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HYDRAULIC MODEL STUDY OF TWIN BUTTES DAM FUSE PLUG SPILLWAY

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16. ABSTRACT

A 1 to 150 scale hydraulic model study of the proposed fuse plug embankment at Twin Buttes Dam in San Angelo, Texas was performed to investigate the discharge capacity of the fuse plug spillway. A secondary consideration was the effect of the mesquite trees located in the long approach channel to the fuse plug spillway. A technique was developed to estimate the equivalent sand grain roughness of the mesquite trees by simulating the trees in a 1 to 30 scale model and performing a momentum balance between two locations. The roughness was then simulated in the 1 to 150 scale hydraulic model, and a discharge rating curve through the fuse plug spillway was completed.

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HYDRAULIC MODEL STUDY OF TWIN BUTTES DAM FUSE PLUG SPILLWAY

by

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May 1988

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Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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The vegetative survey of the area modeled was conducted by J. Rogers of the Southwest Region of the Bureau of Reclamation. Dave Daniels of the Concrete Dams Branch (E&R Center) provided input and consultation during the entire model study.

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GLOSSARY

Letter Symbols and Quantities

A	area
B_1	width of flume at location 1
B_2	width of flume at location 2
C_f	local skin friction coefficient
D	flow depth
D_1	depth at location 1 measured perpendicular to flume bottom
D_2	depth at location 2 measured perpendicular to flume bottom
F	wall force due to changing width of the cross-section
f	friction factor
$\mathbf{F}_r$	Froude number
g	gravitational constant (acceleration)
k_s	equivalent sand grain roughness
L	characteristic length
L_r	length ratio
L_m	a length in the model
L_p	a length in the prototype
Log	logarithm (base 10)
m	subscript used in length *(L)* is model
n	Manning's coefficient
p	subscript used in length *(L)* is prototype
Q	discharge
r	ratio
$\mathbf{R}_e$	Reynolds number
S_f	friction slope
T	time
V	velocity
V_1	mean velocity at location 1
V_2	mean velocity at location 2
V_L	volume
W	body force of the water
X_1	distance from boundary at location 1
X_2	distance from boundary at location 2
ΔX	distance between point gauges

α	alpha, slope of channel bottom with respect to a horizontal plane
β_1 and β_2	beta, momentum correction coefficients to account for nonuniform distribution of velocities and momentum over a channel section
γ	gamma, unit weight of water
θ	theta, slope of water surface with respect to a horizontal plane
Φ	phi, as a function of
ν	nu, kinematic viscosity
ρ	rho, density of water
τ_b	tau, bottom shear stress
τ_w	tau, wall shear stress

PURPOSE

In 1984, the Concrete Dams, Spillways and Outlets Section completed an appraisal design summary evaluating alternatives for conveying a revised PMF (Probable Maximum Flood) under the Safety of Dams modification program [1]. The PMF alternatives considered in the report were:

1. Raise the existing dam crest
2. Breach the existing dam
3. Fuse plug spillway and raise the existing dam crest
4. Auxiliary spillway and raise the existing dam crest

The costs of each of these design alternatives were evaluated in the summary [1]. The fuse plug spillway and raising the existing dam crest was chosen to be the least costly alternative.

A fuse plug is a zoned earth and rockfill embankment, designed to wash out in a predicted and controlled manner when the normal capacity of the service spillway and the outlet works is exceeded.

The fuse plug embankment would replace the existing left embankment (maximum height is 27 feet 8.2 meters) which lies north of the spillway (fig. 1). The fuse plug embankment, as described [1] in the appraisal design study, would be about 4,500 feet (1372 m) long and have a crest width of 30-feet (9.1 m) and crest elevation of 1991 (606.9 m).[1] The fuse plug spillway would begin to discharge when the reservoir elevation exceeds elevation 1985.0 (605 m) by using pilot channels to breach the embankment at selected locations.

The existing main embankment would be raised 5 feet to elevation 1996.5 (1.5 m to 608.5 m) – based on flood routings performed for the appraisal design study. Flood routings performed in the appraisal design study were based on a fuse plug embankment lateral erosion rate of 800 feet (244 m) per hour (0.0677 m/s).

A model study was proposed to evaluate the rate of discharge that could be passed through the fuse plug spillway and to account for the friction losses that would occur because of the long approach channel to the fuse plug spillway. A secondary consideration was the effect of mesquite trees located in the reservoir area that average 6 to 8 feet (1.8 to 2.4 m) high and vary in density up to 26 trees per 190 feet (58 m) diameter circular plot. Mesquite trees would increase the roughness and cause an increase in the water surface elevation in the approach to the fuse plug spillway thus reducing the discharge capacity.

[1] All elevations are in feet above sea level.

INTRODUCTION

The San Angelo Project is located near the city of San Angelo in west-central Texas. One of the main features of the project is Twin Buttes Dam and Reservoir. In addition, O.C. Fisher Dam and Lake, and Lake Nasworthy provide municipal water requirements, irrigation and flood protection (fig. 1).

Twin Buttes Dam, located 6 miles (10 km) southwest of San Angelo, Texas, controls flow in the South and the Middle Concho Rivers and Spring Creek.

Twin Buttes Dam is a 134-foot-high (40.8 m) earthfill dam with a crest width of 30 feet (9.1 m) and a crest length of over 8 miles (12.9 kilometers). The outlet works of the dam is located near the left abutment and includes an approach channel, a concrete intake structure and a 3-barrel concrete conduit. The spillway structure (near the left abutment) is an uncontrolled ogee weir 200-feet (61.0 m) wide. A concrete chute section, 320-feet (97.5 m)-long, extends from the spillway crest to a stilling basin. The spillway crest is at elevation 1969.10 (600.2 m) and utilizes the Middle Concho streambed as the outlet channel.

The planned operation, when the dam was built in 1960, included:

- A reservoir with a dead capacity of 8,354 acre-feet (10.3×10^6 m^3).
- A minimum water surface at elevation 1885 (574.5 m).
- An active conservation capacity of 177,849 acre-feet (219 million $\times 10^6$ m^3) with the top of active conservation at elevation 1940.2 (591.4 m).
- The exclusive flood control capacity contained 454,365 acre-feet (560×10^6 m^3).
- The top of the exclusive flood control capacity was set at elevation 1969.1 (600.2 m).
- The surcharge capacity totaled 446,950 acre-feet at a design maximum water surface elevation of 1985 feet (5.52×10^6 m^3 at 605 m).

The outlet works channel and the spillway outlet channel form a common channel 300-feet (91.4 m) wide leading to the Middle Concho River (fig. 2). The spillway was designed for a discharge of 47,300 ft^3/s with the reservoir at the maximum water surface of 1985 feet (1339 m^3/s at 605.0 m). The outlet works was designed for a normal discharge of 25,000 ft^3/s at a water surface elevation of 1940.2 (708 m^3/s at 591.4 m) and a maximum discharge of 35,700 ft^3/s at the maximum water surface elevation of 1985 (1011 m^3/s at 605.0 m).

Originally, Twin Buttes Dam was designed for an inflow design flood of 725,000 ft^3/s and a 3-day volume of 825,000 acre-feet (20530 m^3/s inflow and 1.0 × 10^6 m^3 volume). The inflow design flood was revised in 1982 and 1986 by the Bureau's Flood Section of the Hydrology Branch. A revised probable maximum storm was used to develop a new PMF. The new PMF has a peak inflow of 1,416,000 ft^3/s with an 18-day volume of 1,900,000 acre-feet (40091 m^3/s inflow and 2.342 × 10^6 m^3/s volume). Flood routings indicated that the existing spillway and outlet works could only pass 44 percent of the PMF.

SUMMARY

Twin Buttes Dam is a 134-foot (40.8 m) high earthfill dam with a crest width of 30 feet (9 m), a crest length of over 8 miles (12.9 kilometers), and a crest elevation of 1991 feet (606.9 m). In 1986, the PMF was revised to a peak inflow of 1.416 million ft^3/s and an 18-day volume of 1.9 million acre-feet (40 210 m^3/s peak and 2342 m^3 volume). The existing spillway and outlet works could only convey 44 percent of the PMF.

Several design alternatives were considered to control the PMF. The least expensive alternative was a fuse plug controlled spillway. The fuse plug embankment would replace a dike along the left abutment and woud be about 4,500 feet long (1372 m) with a crest width of 30 feet (9.1 m) and crest elevation of 1991.0 (606.9 m). The fuse plug spillway would begin to discharge at elevation 1985 (605.0 m), when pilot channels would initiate breaching of the fuse plug embankment at selected locations. Preliminary flood routings indicate that a spillway capacity of 1 million ft^3/s (28317 m^3/s) is necessary to pass the probable maximum flood at a maximum water surface of 1993.0 feet (28 317 m^3/s at 607.5 m).

