MODEL STUDY AND RIPRAP DESIGN FOR

COLUMBIA RIVER

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ABSTRACT

A physical model study was conducted to provide tractive shear values to aid embankment design for protection against large water level changes caused by peaking operations with the Grand Coulee Powerplant extensions. The model design and capabilities are discussed. An embankment design method is described that combines side slope gravity correction with an entrainment function that includes probability of moving. This design method compared favorably with several other design methods.

Introduction. - The purpose of the physical model study was to help determine the effects of hydraulics on stability of rockfill bank armor downstream of the Grand Coulee Third Powerplant extensions.

Some of the natural riverbanks downstream of Grand Coulee Dam are unstable. Wet weather and water drawdown have been suspected as contributing to initiation and aggravation of sliding. The Third Powerplant extension with six units along with the proposed extension of four more units with emergency shutdown during peaking followed by pumping operations can cause changes of water surface elevations up to 39 ft (11.9 m). If both the old and new powerplants are operated at maximum capacity, they will produce a total of about 405 000 ft^3/s (11 500 m^3/s) of downriver flow.

The right and left bank near the dam have been protected by quarried armor placed on slopes from 1-1/2:1 to as steep as 1:1 because of encroachment by private property. About 6 mi (9.7 km) of continuous protective embankment was placed at a 2-1/2:1 slope on the right side of the river starting just downstream of the highway bridge. This embankment was formed of dumped rockfill obtained from excavation for the Third Coulee Forebay and Powerplant. Movement of the placed embankment material has been experienced on the steep slopes near the dam and there has been some sliding on the 2-1/2:1 right embankment further downstream.

General Description of the Model. - The model was built to a scale of 1:120 and was capable of providing individual flow for the spillway, for pairs of outlets, for each of the old powerhouses, and for 10 units of the Third Coulee Powerplant including the proposed extension. In addition to the area just downstream of the dam, the powerplant

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afterbays and about 3.2 mi (5.1 km) of the river downstream of the highway bridge were represented. The bulk of the riverbed was formed with pit run sand with some coarser material added to represent the average of right and left bank material grain analyses provided by project personnel.

Governing Equation for Shear and Flow. - The energy equation for non-uniform flow, including work due to shear on the boundary, can be written as follows:

$$T_o dx/\gamma D = -VdV/g - dD + dh \qquad (1)$$

where T_o is the boundary shear, γ is the specific weight of water, V is velocity, D is the depth of flow, x is distance along the bed in the direction of flow, g is the acceleration of gravity, and h is elevation of the bed. The Darcy-Weisbach friction loss equation was used to define dimensionless tractive shear. This and the other dimensionless variables were defined as:

$$T_{o*} = 8\ T_o/V_c^2\ \rho f$$

$$V_* = V/V_c$$

$$X_* = X/X_c$$

$$D_* = D/X_c$$

$$h_* = h/X_c$$

where an asterisk denotes dimensionless variables, c denotes characteristic values, ρ the density, and f is the Weisbach friction coefficient. Solving for the dimensional variables, substituting them into equation (1) and grouping characteristic variables with constants into terms enclosed in parentheses result in

$$T_{o*}\ dX_*/D_* \cdot (V_c^2\ \rho f X_c/8\ \gamma\ X_c) \quad -V_*\ dX_*\ (V_c^2/g) - dD_*\ (X_c) + dh_*\ (X_c) \qquad (2)$$

Dividing this equation by any one group of variables in parentheses results in, for instance,

$$T_{o*} dx_*/D_* \cdot \left[V_c^2/gX_c\right]\ [f/8] = -V_* dV_* \left[V_c^2/gX_c\right] - dD_* + dh_* \qquad (3)$$

This equation is dimensionless and the terms in the brackets are dimensionless parameters. To apply equation (3) to both the model and prototype, the Froude number, $[V_c^2/gX_c]$, and [f] must be the same for both.

Sediment Scaling and Friction Verification. - The riverbed particle-size distribution was represented by scaling settling velocities according to Froude law. When scaled sediment size is greater than 1.0 mm, the sediment also scales geometrically. When model sediment scales geometrically for larger sizes, including the 90 percent sizes, grain roughness for both the model and prototype are expected to be the

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same. This being the case and if the Reynolds numbers are large enough, model flows and depths should scale.

