SIMULATING ROUGHNESS OF MESQUITE IN SCALE MODELS

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Abstract

In 1984, the USBR (U. S. Bureau of Reclamation) proposed modification of the Twin Buttes Dam with the placement of a fuse plug embankment to control the flow through an auxiliary spillway. A model study of the fuse plug spillway and approach channel was conducted to estimate discharge capacity of the fuse plug spillway. Mesquite trees covered much of the approach channel to the fuse plug embankment.

Since the design flood had never occurred in the approach channel and published data for the friction of mesquite could not be found in the literature, a study of the friction losses was conducted by using scale models of the mesquite trees in the laboratory. The 1 to 30 scale trees were tested in the laboratory's tilting flume to determine frictional resistance and equivalent sand grain roughness of the mesquite trees. The momentum equation was applied between two measuring stations to obtain the shear stress. After the shear stress was determined, the friction factor was calculated from the Darcy-Weisbach equation. The equivalent roughness was computed by solving the Colebrook-White equation. These equations were incorporated into a computer program.

The mesquite trees were then scaled down to the Twin Buttes hydraulic model scale of 1 to 150. Carpet was used to simulate the proper roughness in the 1 to 150 hydraulic model, and the discharge capacity of the fuse plug spillway was determined.

Introduction

In 1984, the USBR studied the safety of the Twin Buttes Dam in Texas. Twin Buttes Dam and Reservoir are located

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6 miles southwest of San Angelo, Texas, and control flow in South and Middle Concho Rivers, figure 1.

