevents sloughing and undermining of channel banks.

2. Fall velocity is an adequate measure to use in selecting the maximum size material for local scour control. The high degree of similarity of particle fall velocity, velocity at the beginning of sediment motion and critical bed shear velocity provides a method of determining the maximum size of particle that will resist erosions.

3. The mean size particle that will resist motion is given by equation 19 for a shape factor of 0.7.

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APPENDIX - NOTATION

The following symbols are adopted for use in this paper.

- C_D - Particle drag coefficient defined as $\frac{F/d_n^2}{\rho_w W_o^2/2}$
 C_1 - Constant
 C_2 - Constant
 d_n - The diameter of a sphere that has the same volume as the particle (mm)
 D - Depth of flow (ft)
 F_M - Force necessary for incipient scour (gm)
 F_R - Resistance force of bed material to scour (gm)
 g - Acceleration due to gravity (980 cm per sec²)
 m - Mass density of the displaced liquid defined as $\frac{\pi}{6} d_n^3 \rho_w$
 M - Mass density of the sphere defined as $\frac{\pi}{6} d_n^3 \rho_s$
 Re - Reynolds number defined as $\frac{W_o d_n}{\nu}$
 R^* - Dimensionless parameter
 R_w^* - Dimensionless parameter
 S - Slope of energy gradient (ft/ft)
 $s.f.$ - Shape factor of a particle defined by $\sqrt{\frac{c}{ab}}$ in which a is longest axis, b is intermediate axis and c is shortest of the three mutually perpendicular axes of the particle.
 t - Time (sec)
 U^* - Bed shear velocity (cm per sec)
 V - Mean velocity of flow (cm per sec)
 W - Fall velocity of a particle at any time (cm per sec)
 W_o - Terminal fall velocity of a particle (cm per sec)

- γ - Gamma, unit weight of water (lbs/ft³)
- ζ - Zeta, constant
- μ - Mu, dynamic viscosity of the fluid (cm² per sec)
- ν - Nu, kinematic viscosity of the fluid (cm² per sec)
- ξ - Xi, constant
- ρ_s - Rho, mass density of the sediment particle (gm-sec² per cm⁴)
- ρ_w - Rho, mass density of the fluid (gm-sec² per cm⁴)
- τ - Tau, tractive force (lbs/ft²)