Friction factor ratios (model to prototype) were computed and from 1 000 000 to 405 000 ft^3/s (28 300 to 11 500 m^3/s), the ratio was 1.00 and increased from 1.02 to 1.06 for 160 000 ft^3/s (4530 m^3/s) and 80 000 ft^3/s (2270 m^3/s), respectively. These friction ratios are the measure of expected model performance in terms of equation (3) because the Froude number is made the same in the model as in the prototype and the friction coefficient is the only remaining dimensionless parameter that needs to be satisfied. However, model friction needs to be verified with actual field and hydrologic data to assure that there are no significant bed form resistance distortions between the model and prototype and to assure that the prototype bed sampling is adequate.

The model was compared with computed water surfaces based on field-verified Manning's "n" values provided by the Sedimentation Section, Water and Power. Model values of water surface elevation agreed to within 3/4 percent of cross section hydraulic radius on the average, and all values were within 2-1/3 percent. Thus, the roughness of the model was considered verified. Since friction was sufficiently reproduced in the model, point velocities, velocity profiles, and secondary flows were expected to scale provided there were no major defects in geometric similitude. Because of the adequate friction scaling, flow shear on the boundary determined from velocity profiles was expected to scale.

Entrainment Scaling. - Gessler (5) modified Shields' entrainment function by adding probability of moving out of a mixture of sediment sizes as a third parameter. For grain Reynolds numbers greater than 400, dimensionless shear becomes constant at a value C_p for any selected probability P of moving and

$$T_p = (\gamma_s - \gamma_w)\, d\, C_p = K_p\, d \qquad (4)$$

where T_p is shear causing movement at probability P, d is diameter of a sediment particle, γ is specific weight, and s and w are subscripts denoting sediment and water. For probabilities of 0.05, 0.5, and 0.85, C_p values are about 0.024, 0.047, and 0.12, respectively. Based on equation (4) for any given probability of moving, the tractive force scale ratio is equal to length ratio. However, Gessler's plot was used to estimate scale effect of grain Reynolds number on shear that moves a particle when scaling from the transition zone for the model to the fully turbulent zone for the prototype. This analysis indicated that shear required to move sediment scales according to the model length ratio only for particles equal to or greater than about 1/4-in (6.4-mm) model or 2.6-ft (0.79-m) prototype for a probability of movement of 0.05.

Although hydraulic shear scales on the flow boundary, the shear required to move a given size particle at a given probability does not necessarily scale. Shear scale effect can be estimated for given probabilities by the Gessler function. However, a modeler cannot

determine the probability of movement of a given particle by simple observation, so it was decided that velocity profiles would be used to determine shear on the boundary. Then Gessler's function would be used to determine what prototype sizes would be expected to move. This approach is further substantiated since nonrandom prototype events of sufficient duration and sediment quantity must be reproduced in a model for verification of time and transport scaling. This requirement is contradictory to the study of bank protection designed not to move under the influence of hydraulic flows.

Results. - Velocity profile data were obtained at 12 different river stations for 6 different discharges. Maximum velocities at 5 ft (1.52 m) above the bed were about 10 ft/s (3 m/s). The maximum tractive force measured in the model was 3.64 lb/ft^2 (174 Pa). Since some of the larger values of tractive forces were found on the side slopes, a method was developed to combine the gravity effects of the side slope with Gessler's relationship.

An approach similar to Carlson (4) for correcting for slope gravity effects was combined with Gessler's entrainment function. The main hypothesis was that the resistance to motion, on the transverse side slope and on the level bottom, is equal to the normal force times the tangent of the angle of repose for the bed material. Taking the ratio of the force on the slope to the force on the level and assuming spherical particles result in

$$T_s/T_l = \cos\phi\,(1 - \tan^2\phi/\tan^2\theta)^{1/2}\,(d_s/d_l) \qquad (5)$$

where T is critical tractive shear, ϕ is the angle of the side slope, θ is the angle of repose, d is the particle diameter, s is a subscript denoting side slope, and l is a subscript denoting on a level surface. Taking this equation, using equation (4) to substitute for T_l, calling the trigonometric function the gravity correction factor K_g, and solving for d_s result in

$$d_s = T_s(1/K_pK_g) \qquad (6)$$

Values of $(1/K_pK_g)$ are given in table 1 for an angle of repose of 42° and specific gravity of 2.65. Table 1 should not be used for particle diameters less than about 3/8 in (10 mm) because of the equation (4) Reynolds number limitation.