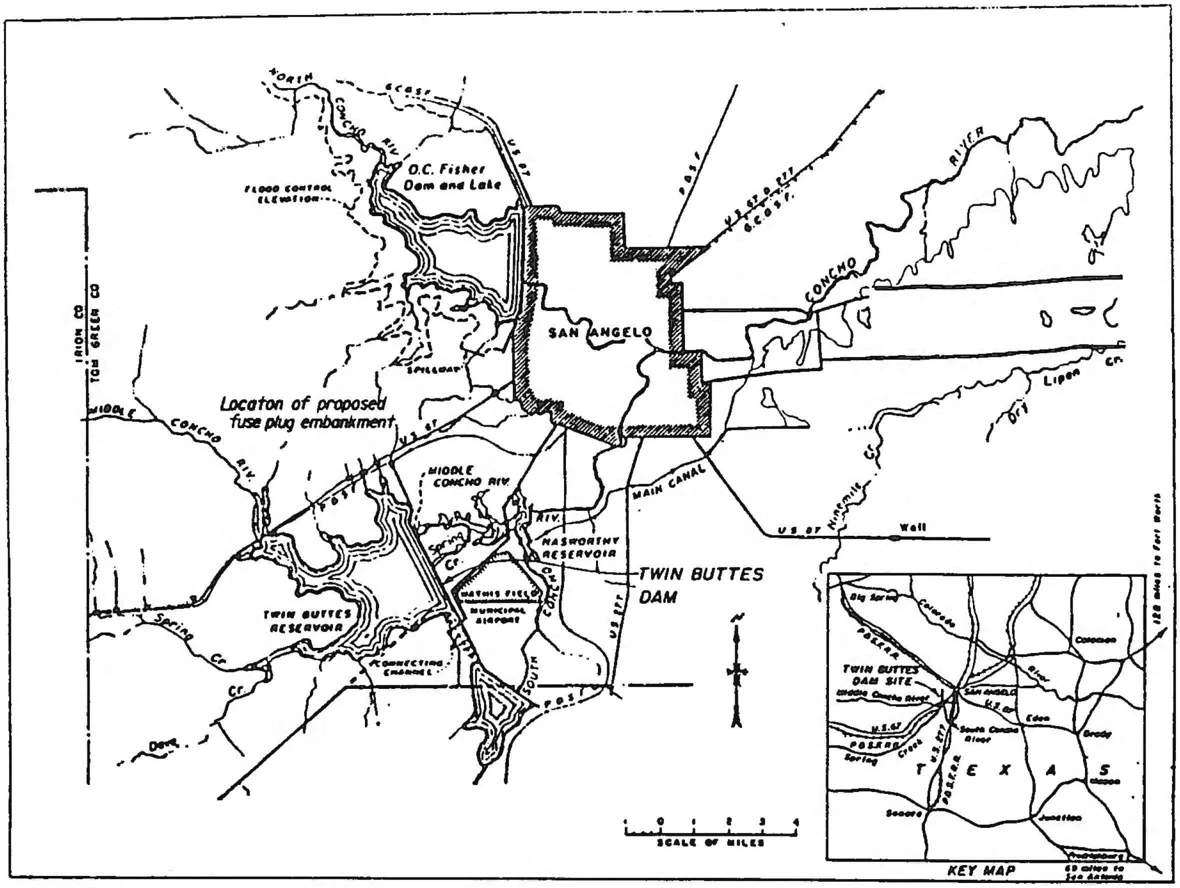

Figure 1. - Vicinity map.

Flood routings indicated that the existing spillway and outlet works could only pass 44 percent of the PMF (probable maximum flood). However, if the existing left embankment of the dam were replaced with a fuse plug embankment, the PMF could be passed. With this modification, the fuse plug embankment would control flow into an auxiliary spillway. Pilot channels would be used to breach the embankment at selected locations when the reservoir elevation reached some critical value.

A study, using a 1 to 150 undistorted scale model, was conducted to evaluate the discharge that could be passed through the fuse plug spillway [Klumpp, 1988]. The flow was restricted somewhat due to mesquite trees which grow in the long approach channel to the fuse plug. The mesquite trees, located in the reservoir area, are 6 to 8 feet high and vary in density up to nine trees per 10,000 square feet.

Prototype friction data were not available for mesquite trees located in the spillway approach channel. Therefore, a unique procedure was developed to estimate the roughness of the mesquite in the scale model. The mesquite trees were simulated, using 1 to 30 scale plastic trees, to develop the roughness data. The study of the mesquite trees was conducted in the laboratory's tilting flume.

Scaling the Mesquite

An environmental specialist from the USBR Southwest Regional Office conducted a vegetative survey to determine the average height, density, and type of vegetation located in the model study area. All shrubs, trees, and ground cover were sampled in 190-foot-diameter sample areas. The average tree or shrub height and canopy diameter were recorded. These data were classified into four vegetation types. Vegetation type IA, mesquite-brush-lowlands, contains an average of 12 mesquite trees per sample plot with an average height of 5.5 feet. Vegetation type IB, mesquite-brush-lowlands, contains an average of 26 trees per sample plot having an average height of 6.8 feet. Upstream of the fuse plug embankment vegetation types IA and IB, figure 2, were predominant. Vegetation types II, IIA, and IIIB and IV were of insignificant height and density relative to this study. Therefore, only the frictional resistance of mesquite trees located in areas IA and IB were studied in the laboratory tilting flume.

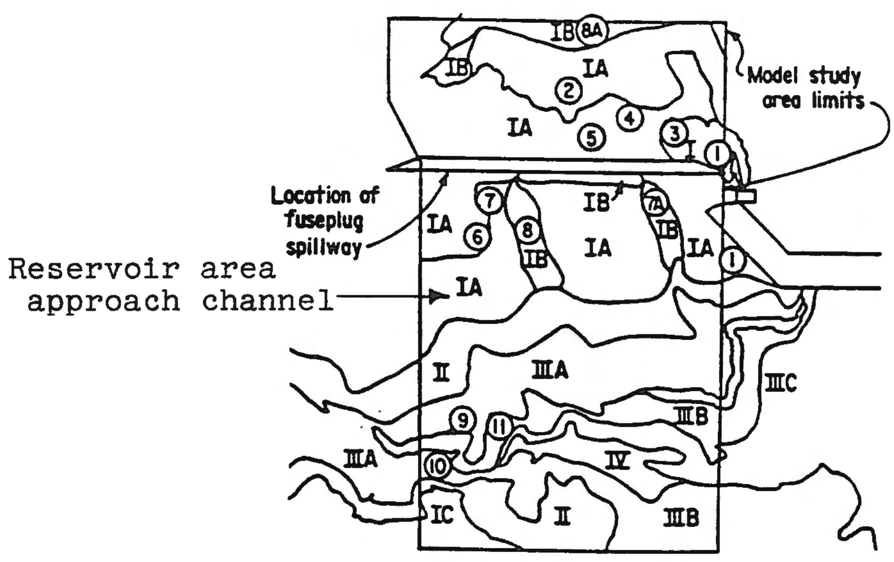

Figure 2. - Vegetation map.