A model study was proposed to determine the flow capacity of the fuse plug spillway. Two main factors considered in the model study were the long approach channel to the fuse plug spillway and the additional friction losses caused by mesquite trees in the reservoir area.

A hydaulic model was constructed to a scale of 1 to 150 that covered 5,000 feet (1524 m) of the upstream approach to the fuse plug and 4,000 feet (1219 m) of the actual fuse plug embankment. Discharge – through the existing ogee service spillway – was measured with a V-notch weir located in a side channel next to the model.

Special techniques were applied to determine the frictional effect of mesquite growing in the fuse plug spillway approach channel. Plastic trees placed in a variable slope rectangular tilting flume (in subsequent references, it will be called a tilting flume) were used to simulate the surface resistance of the mesquite. Mesquite trees were scaled 1 to 30. Then, a pattern of outdoor carpeting was developed in the tilting flume that represented mesquite scaled 1 to 150. The carpet was used in the large hydraulic model of Twin Buttes to simulate prototype mesquite trees.

Plastic trees and outdoor carpet used in the tilting flume were scaled based on a vegetative survey that indicated tree height and density for all the vegetation in the fuse plug study area. Trees and carpet were placed in the flume at the density and average height determined in the field survey for area plots IA and IB. Vegetative type IA, mesquite-brush-uplands, contains an average of 12 mesquite trees per sample plot; vegetative type 1B, mesquite-brush-lowlands, contains an average of 26 trees per sample plot (See table 1). The surface resistance of concrete, plastic trees, and outdoor carpeting was determined by applying the momentum equation between two measurement locations and solving for the shear stress τ_b. Once τ_b was known, the friction factor, f, was calculated from the Darcy-Weisbach equation. The equivalent sand grain roughness k_s was then computed by knowing f and solving the Colebrook-White equation. Equivalent sand grain roughness, k_s, relates the hydraulic losses to the surface type. The equations used to solve for these parameters are given in Appendix A: FCALCULATE.

Model testing and results were divided into two categories: 1) determination of surface resistance of mesquite trees, and 2) determination of discharge rating curves and flow patterns.

The equivalent sand grain roughness of concrete in the large hydraulic model flume tests was 0.001 feet (0.305 mm). The equivalent sand grain roughness of the 1 to 30 scale plastic trees averaged 0.115 feet (35 mm) corresponding to the more dense mesquite vegetation area IB. The outdoor carpet was placed in the tilting flume at the same density as mesquite vegetative type IB. Consequently, the equivalent sand grain roughness of the outdoor carpet (simulating the mesquite at a 1 to 150 scale) should have been one-fifth of the equivalent sand grain roughness of the plastic trees. The equivalent sand grain roughness of the outdoor carpet varied between 0.002 and 0.073 feet (0.6 mm and 22 mm) – averaging 0.021 feet (6.4 mm). This value is close to one-fifth the equivalent sand grain roughness determined for the plastic trees – 0.023 feet (7.0 mm). The carpet then was placed in the large hydraulic model in vegetation areas IA and IB to simulate mesquite friction. The carpet for area IA was cut into rectangular pieces that were one-half the size of those in area IB, because the mesquite trees density was about one-half the density in area IB.

Table 1. – Twin Buttes Dam vegetative survey in the fuse plug model area.

Vegetative type	Description†
IA Mesquite-brush-uplands	Average of 12 mesquite trees having an average height of 5.5 feet. Maximum tree height recorded was 15 feet.
IB Mesquite-brush-lowlands	Average of 26 mesquite trees per sample plot having an average height of 6.8 feet.
IC Mesquite-brush-cleared park area	All underbrush has been cleared. Average of 1 to 2 trees per sample plot having heights of 15 to 18 feet.
ID Mesquite-brushland-slopes	Steep rocky areas with junipers averaging 8 feet high scattered throughout the slope. Mesquite trees average 7 trees per site having an average height of 4.7 feet.
II Saltcedar transition	This area includes mesquite, salt cedar, grasses and annuals. Average of 4 mesquite trees having an average height of 5 feet. Saltcedars were less than 2 per square meter and averaging 4 feet high.
III Saltcedar	
A–Class I	This area included an average of 27 stems per square meter less than 4 feet in height.
B–Class II	This area included an average of 30 stems per square meter ranging from 4 to 5 feet high.
C–Class III	Narrow band of saltcedars averaging 7 feet in height. Some 12-foot trees were common.
IV Annuals	This area includes a mixture of saltcedars and annuals. Plants and saltcedars average 4 feet with about 20 plants per square meter.

† These vegetative types correspond to the vegetative map on figure 10.

The model was tested at several discharges to obtain a discharge rating curve (without mesquite friction) before placing the outdoor carpet. Tests were repeated after the carpet was installed. Tests revealed the effect of mesquite on the fuse plug discharge was negligible below 500,000 ft^3/s (14158 m^3/s). As flow increased, the effect was more pronounced. At reservoir elevation 1996 (608.4 m), the mesquite reduces the discharge by about 4.5 percent 60,000 ft^3/s from 1.37 to 1.31 million ft^3/s, (1699 from 38794 to 37095 m^3/s). Discharges at elevation 1985 feet (605.0 m) include a spillway discharge of 47,300 ft^3/s, and an outlet works discharge of 35,700 ft^3/s, for a combined total of 83,000 ft^3/s (1339 m^3/s +1011 m^3/s = 2350 m^3/s). At elevation 1996, combined spillway and outlet works flow would be 105,000 ft^3/s (2970 m^3/s at 608.4 m). Water surface profile data were recorded during the discharge rating tests. Water surface elevations were obtained from wave probes located throughout the model and from a point gauge that was used near the fuseplug centerline. These data were taken for discharges ranging between 71,100 ft^3/s and 1.4 million ft^3/s (2015 and 39645 m^3/s).

To provide designers data for flood routings, current meter measurements were made along the fuse plug section to obtain the distribution of flow across the fuse plug. Current meter data were obtained before installing the simulated mesquite friction and after the mesquite friction was added to the model.

CONCLUSIONS

The following conclusions are drawn from Twin Buttes Dam model investigation.

1. Fuse plug spillway capacity is 1.37 million ft^3/s (38 794 m^3/s) without mesquite friction, at elevation 1996 feet (608.4 m). This includes 105,000 ft^3/s (2970 m^3/s) through the existing ogee service spillway and the outlet works. Fuse plug capacity with mesquite friction is 1.31 million ft^3/s (37 095 m^3/s) including the existing service spillway and outlet works (fig. 19).

2. Equivalent sand grain roughness of the hydraulic model without the addition of mesquite friction is approximately 0.001 feet (0.305 mm).

3. Because field data could not be found for friction of mesquite trees, a 1 to 30 scale model of mesquite trees was used in a tilting flume to test for the friction factor and the average equivalent sand grain roughness of mesquite. Average value for the equivalent sand grain roughness of the simulated mesquite was 0.115 feet (35 mm).

4. Outdoor carpet was used to simulate the mesquite scaled 1 to 150 in the hydraulic model. Average equivalent sand grain roughness of the carpet was 0.021 feet (6.4 mm) – close to one-fifth the average value for the equivalent sand grain roughness of the simulated mesquite in the 1 to 30 scale model.

APPLICATIONS

A unique procedure was developed to estimate the roughness of the mesquite in the 1 to 150 scale model. Prototype friction data were not available for mesquite trees located in the spillway approach channel. Consequently, mesquite trees were simulated using plastic trees at a 1 to 30 scale to develop roughness data. The equivalent sand grain roughness of mesquite was computed by solving the momentum equation to obtain shear stress, and then using the Darcy-Weisbach and Colebrook-White equations. These equations were incorporated into a computer program (FALCULATE). The computer program equations are general enough that they can be applied to similar situations. Using scale models of roughness elements may be possible in future hydraulic model studies, where prototype water surface elevation data are inadequate.