Table 1 shows that erosion stability decreases rapidly as slopes become steeper than 2:1. In fact, $1/K_pK_g$ asympotically approaches infinity at the angle of repose of 42° or Z of 1.11 because K_g in equation (6) approaches 0. Table 1 also shows that slopes of 5:1 are essentially flat in terms of bank erosion stability; values of $1/K_pK_g$ are within 5 percent of flat bed values at this slope.

For tractive force values determined with the model or from any other source, values from table 1 or a plot of its data at a selected side slope can be multiplied by tractive force resulting in the riprap size needed to protect the bank.

Table 1. - Values of $(1/K_pK_g)$ for equation (6)
$(1\ lb/ft^2) = 47.88\ Pa)$

Side slope Z	Probability of moving P = 0.05	P = 0.5	P = 0.85
1.11	-	-	∞ -
1.5	4.51	2.36	0.96
1.75	3.75	1.96	0.79
2.0	3.38	1.77	0.73
2.5	3.03	1.58	0.65
3.0	2.86	1.50	0.61
4.0	2.71	1.42	0.59
5.0	2.63	1.38	0.56
Flat	2.52	1.32	0.54

* τ in (Pa) and these values in eq 6 give d in (mm)

Comparisons With Other Riprap Design Methods. - The 6-mi (9.7-km) reach of river downstream of Grand Coulee Dam has been divided into 12 river stabilization areas based on river hydraulics and local geology. The riverbank stabilization areas are outlined in figure 1. In order to prevent erosion of the banks, riprap was chosen by designers as the preferred protection measure because it is independent of complex manufacturing and placing processes, readily available at this location, and relatively inexpensive. Sizing of the riprap has been a recurring problem for designers. Many methods have been developed to calculate a representative riprap rock size or D_{50} for which 50 percent of the material is finer by weight.

A study (1) was completed by the Sedimentation Section, Water and Power, which included backwater curves and data on average velocity and maximum tractive forces computed for each stabilitzation area. A representative riprap size determined by the California Division of Highways method (2) using side slopes ranging from 2:1 to 2.94:1 for each area was also recommended in the study.

Calculations were made using data and the design method from the physical model study and data from the sedimentation study to compare the physical model approach with other design methods by the Water and Power Resources Service (6), Bureau of Public Roads (7), California Division of Highways, Army Corps of Engineers, after Campbell (3) and Simons and Senturk (8). The representative riprap size, D_{50}, determined using each method and a side slope of 2:1 is tabulated according to river stabilization area on table 2.

The Bureau of Public Roads' approach is similar to Water and Power's method. This approach uses an empirical curve developed for relating velocity to the size of stone, and there are additional curves to account for side slope as a variable. Calculated values of D_{50} by these methods are generally lower than by other methods.

The California Division of Highways' study gives expressions and nomographs relating representative rock weight to average velocity, specific gravity, and side slope. With the suggested increase in average velocity computed for bends, values of D_{50} are generally calculated higher than by other methods.

Campbell, working for the Army Corps of Engineers, based his riprap sizing method on cube stability with a trial and error procedure using velocity, bank slope, and specific rock weight to compute representative rock weight. The D_{50} values obtained from this method compared closely with those recommended from the sedimentation degradation study.

Simons and Senturk's method is a refinement of Campbell's method incorporating a safety factor into relations using side slope, velocity, specific weight of rock, and effective rock size. They recommend a safety factory of 1.5 and the method provides the highest calculated D_{50} values.

Conclusions. - In modeling, shear on the boundary can scale but the shear that moves a particular size particle does not necessarily scale. An entrainment function such as Gessler's modification of Shields' function can be used to estimate the diameter of particle and larger that will move similarly. For a frictionally verified model that is directed toward the goal of no bank movement, measuring shear by velocity profile and using an entrainment function to determine the size material needed for protection are more expedient. Doing this can save time compared to trying different sizes and trying to determine when model movement is at critical shear.