The tilting flume facility, used to study the frictional resistance of the mesquite trees (fig. 3) was 3 feet wide and 60 feet long. Five point gauges were used in the flume to measure water surface elevations. The first gauge was placed 40 feet from the entrance to the flume. Plastic trees that were similar in texture to the mesquite were placed at random locations in the tilting flume facility by using X-Y coordinates generated by a random number program. Mesquite trees were scaled based on an average height, canopy, and density. Plastic trees were studied in the flume at two different densities typical of vegetative types IA and IB. These 2-inch trees represented full scale trees at 1 to 30 (fig. 4). Then, patches of outdoor carpet were tested in the tilting flume to determine the proper arrangement in order to simulate the correct frictional loss in the hydraulic model of the fuse plug (fig. 5). Further discussions on these tests are presented in the Application of Study to the Fuse Plug Model.

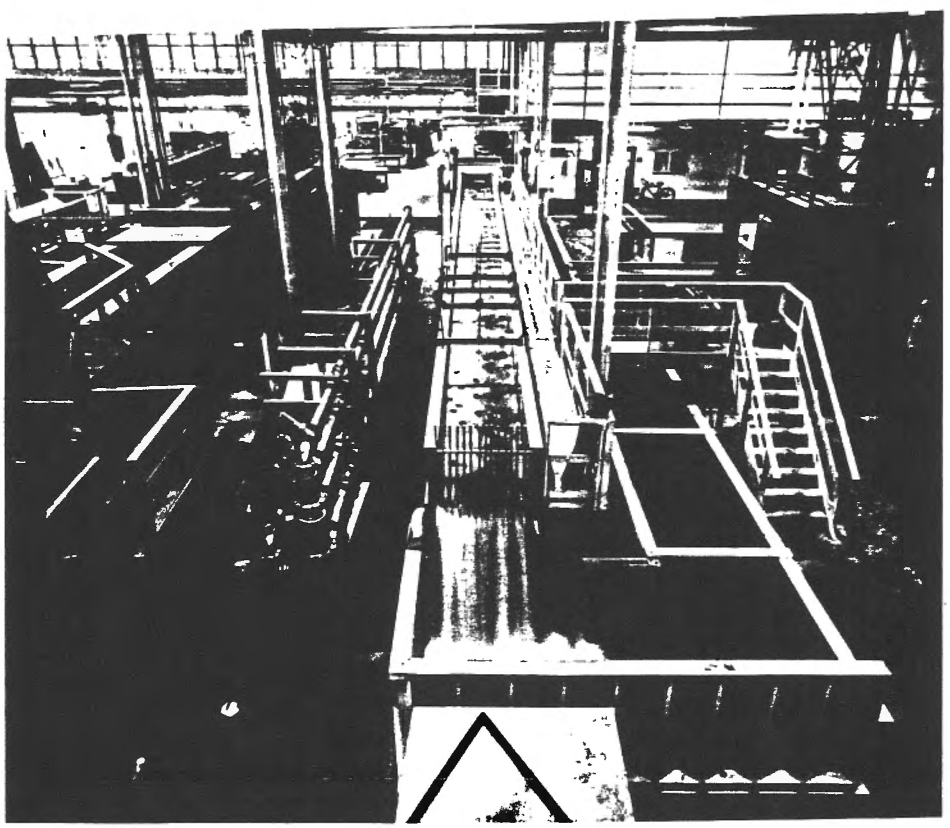

Figure 3. - Tilting flume facility.

Figure 4. - Testing plastic trees in the tilting flume facility.