THE MODEL

Hydraulic Similitude

To investigate flow conditions with a model, hydraulic similitude must exist between model and prototype. The primary forces that influence hydraulic flow conditions are gravity, viscosity, pressure, surface tension and elasticity. The inertial force is the vector sum of all forces. When gravitational forces predominate, which is the case with most open hydraulic structures, a basis for similitude can be established by equating the ratio of gravitational forces to inertial forces and neglect the other forces. Flow in Twin Buttes Dam model was simulated by using the dimensionless Froude number that relates inertial force to gravity force.

$$\mathbf{F}_r = \frac{V}{\sqrt{Lg}} \tag{1}$$

Using the Froude number, model and prototype parameters can be determined from the following similitude equations.

$$L_r = \frac{L_m}{L_p} \tag{2}$$

$$A_m = L_r^2 A_p \tag{3}$$

$$V_{Lm} = L_r^3 V_{Lp} \tag{4}$$

$$T = L_r^{1/2} \tag{5}$$

$$V_m = L_r^{1/2} V_p \tag{6}$$

$$Q_m = L_r^{5/2} Q_p \tag{7}$$

Flow resistance must be correctly simulated in the model to obtain water surface profiles and flow through the fuse plug. The model is operated whereby the model friction factor, f, is equal to the prototype friction factor.

The friction factor, f, is a function of relative roughness of the boundary, k_s/D, and the Reynolds number, $\mathbf{R}_e$:

$$f\,\Phi\,(k_s/D,\ \mathbf{R}_e) \tag{8}$$

This functional relationship is displayed by the Moody diagram on figure 3 [2].

Velocities and depths are smaller in the model than in the prototype which produces a smaller model Reynolds number. However, if model Reynolds numbers are large enough, the friction factors lie in the completely turbulent zone of the resistance diagram. Since, in this zone, the friction factor is constant and independent of Reynolds number, the model and prototype friction factors are equal. Thus, for frictional similitude, it is only necessary to geometrically scale the equivalent sand grain roughness, k_s.

Reynolds numbers in Twin Buttes Dam model varied between 25,000 and 40,000. The $\mathbf{R}_e$ were large enough that the friction factor plotted on the horizontal portion of the resistance curve – the completely turbulent zone. Equality in friction factors between model and prototype was obtained by scaling the roughness elements.

Description

Twin Buttes Dam and Reservoir hydraulic model was designed to simulate as much topography upstream of the fuse plug as possible (fig. 4). Model area included the area upstream of the fuse plug, the spillway, and a portion of the downstream topography. The hydraulic model scale selected was 1 to 150 (undistorted). The model constructed, in the laboratory, was 28 feet wide by 46 feet long (8.5 by 14.0 m) (fig. 5). More than 5,000 feet (1524 m) of upstream approach channel to the fuse plug was modeled; 4,000 feet (1219 m) of the proposed fuse plug was used in the scale model.

The large hydraulic model construction was accomplished by dividing the area to be modeled into a grid system in the east-west and north-south directions. Reservoir topography was taken from a 1:400 scale topography map and converted to the model scale along each grid line. Then, model elevations were transferred to ¾-inch (19 mm) plywood templates, and the templates were cut to model elevations. The plywood templates were placed vertically on the model floor along grid lines running in each direction. Sand was placed in each plywood box formed by the templates, and a thin layer of concrete mortar was placed on top of the sand to bring the topography to elevations of the templates.

The model fuse plug was constructed of urethane in sections that could be added or removed to simulate flow conditions as the washout progressed. At the maximum section, the model fuse plug height was just over 2 inches (51 mm). The fuse plug was anchored in the model by bolting it to a wood base.

Flow from the existing ogee service spillway was delivered into a side channel (fig. 6). Discharge through the ogee spillway was measured in the model with a V-notch weir.

Model Measurements and Instrumentation

Point gauges were used in both the 1 to 150 scale large hydraulic model and the tilting flume to measure water surface elevations. Because of surface fluctuations in the flumes, a wave probability probe was attached to each point gauge to obtain an average reading (fig. 7). The wave probability probe is an electrical averaging device used to determine when the point gauge is in contact with the water surface approximately 50 percent of the time.

In the large hydraulic model, water surface elevations were recorded upstream of the fuse plug with a hook gauge attached to a stilling well. The hook gauge was located in the deepest part of the reservoir.

Capacitance wave probes also were located throughout the upstream approach channel to the fuse plug to measure water surface elevations (fig. 8). The probes were calibrated to the hook gauge readings by ponding the water in the reservoir to establish a level water surface. Water surface elevations read at the hook gauge corresponded to voltage readings from the wave probes. Wave probe data were recorded with a digital voltmeter using an HP 9816 (Hewlett Packard) computer to monitor the data and record it on floppy disks (fig. 9). A linear regression of the voltage readings from each channel of the wave probes, and the hook gauge readings of water surface elevations was then computed. After the regression was completed, probes were used to measure water surface elevations throughout the approach to the fuse plug.

An Ott current meter was used to measure velocities at the fuse plug section. These data were used to compute the distribution of flow at the fuse plug. Current meter readings were obtained at different elevations before installing the simulated mesquite and with the mesquite in place.

The laboratory venturi meter system was used to measure discharge to the models.

Scaling the Mesquite

A vegetative survey was conducted by the environmental specialist of the Environmental Affairs Office in the Bureau's Southwest Regional Office (Amarillo, Texas) to determine the average height, density, and type of vegetation in the model study area. Sample sites were selected from a computer generated grid system. All shrubs, trees, and ground cover were sampled within each 190-foot (58 m) circular sample area (fig. 10). Average tree, or shrub height, and canopy diameter were recorded. In areas containing immature saltcedars, sample plots of one square meter were used because of the large density of the saltcedar.

Topography of the model study area contains very small changes in slope. Velocities do not increase significantly until the flow approaches the fuse plug spillway. Upstream near the fuse plug embankment, vegetative types IA and IB (fig. 10, table 1) predominate. Vegetative type IA, mesquite-brush-uplands, contains an average of 12 mesquite trees per sample plot and has an average height of 5.5 feet (1.7 m). Vegetative type IB, mesquite-brush-lowlands, contains an average of 26 trees per sample plot having an average height of 6.8 feet (2.1 m).

Frictional resistance of mesquite trees located in areas IA and IB was an important consideration in the model study. Prototype water surface elevation data do not exist for the approach channel to the fuse plug spillway, since design flow has never occurred. In addition, published friction data for mesquite trees could not be found in the literature. Mesquite trees will have an effect on the amount of flow through the fuse plug spillway channel. Therefore, a separate study of the friction losses was necessary to model the mesquite trees in the laboratory. Because frictional resistance of the trees was not available, scale models of trees were studied in the laboratory tilting flume to determine their frictional resistance for use in the large 1:150 scale model.

Frictional resistance of the concrete surface in the hydraulic model was studied. Determination of the average equivalent sand grain roughness of the concrete surface was necessary to assure the model was not already rough enough without having to add an additional roughness element to simulate the mesquite friction.

To establish the surface resistance of the mesquite and the concrete surface in the hydraulic model, the following sequence was performed:

1. Determine surface roughness of concrete in the large hydraulic model.

2. Determine roughness of mesquite by simulating the trees with plastic model plants in the tilting flume facility.

3. Install appropriate roughness elements in the large hydraulic model to simulate the effect of the mesquite.

Two flumes were used in the friction studies. The first flume was constructed inside the hydraulic model to determine the "as built" frictional characteristics of the concrete surface. The flume constructed in the hydraulic model was 3-feet wide, 2-feet high and 40-feet long (0.9- by 0.6- by 12.2-m, respectively) (fig. 11). Ten point gauges were placed along the flume to obtain water surface elevations. Data obtained from this flume study were used to estimate the roughness of the concrete surface.

The second facility used in frictional resistance studies was a tilting flume (fig. 12). The flume was 3-feet wide and 60-feet long (0.9- by 18.2-m). Five point gauges were used in the flume to measure water surface elevations. The first gauge was placed 40 feet (12.2 m) from the entrance to the flume. Plastic trees 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. Trees were scaled based on both an average height, and the canopy and density. The plastic trees were studied in the model at two different densities typical of vegetative types IA and IB. These 2-inch (50.1 mm) trees represented full scale trees at 1 to 30. Then, outdoor carpet was placed in the tilting flume to simulate the correct frictional loss in the hydraulic model at a scale of 1 to 150.

After completing friction tests in both flumes, carpeting was placed in the Twin Buttes hydraulic model according to the distribution of vegetation types IA and IB determined in the field survey (fig. 10).

Surface Roughness Estimation

Three approaches for computating surface roughness were considered:

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

2. The momentum equation could be solved between two locations to obtain the shear stress, τ_b. Compute the friction factor, f, from its relationship to shear stress and solve for k_s from the Colebrook-White equation. The characteristic length here is the depth.

3. The momentum equation could be solved as in the second approach except the equation relating the local skin friction coefficient, C_f, and Reynolds number for fully turbulent flow over a flat plate are used to estimate K_s.