A design method was developed that combines gravity slope effects with Gessler's entrainment function. This design method and several other embankment design methods are compared in table 2. The new method produced results within the scatter of the other methods. Tractive force values from models or field measurement can be used with values from table 1 to compute the diameter of protective cover material on any embankment slope. This table is for an angle of repose of 42° and particle diameters greater than about 3/8 in (10 mm). Equation (6) can be used to compute tables or curves for values at other angles of repose.

Acknowledgments. - The success of this study was mainly due to close cooperation and liaison with Water and Power project planning, hydrology, design, geology, and laboratory personnel. P. Julius obtained most of the model data.

Table 2. - Summary of riprap design methods sizing for D_{50} in feet

Q = Design Discharge = 400 000 ft^3/s (11 300 m^3/s)

River stabilization area	2 and 3	4	5	6	7	8 and 9
Average velocity* (ft/s)	10.36	10.36	9.77	9.2	9.2	11.3
Tractive shear* (lb/ft^2)	1.70	1.70	1.30	1.86	1.86	2.09
Tractive shear** (lb/ft^2)	1.16	2.08	0.82	0.82	3.64	-
Largest τ of above used for designs below						
D_{50} sizes (ft):						
Physical model study	0.9 ~~1.3~~	1.1	0.7	1.0 ~~1.3~~	1.9	1.09 ~~1.0~~
USBR Monograph 25 (Based on $V_b = 0.7 V_m$)	0.8 ~~1.0~~	0.8 ~~1.3~~	0.7	0.6 ~~1.0~~	0.6 ~~1.4~~	1.0 ~~0.9~~
Bureau of Public Roads	0.6	0.6 ~~0.9~~	0.5 ~~0.6~~	0.5 ~~0.7~~	0.5 ~~1.0~~	0.7
California Division of Highways	2.1	2.1	1.9	1.7	1.7	2.5
Army Corps after Campbell	1.6	1.6	1.4	1.4	1.4	1.8
Simons and Senturk	2.3 ~~2.8~~	2.3 ~~2.8~~	1.8	2.5	2.5	2.8
Sedimentation degradation study	1.6	1.6	1.5	1.3	1.3	2.0

Velocity in ft/s
Tractive force in lb/ft^2

1 ft = 0.305 m
1 ft/s = 0.305 m/s
1 lb/ft^2 = 47.88 Pa

* Values from degradation study.
** Values from physical model study.

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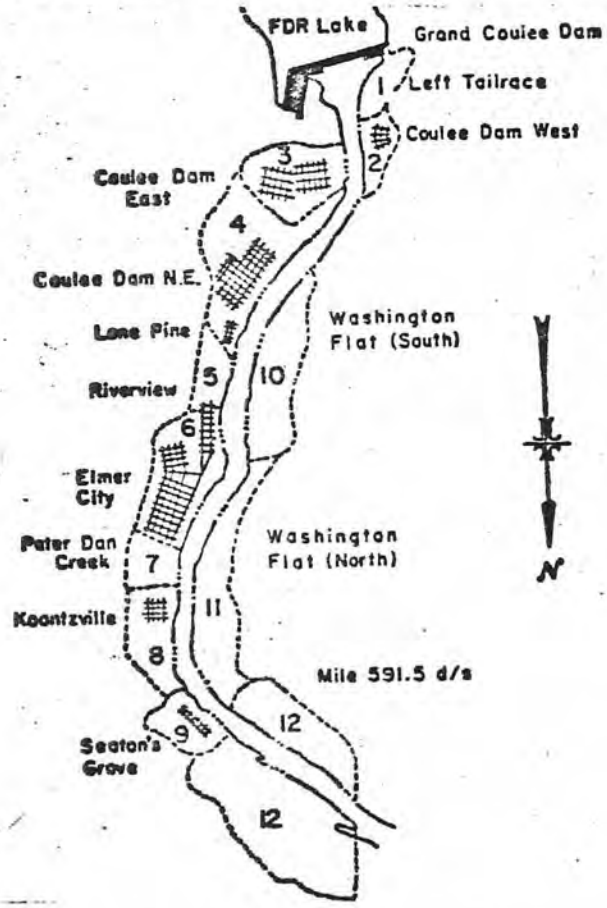

Figure 1. - Riverbank stabilization areas downstream from Grand Coulee Dam.

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