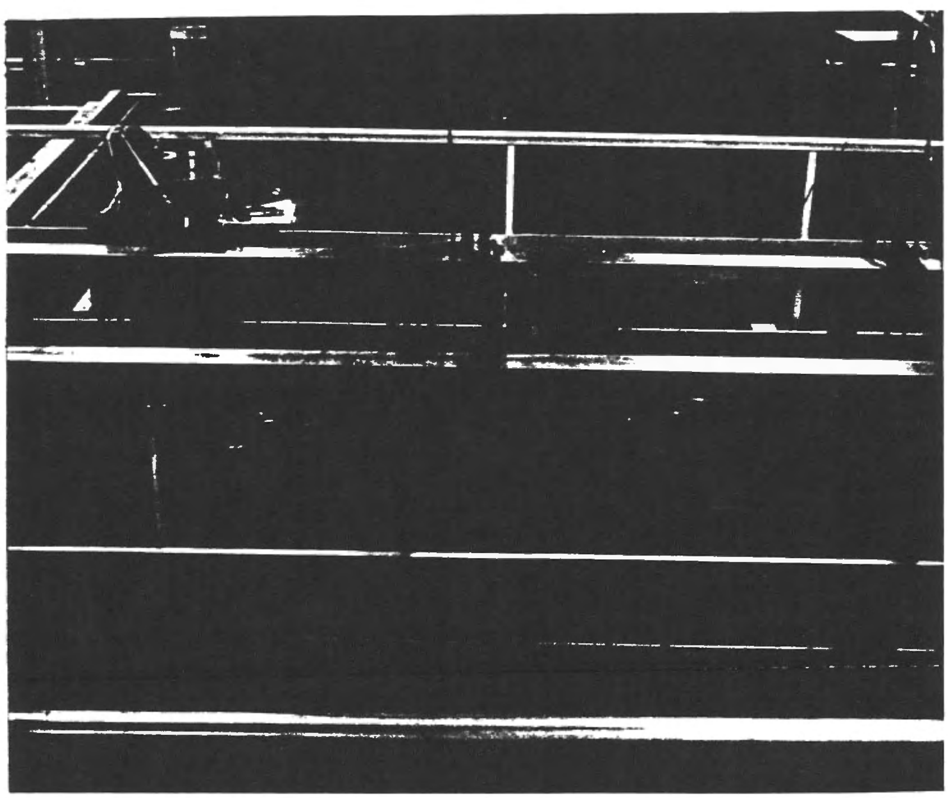

Figure 5. - Carpet used to simulate mesquite trees at 1 to 150 scale.

Surface Roughness Estimation

Two basic approaches were considered for estimating surface roughness:

1. An energy balance could be written between two point gauges solving for the energy loss. The Darcy-Weisbach equation is used to obtain the friction factor, f. The equivalent sand grain roughness, k_s, is determined using the Colebrook-White equation. In this case, the characteristic length is the hydraulic radius of the cross section.

2. The momentum equation could be solved between two locations to obtain shear stress, τ_b. The friction factor could then be computed from its relationship to τ_b in the Darcy-Weisbach equation. The Colebrook-White equation would then be used to solve for k_s.

Both methods were studied; it was found that the momentum method using shear stress gave the most consistent results.

The energy method for computing friction slope and f is based on the assumption of uniform flow. This condition was violated in the large hydraulic model because bottom slope and depth vary quite rapidly in some areas.

Writing the momentum equation between two point gauges, figure 6, and solving for the bottom shear τ_b results in the following equation:

$$\tau_b = \gamma \left(\frac{D_1+D_2}{2} \right) \sin\alpha + \frac{\gamma}{(B_1+B_2)\,\Delta X}$$

$$(B_1 D_1^2 \cos\alpha - B_2 D_2^2 \cos\alpha) + \frac{\gamma}{4}(B_2-B_1)(D_1+D_2)^2 \tag{1}$$

$$\frac{1}{(B_1+B_2)\,\Delta X} - 2\tau_w \left(\frac{D_1+D_2}{B_1+B_2} \right) \cos\left(\frac{\alpha-\theta}{2} \right)$$

$$- \frac{2\rho Q}{(B_1+B_2)\,\Delta X} \left[V_2 \cos\left(\frac{\alpha-\theta}{2} \right) - V_1 \cos\left(\frac{\alpha-\theta}{2} \right) \right]$$