All three methods were investigated; it was found that the momentum method using shear stress gave the most consistent results.

The energy method for computing friction slope and f (the first approach) is based on the assumption of uniform flow. This condition was violated in the large hydraulic model where the bottom slope and the depth change with distance from the baffle.

The third approach, using the equation from Schlichting's "Boundary Layer Theory" [3] for flow over a rough plate, resulted in excessively large estimates of k_s. This was caused by difficulties in accurately determining the boundary layer thickness in the laboratory model. A more detailed description of the momentum balance is given in the next section.

MODEL RESULTS AND ANALYSIS

Model testing and results can be divided into two categories. The first was the determination of the mesquite roughness. The second was the determination of the discharge rating relationship and distribution of flow.

Mesquite Roughness Estimation

Determination of mesquite roughness was accomplished by solving the momentum equation for shear stress. The friction factor was calculated from the Darcy-Weisbach equation, and the average equivalent sand grain roughness was computed from the Colebrook-White equation. These equations were incorporated into FCALCULATE (app. A). Data were collected and used in FCALCULATE to estimate equivalent sand grain roughness of mesquite for both the prototype and model scales.

The momentum balance written between two point gauges (fig. 13) is given by:

$$F + W\sin\alpha + (D_1^2\cos\alpha)\frac{\gamma B_1}{2} - (D_2^2\cos\alpha)\frac{\gamma B_2}{2}$$

$$- \tau_w\left(\frac{D_1+D_2}{2}\right)2\Delta X - \tau_b\left(\frac{B_1+B_2}{2}\right)\Delta X$$

$$= \rho Q\left[\beta_2 V_2\cos\left(\frac{\alpha-\theta}{2}\right) - \beta_1 V_1\cos\left(\frac{\alpha-\theta}{2}\right)\right] \quad (9)$$

The tilting flume has almost a uniform cross section, and the effect of nonuniform velocity head and momentum is small; therefore, momentum coefficients, β, were assumed to be unity.

The body force can be further defined by:

$$W = \gamma \Delta X \left(\frac{B_1 + B_2}{2} \right) \frac{D_1 + D_2}{2} \tag{10}$$

Wall shear is estimated from equation 21.12 in Schlichting [3] for a smooth flat plate. Averaging over the section, the wall shear is defined by:

$$\tau_w = 0.0148\, \rho\, \nu^{0.2} \left(\frac{V_1^{1.8}}{X_1^{0.2}} \right) + \frac{V_2^{1.8}}{X_2^{0.2}} \tag{11}$$

Wall force caused by change in width acting on the section is given by:

$$F = \frac{\gamma}{4} (B_2 - B_1)(D_1 + D_2)^2 \cos \alpha \tag{12}$$

Combining equations (9), (10), and (12) and solving for the bottom shear τ_b:

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

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

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

$$- \frac{2\rho Q}{(B_1 + B_2)\, \Delta X} \left[V_2 \cos \left(\frac{\alpha - \theta}{2} \right) - V_1 \cos \left(\frac{\alpha - \theta}{2} \right) \right] \tag{13}$$

Once τ_b is known then the average Darcy-Weisbach friction factor, f, over the test length can be calculated [4] from:

$$\tau_b = \frac{f \rho}{8} \left(\frac{V_1^2 + V_2^2}{2} \right) \tag{14}$$

Finally, the surface roughness, k_s can be computed by solving the Colebrook-White equation according to [5].

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

and

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

The momentum, Darcy-Weisbach, and Colebrook-White equations outlined in this section were incorporated in FCALCULATE (app.) A.

Using the momentum approach, flume studies were conducted to estimate k_s. The k_s value for the concrete only in the large model was estimated (by the momentum approach) to determine the roughness of the original concrete surface in the model.

Point gauge readings were taken at ten locations to obtain water surface elevations. These data were used in FCALCULATE to estimate f and k_s between each measurement location. Data from the first five point gauge locations closest to the baffle were not used because the Reynolds number was less than 60,000. This is out of range for the solution of the Colebrook-White equation. In some cases, the value of the Reynolds number exceeded 60,000, but the friction factor computed for the water surface elevation and discharge, at the first five point gauges, was below the smooth curve on the resistance diagram. These data were also out of range for solution of the Colebrook-White equation. These results could have been caused by excessive turbulence that occurred in the flume close to the baffle or because the boundary layer was not completely developed.

Point gauge data collected at locations 6 through 9 were originally used to compute f and k_s. However, after studying the results, the values of f and k_s were computed using only the end points (locations 6 and 9). This allowed readings to be taken with a longer distance between point gauges and increased the accuracy in determining the friction losses, therefore obtaining good estimates of f and k_s.

Concrete surface friction data for the large hydraulic model flume are summarized in table (2). Data computed for surface resistance of concrete corresponded to a discharge of 3.84 ft³/s [0.109 m³/s (109 L/s)]. The equivalent sand grain roughness for concrete estimated at this discharge was 0.001 feet (0.305 mm). Published data for the equivalent sand grain roughness of concrete range between 0.001 and 0.01 feet (0.305 to 3.05 mm).

Plastic trees were then placed in the tilting flume to simulate the mesquite; they represented mesquite trees at a 1 to 30 scale. Testing was done in the tilting flume facility to obtain a wider range of Reynolds numbers, velocities, and depths. Figure 14 shows the flume operating with the plastic trees in place. Two different densities of mesquite were tested in the flume. These densities corresponded to vegetative types IA and IB (table 1 fig. 10).

Testing in the tilting flume with plastic trees was performed for slopes ranging between 0.3 and 4 percent and discharges ranging between 3 and 11 ft³/s [0.085 to 0.311 m³/s (85 to 311 L/s)]. Slight changes in slope along the flume were measured by using a surveying level to determine the elevations at each point gauge location and at the end points

Table 2. – Concrete surface friction data for the large hydraulic model flume.[1]

Longitudinal slope %	Discharge ft^3/s	Cross-section width ft	Flow depth ft	Bottom elevation ft	Cross-section area ft^2	Velocity average ft/s	Reynold's number R_e	Friction factor f	Equivalent sand grain roughness, K_s	Manning's n	Friction slope S_f
Varies	3.842	2.938	0.626	10.955	1.839	2.739	1.09×10^6	0.022	0.001	0.010	0.00110
		2.953	0.384	10.834	1.134						

[1] 1 ft = 0.3048 m   1 ft^2 = 0.0929 m^2 1 ft/s = 0.3048 m/s   1 ft^3/s = .02831 m^3/s

of the flume. Investigations were conducted for both supercritical and subcritical flows (fig. 15 and 16).

Depths were measured in the flume with point gauges attached to the wave probability probe at four locations beginning 40 feet (12.2 m) downstream of the baffle. Depths were recorded for a range of discharges for both mesquite densities. The data were analyzed with program FCALCULATE (app. A) to compute f and k_s .

Friction data are summarized in table 3. The friction factor varied between 0.074 and 0.181 and the equivalent sand grain roughness varied between 0.057 and 0.210 feet (17.4 and 64.0 mm) – averaging 0.115 feet (35 mm). Originally, f and k_s were computed at each point gauge location for each discharge and slope. After analyzing the data, it was decided that a better water surface profile curve could be computed with a linear regression of the measured data. Then f and k_s were computed between the two end points of the fitted data.

The k_s value computed for the plastic trees averaged 0.115 feet (35 mm). Scaling the k_s value from the flume at a scale of 1 to 30 to the large hydraulic model scale of 1 to 150 resulted in a k_s value of 0.02 feet (6.1 mm). Outdoor carpeting having a coarse texture was selected to simulate the mesquite at the smaller scale. The height of the carpet nap was about ⅓ inch (8 mm), which is close to one-fifth the height of the plastic trees [2 in, (50.1 mm)].

The carpeting was cut into small rectangular pieces and placed in the titling flume (fig. 17) at the same density as the mesquite vegetative type IB. The tilting flume was operated with the carpet in place for a number of different discharges and slopes to verify that the roughness of the carpet would be close to a k_s value of 0.02 feet (6.1 mm) (fig. 18). Friction data, for the outdoor carpet used to simulate the mesquite, are summarized in table 4. The friction factor varied between 0.023 and 0.062, and the equivalent sand grain roughness varied between 0.002 and 0.073 feet (6.1 and 22.3 mm) – averaging 0.021 feet (6.4 mm).