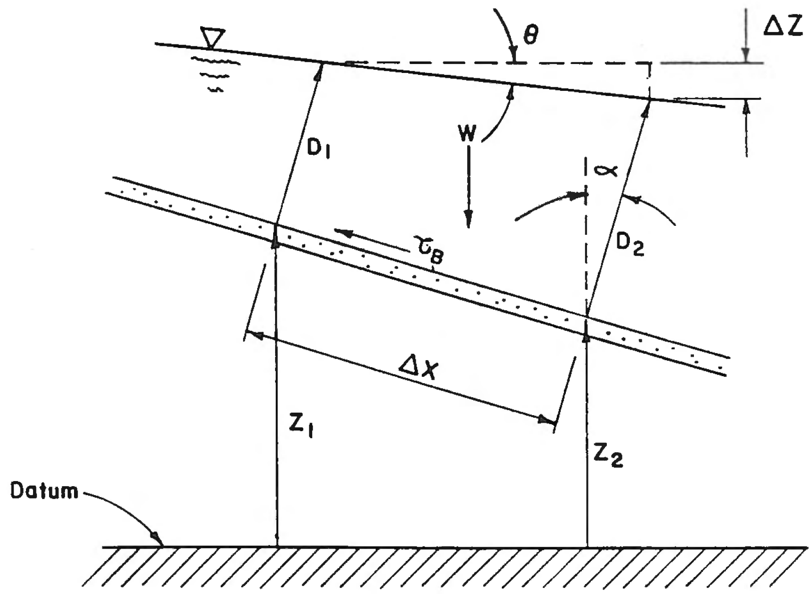

Figure 6. - Momentum balance diagram.

Wall shear is estimated from the equation for flow over a smooth flat plate [Schlichting, 1968]. Averaging over the section, the wall shear is defined by:

$$\tau_w = 0.0148\, \rho\, \nu^{0.2} \left(\frac{V_1^{1.8}}{X_1^{0.2}} \right) + \frac{V_2^{1.8}}{X_2^{0.2}} \tag{2}$$

After the bottom shear τ_b is known then the average Darcy-Weisbach friction factor, f, over the test length can be calculated [Rouse, 1946] from:

$$\tau_b = \frac{f\rho}{8} \left(\frac{V_1^2 + V_2^2}{2} \right) \tag{3}$$

Finally, the surface roughness, k_s, can be computed by applying the Colebrook-White equation according to [Henderson, 1966]:

$$\frac{1}{\sqrt{f}} = 1.56 - 2 \log \left[\frac{k_s}{D} + \frac{15}{R_e \sqrt{f}} \right]$$

and (4)

$$R_e = \frac{VD}{\nu}$$

Plastic trees were placed in the tilting flume to simulate mesquite trees at the 1 to 30 scale. Two different densities of mesquite were tested in the flume corresponding to vegetation types IA an IB. By testing in the tilting flume, it was possible to obtain a wider range of Reynolds numbers, velocities, and depths.

Slopes ranging between 0.3 and 4 percent and discharges ranging between 3 and 11 ft^3/s were utilized for testing the plastic trees. Slight changes in slope along the flume were measured by using a surveying level to determine the elevations at each point gauge and the end points of the flume. Investigations were conducted for both supercritical and subcritical flows.

Depths were measured in the flume with point gauges attached to a wave probability probe at four locations 40 feet downstream of the inlet to the flume. The water surface elevation data were smoothed with a linear regression of the measured data prior to computing f and k_s.

The friction factor, f, varied between 0.074 and 0.181, and the equivalent sand grain roughness, k_s, varied between 0.057 and 0.210 foot. The average sand grain roughness, k_s, for the plastic trees simulating the IB vegetation type was 0.115 foot. The equivalent sand grain roughness of the mesquite in the fuse plug model is then one-fifth of this value or 0.023 foot.

Application of Study to the Fuse Plug Model

A large model of the Twin Buttes Dam and Reservoir area was constructed in the laboratory at an undistorted scale of 1 to 150.

The average equivalent sand grain roughness of the concrete surface was first determined to verify that the model was not already rough enough without having to add an additional roughness element to simulate the mesquite.

Water surface elevations were obtained at ten point gauges located within a temporary 3-foot-wide flume placed inside the fuse plug model. These data were analyzed using the momentum method described above and used to determine the "as-built" frictional characteristics of the concrete surface. It was determined that the roughness of the concrete surface was 0.001 foot which is not rough enough to simulate the mesquite trees. Therefore, it was necessary to add additional roughness elements.

Outdoor carpeting with a coarse texture was selected to simulate the mesquite in the fuse plug model. The height of the carpet nap was 1/3 inch, which is close to one-fifth the height of the plastic trees. The carpet was cut into small rectangular pieces and placed in the tilting flume at the same density as vegetation type IB. The tilting flume was operated at different discharges and slopes to verify that the roughness of the carpet would be close to a k_s value of 0.02 foot. Results of testing provided a friction factor that varied between 0.023 and 0.062, and equivalent sand grain roughness that varied between 0.002 and 0.073 foot, averaging 0.021 foot.

After testing the tilting flume, patches of carpet were placed in the fuse plug model. Where vegetation type IA existed, the carpet squares were cut to one-half the original size because vegetation type IA contains about one-half the number of mesquite of vegetation type IB.

The fuse plug model was tested at several discharges with and without the simulated mesquite to obtain a discharge-rating curve (fig. 7). The simulated mesquite reduced the discharge through the fuse plug spillway by approximately 6 percent for discharges exceeding 1 million ft^3/s (fig. 8).

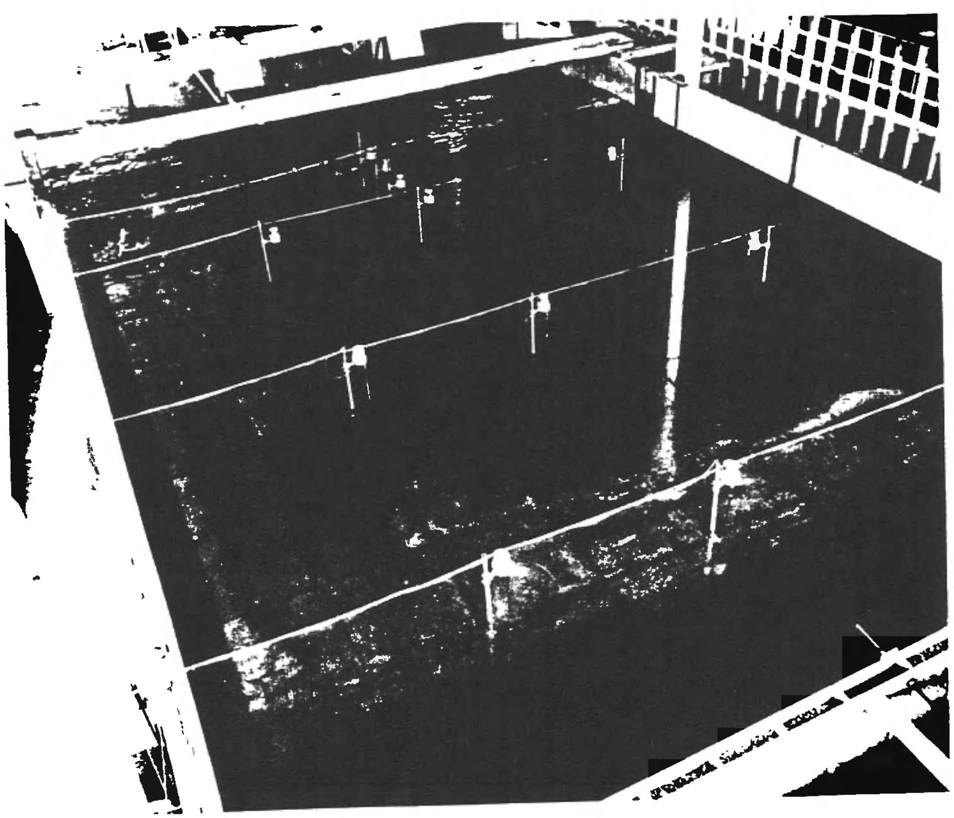

Figure 7. - Testing in the fuse plug model with simulated mesquite.