Because the testing confirmed that average roughness of the outdoor carpet (0.021 feet) was very close to the scaled K_s value of 0.02 feet, the outdoor carpet was placed in the large hydraulic model. The same pattern of rectangular squares used in the tilting flume was used in the large hydraulic model in the area of the model where vegetative types IA and IB exist (fig. 8). The k_s value of 0.02 feet (6.1 mm) represents the surface resistance of the mesquite corresponding to vegetative type IB. Because vegetative type IA contains about one-half the number of mesquite, the carpet squares for vegetative type IA were

Table 3. – Mesquite tree friction data using 1 to 30 scale plastic trees.[1]

Longitudinal slope %	Discharge ft³/s	Cross-section width ft	Flow depth ft	Bottom elevation ft	Cross-section area ft²	Velocity average ft/s	Reynold's number $\mathbf{R_e}$	Friction factor f	Equivalent sand grain roughness, K_s	Manning's n	Friction slope S_f
0.3	5.048	2.969	0.703	10.754	2.087	2.432	1.42×10^5	0.111	0.132	0.023	0.00379
		2.969	.695	10.695	2.063						
.3	7.006	2.969	.829	10.880	2.462	2.888	1.96×10^5	.108	.148	.023	.00449
		2.969	.805	10.805	2.391						
.3	9.015	2.969	.922	10.973	2.737	3.410	2.53×10^5	.088	.113	.020	.00447
		2.969	.896	10.896	2.660						
.5	3.005	2.969	.501	10.572	1.487	2.106	0.84×10^5	.181	.193	.029	.00659
		2.969	.462	10.462	1.371						
.5	5.020	2.969	.675	10.746	2.005	2.507	1.41×10^5	.129	.165	.025	.00483
		2.969	.673	10.673	1.999						
.5	7.070	2.969	.843	10.914	2.504	2.836	1.98×10^5	.131	.210	.025	.00051
		2.969	.836	10.836	2.482						
.5	8.997	2.969	.950	11.021	2.820	3.140	2.53×10^5	.077	.093	.019	.00331
		2.969	.981	10.981	2.913						
.5	10.656	2.969	1.382	11.465	4.103	2.534	2.99×10^5	.074	.124	.018	.00147
		2.969	1.453	11.453	4.314						
.8	5.055	2.969	0.515	10.643	1.529	3.044	1.42×10^5	.080	.057	.020	.00537
		2.969	.612	10.612	1.817						
.8	7.046	2.969	.634	10.762	1.882	3.703	1.978×10^5	.095	.092	.021	.00822
		2.969	.648	10.648	1.924						
.8	9.080	2.969	.788	10.916	2.340	3.659	2.55×10^5	.077	.079	.019	.00510
		2.969	.890	10.890	2.642						
4.0	7.056	2.969	.394	10.997	1.170	6.331	1.98×10^5	.082	.040	.020	.0347
		2.969	.358	10.358	1.064						
4.0	9.040	2.969	.434	11.037	1.288	7.097	2.54×10^5	.082	.047	.020	.03852
		2.969	.424	10.424	1.260						
Average									0.115		

[1] 1 ft = 0.3048 m   1 ft² = 0.0929 m²   1 ft/s = 0.3048 m/s   1 ft³/s = 0.02831 m³/s

Table 4. – Mesquite tree friction data using 1 to 150 scale outdoor carpeting.[1]

Longitudinal slope %	Discharge ft³/s	Cross-section width ft	Flow depth ft	Bottom elevation ft	Cross-section area ft²	Velocity average ft/s	Reynold's number $\mathbf{R_e}$	Friction factor f	Equivalent sand grain roughness, K_s	Manning's n	Friction slope S_f
0.3	3.066	2.969	0.550	10.604	1.632	1.813	0.861×10^5	0.056	0.026	0.017	0.00135
		2.969	.591	10.591	1.754						
.3	5.485	2.969	.797	10.845	2.365	2.255	1.54×10^5	.023	.002	.011	.00069
		2.969	.843	10.843	2.503						
.3	4.145	2.969	.702	10.755	2.083	1.934	1.16×10^5	.058	.036	.017	.00126
		2.969	.743	10.743	2.207						
.3	7.089	2.969	.919	10.973	2.728	2.529	1.99×10^5	.026	.004	.012	.00086
		2.969	.971	10.971	2.882						
.3	8.848	2.969	.811	10.865	2.408	3.641	2.48×10^5	.044	.021	.015	.00310
		2.969	.826	10.826	2.452						
.5	5.444	2.969	.891	10.974	2.645	1.970	1.53×10^5	.036	.013	.014	.00692
		2.969	.974	10.974	2.892						
.5	6.362	2.969	1.084	11.170	3.218	1.905	1.78×10^5	.042	.024	.014	.00062
		2.969	1.169	11.169	3.471						
.5	7.685	2.969	0.664	10.750	1.971	3.598	2.16×10^5	.026	.003	.012	.00213
		2.969	0.785	10.785	2.331						
.5	7.976	2.969	1.206	11.292	3.582	2.157	2.24×10^5	.062	.073	.017	.00102
		2.969	1.286	11.286	3.819						
.5	8.986	2.969	1.131	11.217	3.359	2.591	2.52×10^5	.061	.066	.017	.00153
		2.969	1.208	11.208	3.587						
2.0	4.001	2.969	0.263	10.568	0.780	5.443	1.12×10^5	.031	.002	.012	.01520
		2.969	.234	10.234	0.695						
2.0	8.099	2.969	.423	10.728	1.257	6.855	2.27×10^5	.024	.001	.011	.01880
		2.969	.376	10.376	1.115						
2.0	6.196	2.969	.336	10.641	0.997	6.243	1.74×10^5	.042	.0072	.014	.01980
		2.969	.333	10.333	0.988						
Average									0.021		

[1] 1 ft = 0.3048 m 1 ft² = 0.0929 m² 1 ft/s = 0.3048 m/s 1 ft³/s = 0.02831 m³/s

cut to one-half the size of the carpet squares associated with area IB and placed in the large hydraulic model.

Discharge Rating Curve

The 1 to 150 scale model was tested at several different discharges to obtain a discharge–rating curve with and without the simulated mesquite. Velocity measurements were made across the section at the fuse plug to determine the distribution of unit discharges across the fuse plug to assist designers in flood routing investigations.

The discharge relationship curve for both cases is summarized on figure 19 and in table 5. Discharges in the rating curves include a flow through the spillway and outlet works that vary from 83,000 ft³/s at elevation 1985 (2350 m³/s at 605.0 m) to 105,000 ft³/s at elevation 1996 (2973 m³/s at 608.4 m) (fig. 2). The model flows for the ogee spillway and outlet works were close to those given in the rating curve (fig. 2). Below 500,000 ft³/s (14158 m³/s), the effect of mesquite on the fuse plug discharge was negligible. As the flow was increased the effect of the mesquite friction was more pronounced. For example, at elevation 1990 the discharge is 870,000 ft³/s (24636 m³/s at 606.6 m) with mesquite friction, and 900,000 ft³/s (25485 m³/s) without mesquite. At elevation 1996, the discharges were 1.31 and 1.37 million ft³/s (37095 and 38794 m³/s at 608.4 m) for the two cases.

Water surface profile data were obtained simultaneously with discharge data. Data were obtained using wave capacitance probes located throughout the model and with a point gauge located close to the fuse plug. Water surface profile data are summarized on figure 20 for discharges ranging between 71,100 ft³/s and 1.4 million ft³/s (2015 and 39645 m³/s).

Velocity measurements without mesquite friction were recorded at 1.1 and 1.4 million ft³/s discharges (31150 and 39645 m³/s). These data are summarized in tables 6 and 7 and correspond to elevations 1994.6 and 1997.5 (608.0 and 608.8 m).

Velocity measurements were taken at elevations 1980, 1985, 1991, 1993.5, and 1995 (603.5, 605.0, 606.9, 607.6, and 608.1 m) with the mesquite friction. Data for elevations 1980, 1985 and 1991 were not used because more than one-half the current meter propeller was out of the water for most of the measurements. Measured and computed discharges varied more than 10 percent, which meant that individual velocity measurements could have varied as much as 50 percent. Unit discharge data for elevations 1993.5 and 1995 (607.6 and 608.1 m) are summarized in tables 8 and 9.

Table 5. – Fuse plug spillway rating curve data.[1]

Elevation ft	Discharge, ft³/s
Without Mesquite Friction	
1978.40	256,000
1982.15	427,000
1984.70	558,000
1987.25	716,000
1989.20	844,000
1990.70	951,000
1992.80	1,105,000
1994.45	1,241,000
1995.95	1,382,000
1997.45	1,514,000
With Mesquite Friction	
1972.40	71,100
1974.35	122,000
1977.20	210,800
1979.67	317,700
1980.65	347,800
1982.00	423,200
1984.55	549,100
1986.20	620,900
1986.95	686,200
1989.50	837,000
1990.55	896,300
1991.00	925,000
1991.30	967,300
1993.25	1,103,200
1994.30	1,171,800
1994.90	1,239,700
1995.20	1,247,600
1996.40	1,371,600
1997.00	1,415,600
1998.05	1,515,900

[1] 1 ft = 0.3048 m
1 ft³/s = 0.02831 m³/s

Table 6. – Unit discharge distribution without mesquite friction – elevation 1994.6.[1]

Distance from right edge of fuse plug, ft	Depth ft	Velocity ft/s	Discharge ft^3/s	Unit discharge $(ft^3/s)/ft$
250	3.00	3.75	2,810	11
400	6.75	10.94	11,070	74
550	9.00	13.06	17,640	118
700	13.50	11.70	23,680	158
850	14.25	10.82	23,140	154
1000	13.50	7.25	14,680	98
1150	15.00	9.31	20,950	140
1300	19.50	15.32	44,800	299
1450	21.00	18.02	56,770	378
1600	20.25	19.76	60,040	400
1750	18.00	21.64	58,440	390
1900	19.50	24.30	71,090	474
2050	19.50	24.12	70,550	470
2200	18.00	25.40	68,590	457
2350	18.00	22.74	61,410	409
2500	18.00	20.31	54,850	366
2650	16.50	22.10	54,700	365
2800	17.25	23.89	61,820	412
2950	19.50	22.47	65,720	438
3100	19.50	21.74	63,580	424
3250	18.75	21.05	59,200	395
3400	21.00	19.90	62,690	418
3550	19.50	19.08	55,800	372
3775	16.50	19.67	48,690	216
Total			1,132,710	

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

Table 7. – Unit discharge distribution without mesquite friction – elevation 1997.5.[1]

Distance from right edge of fuse plug, ft	Depth ft	Velocity ft/s	Discharge ft^3/s	Unit discharge $(ft^3/s)/ft$
225	19.50	19.31	84,700	376
375	21.00	20.10	63,350	422
525	23.25	20.90	72,900	486
675	22.50	21.50	72,750	485
825	22.50	22.26	75,150	501
975	22.50	23.15	78,100	521
1125	21.00	24.07	75,850	506
1275	20.25	22.26	67,600	451
1425	21.00	22.04	69,450	463
1575	20.25	24.43	74,200	495
1725	19.50	26.19	76,600	511
1875	22.50	24.30	82,000	547
2025	22.50	23.46	79,150	528
2175	21.75	22.40	73,100	487
2325	21.75	20.94	68,300	455
2475	22.50	18.56	62,650	418
2625	22.50	17.94	60,550	404
2775	19.50	13.26	38,750	258
2925	16.50	11.80	29,200	195
3075	16.50	14.32	35,500	237
3225	16.50	14.49	35,900	239
3375	13.50	14.19	28,700	191
3525	10.50	13.21	20,800	139
3775	6.00	4.64	6,950	28
Total			1,432,200	

[1] 1 ft = 0.3048 m 1 ft/s = 0.3048 m/s
1 ft^3/s = 0.02831 m^3/s

Table 8. – Unit discharge distribution with mesquite friction – elevation 1993.5.[1]

Distance from right edge of fuse plug, ft	Depth ft	Velocity ft/s	Discharge ft³/s	Unit discharge (ft³/s)/ft
150	18.75	16.77	47,122	314
300	22.05	18.86	62,278	415
450	23.25	17.68	61,727	412
600	21.75	19.76	64,483	430
750	22.05	20.59	68,065	454
900	21.90	19.91	65,130	435
1050	20.55	20.34	62,829	419
1200	20.55	19.63	60,625	404
1350	15.90	19.78	47,174	315
1500	18.15	21.15	57,594	384
1650	18.45	19.38	53,736	358
1800	20.55	19.36	59,798	399
1950	21.00	20.97	66,136	441
2100	21.90	18.38	60,349	402
2250	23.25	18.92	65,861	439
2400	19.35	16.82	48,775	325
2550	19.35	15.70	45,469	303
2700	13.20	11.29	22,321	149
2850	14.25	11.35	24,250	162
3000	14.70	10.99	24,250	162
3150	17.25	10.78	27,832	186
3300	12.45	10.04	18,739	125
3825	7.65	9.09	10,472	28
Total			1,125,201	

[1] 1 ft = 0.3048 m 1 ft/s = 0.3048 m/s
1 ft³/s = 0.02831 m³/s

Table 9. – Unit discharge distribution with mesquite friction – elevation 1995.0.[1]

Distance from right edge of fuse plug, ft	Depth ft	Velocity ft/s	Discharge ft³/s	Unit discharge (ft³/s)/ft
150	20.7	17.17	53,460	356
300	22.4	18.89	63,381	423
450	23.9	18.76	67,239	448
600	21.2	19.93	63,105	421
750	21.8	21.07	68,616	457
900	21.8	21.30	69,443	463
1050	20.7	20.39	63,381	423
1200	21.5	19.78	63,656	424
1350	17.0	21.21	54,011	360
1500	19.2	20.93	60,349	402
1650	18.6	21.35	59,523	397
1800	19.5	21.35	62,003	413
1950	20.7	21.25	65,861	439
2100	20.3	20.15	61,176	408
2250	23.7	19.50	69,443	463
2400	22.5	17.59	59,247	395
2550	19.7	16.26	47,949	320
2700	14.1	12.06	25,628	171
2850	14.3	11.13	23,699	158
3000	14.1	11.45	24,250	162
3150	14.7	11.72	25,903	168
3300	11.4	11.48	19,565	130
3450	8.7	8.22	10,747	72
3825	5.6	3.54	7,367	49
Total			1,189,002	

[1] 1 ft = 0.3048 m 1 ft/s = 0.3048 m/s
1 ft³/s = 0.02831 m³/s

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APPENDIX A: PROGRAM FCALCULATE

Computer program is used to compute friction factor, *f*, and equivalent sand grain roughness, K_s , from a momentum balance.

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100   !PROGRAM FCALCULATE
110   !*************************************************************************
120   !*************************************************************************
130   !***                                                                   ***
140   !    PROGRAM FCALCULATE USES A MOMENTUM BALANCE TO CALCULATE THE
150   !    FRICTION FACTOR AND EQUIVALENT SAND GRAIN ROUGHNESS BETWEEN
160   !    TWO LOCATIONS. REQUIRED INPUT TO THE MODEL IS THE SLOPE AND
170   !    WATER SURFACE ELEVATION AT EACH LOCATION. THE PROGRAM COMPUTES
180   !    ALL OF THE FORCES THAT ACT ON THE BODY BETWEEN TWO LOCATIONS
190   !    WITH THE MOMENTUM BALANCE.  THEN, THE BOTTOM SHEAR STRESS IS
200   !    SOLVED IN THE PROGRAM.  ONCE THE BOTTOM SHEAR STRESS IS FOUND,
210   !    THEN THE FRICTION FACTOR IS OBTAINED FROM ITS RELATIONSHIP TO
220   !    TO THE SHEAR STRESS FROM THE DARCY-WEISBACH EQUATION.  THE EQUIVA-
230   !    LENT SAND GRAIN ROUGHNESS IS SOLVED FOR IN THE COLEBROOK-WHITE
240   !    EQUATION WITH A TRIAL AND ERROR PROCEDURE INVOLVING A NEWTON
250   !    ITERATION SCHEME.  THE PROGRAM WAS WRITTEN BY C. KLUMPP BETWEEN
260   !    AUGUST AND NOVEMBER 1986.
270   !***                                                                   ***
280   !*************************************************************************
290   !*************************************************************************
300   OPTION BASE 1
310   COM E(10),V(10),A(10),D(10),B(10),X(10),Rn(10),Sf(10),Fr(10),P(10)
320   COM Hf(9),Rbar(9),N(9),Re(10),Vbar(10),F(9),Ks(9),C(10),Rebar(10)
330   COM Delta(10),El(10),Elcal(10),Taub(9),Tauw(9),Zdata(10),Cf(9),Rx(9)
340   COM Vbar2(9),Deltaw(7),Dep(4,7),Bot(4,7),Cksm(4)
350   DIM Requation$[30],Title$[80]
360   REAL Q,Nu
370   G=32.2
380   !*************************************************************************
390   !FIRST INPUT TITLES, WATER SURFACE ELEVATIONS, AND Z VALUES.
400   !*************************************************************************
410   INPUT "ENTER RUN NO.",Runo
420   MASS STORAGE IS ":,706,0"
430   ASSIGN @Path2 TO "XCOORD";FORMAT OFF
440   ENTER @Path2;X(*),B(*)
450   ASSIGN @Path2 TO *
460   FOR I=1 TO 2
470   INPUT "ENTER YOUR Z DATA",Zdata(I)
480   PRINT "ZDATA(I)=",Zdata(I)
490   NEXT I
500    FOR J=1 TO 2
510    INPUT "ENTER THE DEPTH",D(J)
520     PRINT "D(j)=",D(J)
530     El(J)=D(J)+Zdata(J)
540   NEXT J
550   INPUT "DO YOU WANT TO STORE DEPTHS?",B$
560   IF B$[1,1]="Y" THEN GOSUB Storedata
570   INPUT "DISCHARGE YOU ARE USING",Q
580   !*****************************************************************
590   ! NOW CALCULATE AREAS, WETTED PERIMETERS, AND HYDRAULIC RADIUS
600   !*****************************************************************
610   FOR J=1 TO 2
620     C(J)=J
630   !PRINT "C(J)=",C(J)
640     A(J)=B(J)*D(J)
650     V(J)=Q/A(J)
660     Fr(J)=V(J)/(SQR(D(J)*G))
670     P(J)=D(J)*2+B(J)
680     R(J)=A(J)/P(J)
690   NEXT J
```