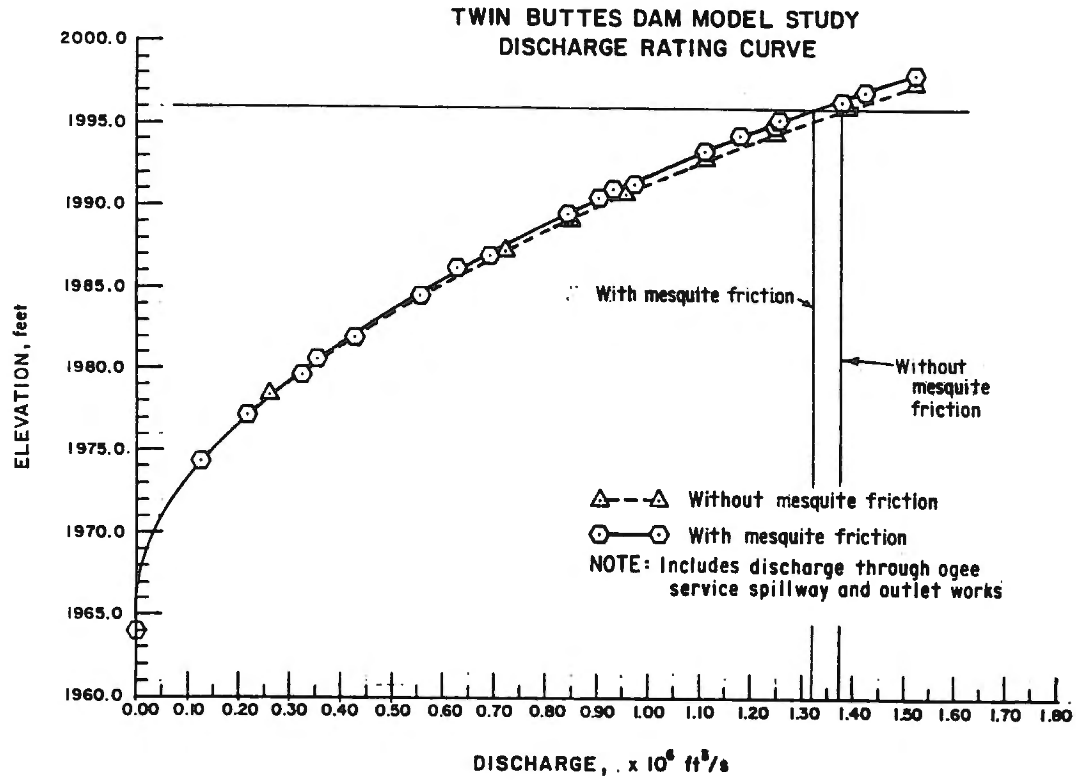

Figure 8. - Twin Buttes Dam fuse plug spillway rating curve.

Conclusions

1. A unique procedure was developed to determine equivalent sand grain roughness for vegetation in a shallow flow condition. Good results were obtained in using the 1 to 30 scale model to develop roughness data to be used in the 1 to 150 scale model of the entire fuse plug spillway approach channel.

2. For the Twin Buttes fuse plug spillway study the design discharge was reduced by 6 percent by adding roughness elements, simulating mesquite trees in the approach channel.

Appendix 1 - References

1. Bureau of Reclamation, Appraisal Design Summary Evaluation of Alternatives, Safety of Dams Modification, Twin Buttes Dam, San Angelo Project, Texas, Denver, Colorado, October 1984.

2. Henderson, F. M., Open Channel Flow, The Maxmillan Company, New York, New York, 1966, p. 95.

3. Hunter, Rouse, Elementary Mechanics of Fluid, John Wiley and Sons, New York, New York, 1946, p. 201.

4. Klumpp, Cassie C., "Hydraulic Model Study of Twin Buttes Dam Fuse Plug Spillway," REC-ERC-88-02, Bureau of Reclamation, May 1988.

5. Schlichting, Hermann, Boundary Layer Theory, McGraw-Hill, Inc., New York, New York, 1968, pp. 597-601.

Appendix 2 - Glossary

B_1 width of flume at location 1
B_2 width of flume at location 2
D_1 depth at location 1 measured perpendicular to flume bottom
D_2 depth at location 2 measured perpendicular to flume bottom
f friction factor
k_s equivalent sand grain roughness
Log logarithm (base 10)
Q discharge
R_e Reynolds number
V_1 mean velocity at location 1
V_2 mean velocity at location 2
X_1 distance from boundary at location 1
X_2 distance from boundary at location 2

α slope of channel bottom with respect to a horizontal plane
γ unit weight of water
θ slope of water surface with respect to a horizontal plane
ν kinematic viscosity
ρ density of water
τ_b bottom shear stress
τ_w wall shear stress

Appendix 3 - Conversions

1 ft = 0.3048 meter   1 ft^3/s = 0.02831 m^3/s