```
700   Nu=1.2E-5
710   FOR Nn=1 TO 1
720     Rbar(Nn)=(R(Nn)+R(Nn+1))/2
730     Vbar(Nn)=(V(Nn)+V(Nn+1))/2
740     Vbar2(Nn)=((V(Nn)*V(Nn))+(V(Nn+1)*V(Nn+1)))/2
750   NEXT Nn
760   !*********************************************************************
770   !COMPUTE THE MOMENTUM BALANCE BETWEEN EACH LOCATION AND SOLVE FOR SHEAR
780   !STRESS.  AFTER THE SHEAR STRESS IS KNOWN, SOLVE FOR THE FRICTION FACTOR.
790   !*********************************************************************
800   FOR J=1 TO 1
810     Deltaz=Zdata(J+1)-Zdata(J)
820     Length=X(J+1)-X(J)
830     Wbar=(B(J)+B(J+1))/2
840     Alpha1=-ASN(Deltaz/Length)
850     Deltay=D(J+1)-D(J)
860     Theta=-ASN((Deltaz+(Deltay*COS(Alpha1)))/Length)
870     Tauwpar1=V(J)^1.8/X(J)^.2
880    !PRINT "WBAR=",Wbar,"TAUPAR1=",Tauwpar1
890     Taupar2=V(J+1)^1.8/X(J+1)^.2
900     Rho=62.4/32.2
910     Tauw(J)=.0148*Rho*(Nu)^.2*(Tauwpar1+Taupar2)
920    !PRINT "TAUPAR2=",Taupar2,"TAUW(J)=",Tauw(J)
930     Dsqrminus=(D(J)*D(J))-(D(J+1)*D(J+1))
940     Ddivwbar=(D(J)+D(J+1))/(B(J)+B(J+1))
950     Recipdepth=1/D(J+1)-1/D(J)
960    !PRINT "DSQRMINUS=",Dsqrminus,"DDIVWBAR=",Ddivwbar
970    !PRINT "RECIPDEPTH=",Recipdepth,"LENGTH=",Length
980    PRINT "ALPHA1=",Alpha1
990    Term1=B(J)*(D(J)*COS(Alpha1)*D(J))
1000   PRINT "TERM1=",Term1
1010   Term2=B(J+1)*(D(J+1)*COS(Alpha1)*D(J+1))
1020   PRINT "TERM2=",Term2
1030   Term3=Term1-Term2
1040    Angle1=COS((Alpha1-Theta)/2)
1050   Presforce=62.4/((B(J)+B(J+1))*Length)*Term3
1060    Tauwforce=Ddivwbar*Tauw(J)*2*Angle1
1070    Qtrho=Rho*Q
1080    Vdata=V(J+1)*Angle1-V(J)*Angle1
1090    Qdeltav=Qtrho*Vdata*(1/(Wbar*Length))
1100    Wallforc=62.4/4*((B(J+1)-B(J))*(D(J)+D(J+1))*(D(J)+D(J+1))*1/((B(J+1)+B(
J))*Length))
1110    Pforce=(62.4*(D(J)+D(J+1))*SIN(Alpha1))/2
1120    !PRINT "PFORCE=",Pforce,"SIN(ALPHA1)=",SIN(Alpha1)
1130    Taub(J)=Presforce+Pforce+Wallforc-Tauwforce-Qdeltav
1140    !PRINT "QDELTAV=",Qdeltav,"PRESFORCE=",Presforce
1150    !PRINT "TAUFORCE=",Tauforce
1160    PRINT "TAUB(j)=",Taub(J),"PFORCE=",Pforce
1170    Factor7=(D(J)+D(J+1))/(D(J)*D(J+1))
1180    F(J)=(8*Taub(J))/(Rho*Vbar2(J))
1190    Cf(J)=Taub(J)/(.5*Rho*Vbar(J)*Vbar(J))
1200   !PRINT "FACTOR7=",Factor7,"F(j)=",F(J)
1210    Nu=1.2E-5
1220    Rx1=(X(J)*V(J))/Nu
1230    Rx2=(X(J+1)*V(J+1))/Nu
1240    Rx(J)=(Rx1+Rx2)/2
1250    GOSUB Printnum
1260  NEXT J
1270  !*********************************************************************
1280  !PRINT OUT RESULTS FOR INPUT, MOMENTUM BALANCE AND FRICTION F6ACTOR
```

```
1290  !*************************************************************************
1300  GOSUB Printrx
1310  !*************************************************************************
1320  !COMPUTE THE REYNOLDS NUMBER
1330  !*************************************************************************
1340  FOR J=1 TO 2
1350    Reynoldnum=V(J)*X(J)/Nu
1360    Reynoldnum=Reynoldnum^.2
1370    Delta(J)=(.38*X(J))/Reynoldnum
1380  !PRINT "DELTA(j)=",Delta(J)
1390  Dvalue=D(J)
1400   ! Dvalue=Delta(J)
1410   !IF Delta(J)>=D(J) THEN Dvalue=D(J)
1420    Re(J)=(V(J)*Dvalue)/Nu
1430  NEXT J
1440  FOR J=1 TO 1
1450    Rebar(J)=(Re(J)+Re(J+1))/2
1460  NEXT J
1470  !*********************************************************************
1480  !SOLVE THE COLEBROOK-WHITE EQUATION TO OBTAIN THE ROUGHNESS
1490  !*********************************************************************
1500  FOR Jk=1 TO 1
1510    Dbar=(D(Jk)+D(Jk+1))/2
1520    IF F(Jk)<0. THEN Ks(Jk)=0.
1530    IF F(Jk)<0 THEN GOTO 1590
1540    IF Rebar(Jk)<=6.0E+4 THEN GOTO 1590
1550    GOSUB Roughness
1560    Ks(Jk)=Kz1
1570    IF F(Jk)<=.001 THEN Ks(Jk)=0.
1580    !PRINT "F(JK) =",F(Jk),"KS(JK) =",Ks(Jk)
1590  NEXT Jk
1600  !*********************************************************************
1610  !NOW CALCULATE THE MANNING'S N VALUE
1620  !*********************************************************************
1630  FOR I=1 TO 1
1640    E1=El(I)+((V(I)*V(I))/(2*G))
1650    E2=El(I+1)+((V(I+1)*V(I+1))/(2*G))
1660    Hf(I)=E1-E2
1670    Sf(I)=ABS(Hf(I))/(X(I+1)-X(I))
1680  NEXT I
1690  FOR Kk=1 TO 1
1700    Abar(Kk)=(A(Kk)+A(Kk+1))/2
1710    N(Kk)=(1.487*Abar(Kk)*Rbar(Kk)^.6667*Sf(Kk)^.50)/Q
1720  NEXT Kk
1730  !*********************************************************************
1740  !FINISH AND PRINT THE REST OF THE RESULTS
1750  GOSUB Printdata
1760  STOP
1770  !************************************************************
1780  !*************************************************************
1790  !THIS IS A SUBROUTINE TO STORE DATA TO A FILE
1800  !*********************************************************************
1810 Storedata: !
1820  INPUT "NUMBER OF DEPTHS AND ELEVATIONS YOU ARE STORING",Anum
1830  Anum1=INT(((Anum1)*8/256)*2)+1
1840  INPUT "NAME OF FILE YOU WANT TO STORE DATA ON",File$
1850  CREATE BDAT File$,Anum1
1860  ASSIGN @Path3 TO File$;FORMAT OFF
1870  OUTPUT @Path3;E(*),D(*)
1880  ON END @Path3 GOTO 1890
```

```
1890  RETURN
1900  !************************************************************
1910  !************************************************************
1920  !THIS IS A  SUBROUTINE TO READ ELEVATIONS AND DEPTH FROM A FILE
1930  !******************************************************************
1940  !******************************************************************
1950 Readfile: !
1960  INPUT "NAME OF FILE YOU WANT TO READ",Filnam$
1970  MASS STORAGE IS ":,706,0"
1980  ASSIGN @Path3 TO Filnam$;FORMAT OFF
1990  ENTER @Path3;E(*),D(*)
2000  ON END @Path3 GOTO 2010
2010  RETURN
2020  !*******************************************************************
2030  !THIS IS A SUBROUTINE TO PRINT DATA
2040  !*******************************************************************
2050 Printdata: !
2060  ASSIGN @Path1 TO 701
2070  OUTPUT @Path1 USING "80A,/";Title$
2080  OUTPUT @Path1 USING "30X,7A,D,/";"RUN NO.",Runo
2090  OUTPUT @Path1 USING "25X,12A,2D.3D,X,3A,//";"DISCHARGE = ",Q,"CFS"
2100  OUTPUT @Path1;"POINT      X-        WIDTH    DEPTH   ELEVATION    AREA     W
ETTED      HYDRAULIC"
2110  OUTPUT @Path1;"GAGE    COORDINATE                                            P
ERIMETER    RADIUS"
2120  OUTPUT @Path1 USING "//"
2130 Image2:IMAGE (2X,2D,7X,2D.3D,5X,D.3D,2X,2D.3D,3X,3D.3D,4X,2D.3D,5X,2D.3D,4X
,2D.3D,/)
2140  FOR Ii=1 TO 2
2150    OUTPUT @Path1 USING Image2;C(Ii),X(Ii),B(Ii),D(Ii),El(Ii),A(Ii),P(Ii),R(
Ii)
2160  NEXT Ii
2170  OUTPUT @Path1 USING "//"
2180  OUTPUT @Path1 USING "5A,3X,5A,2X,4A,5X,9A,3X,8A,3X,10A,3X,9A,3X,8A";"POINT
","DELTA","VBAR","REYNOLD'S","FRICTION","EQUIVALENT","MANNING'S","FRICTION"
2190  OUTPUT @Path1 USING "4A,20X,6A,6X,6A,5X,11A,2X,7A,5X,8A";"GAGE","NUMBER","
FACTOR","SAND ROUGH.","N VALUE","SLOPE-SF"
2200  OUTPUT @Path1 USING "//"
2210 Image3:IMAGE (2D,20X,8D.D,/)
2220 Image4:IMAGE (5X,2D.3D,3X,2D.3D,16X,2D.3D,5X,SD.3DE,4X,D.3D,3X,SD.3DE)
2230  FOR Ll=1 TO 1
2240  PRINT "REBAR=",Rebar(Ll)
2250    OUTPUT @Path1 USING Image3;C(Ll),Rebar(Ll)
2260    IF Ll=10 THEN GOTO 2290
2270    OUTPUT @Path1 USING Image4;Delta(Ll),Vbar(Ll),F(Ll),Ks(Ll),N(Ll),Sf(Ll)
2280  !PRINT "DELTA(Il)=",Delta(Ll),"VBAR(Ll)=",Vbar(Ll),"F(Ll)=",F(Ll),"SF(Ll)=
",Sf(Ll)
2290  NEXT Ll
2300 Image7:  IMAGE(//)
2310  OUTPUT @Path1 USING Image7
2320  FOR J=1 TO 1
2330  IF (Cksm(J)>0.) THEN OUTPUT @Path1 USING "63A";"***SURFACE ROUGHNESS SET T
O ZERO, FRICTION BELOW ""SMOOTH"" CURVE"
2340  IF Cksm(J)>=0. THEN GOTO 2360
2350  NEXT J
2360  RETURN
2370  !*****************************************************************
2380  !******************************************************************
2390  !THIS IS A SUBROUTINE THAT CALCULATES THE EQUIVALENT SAND ROUGHNESS
2400  !****************************************************************
```

```
2410  !**********************************************************************
2420 Roughness: !
2430  F1=F(Jk)
2440  IF F1<=.001 THEN GOTO 2720
2450  R1=Dbar
2460  !IF Delta(Jk)>=Dbar THEN R1=Dbar
2470  Rebar1=Rebar(Jk)
2480  Kz=.001
2490  Kz1=Kz
2500  LOOP
2510  Funca=Kz1/R1
2520  Lfunca=LGT(Funca)
2530  Funcb=15/(Rebar1*SQR(F1))
2540  Cksm(Jk)=1./SQR(F1)-1.56+2*(LGT(Funcb))
2550  IF (Cksm(Jk)>=0.) THEN Kz2=0.
2560  EXIT IF Cksm(Jk)>=0.
2570  Gcalc1=2*(LGT(Funca+Funcb))
2580    Gcalc=1/SQR(F1)-1.56+Gcalc1
2590    G1=Kz1/R1+15.0/(Rebar1*SQR(F1))
2600    Derg=(.4343/G1)*(2/R1)
2610    Kzt=Kz1-(Gcalc/Derg)
2620    Kz2=Kzt
2630    IF Kzt<=0 THEN Kz2=.50*Kz1
2640  EXIT IF ABS((Kz2-Kz1)/Kz1)<=.001
2650    IF ABS((Kz2-Kz1)/Kz1)>.001 THEN Kz1=Kz2
2660  END LOOP
2670    ! Rz=4*R1
2680    ! Rz2=10^(1/(2*SQR(F(Jk)))-.56)
2690    ! Kz1=Rz/Rz2
2700    Kz1=Kz2
2710    PRINT "CKSM=",Cksm(Jk)
2720  RETURN
2730 Boundaryt:    !
2740  FOR Iz=1 TO 5
2750    Const=-.2
2760    Const1=(V(Iz)*X(Iz))/Nu
2770    Const2=Const1^Const
2780    Delta(Iz)=.37*Const2*X(Iz)
2790    PRINT Delta(Iz)
2800  NEXT Iz
2810  RETURN
2820  !**********************************************************************
2830  !THIS SUBROUTINE PRINTS OUT THE RESULTS OF THE MOMENTUM BALANCE
2840  !**********************************************************************
2850 Printnum: !
2860  ASSIGN @Path1 TO 701
2870  IF J>1 THEN GOTO 2910
2880  OUTPUT @Path1 USING "@"
2890  OUTPUT @Path1 USING "2A,3X,10A,3X,10A,3X,9A,2X,9A,2X,7A,2X,6A,2X,6A,/";"NO
","WALL SHEAR","BOT. SHEAR","PRESFORCE","TAUWFORCE","QDELTAV","PFORCE","WFORCE"
2900 Image5:IMAGE (2D,4X,SD.4D,4X,SD.4D,4X,S2D.4D,4X,S2D.4D,3X,S2D.4D,1X,S2D.4D,
S2D.4D,2X,S2D.4D,/)
2910  OUTPUT @Path1 USING Image5;J,Tauw(J),Taub(J),Presforce,Tauwforce,Qdeltav,P
force,Wallforc
2920  OUTPUT @Path1 USING "/"
2930  RETURN
2940  !**********************************************************************
2950  !THIS SUBROUTINE PRINTS THE RESULTS OF USING THE LOCAL RESISTANCE FACTOR
2960  !FOR FLOW OVER A ROUGH PLATE FROM SCHLICTING TO COMPUTE THE SAND GRAIN
2970  !ROUGHNESS
```

```
2980  !**********************************************************************
2990 Printrx:!
3000  ASSIGN @Path1 TO 701
3010  OUTPUT @Path1 USING "2A,6X,2A,9X,2A,/";"NO","CF","RX"
3020  FOR J=1 TO 1
3030    OUTPUT @Path1 USING Image6;J,Cf(J),Rx(J)
3040 Image6:IMAGE (2D,4X,D.5D,3X,8D.D,/)
3050  NEXT J
3060  OUTPUT @Path1 USING "//"
3070  RETURN
3080  END
```

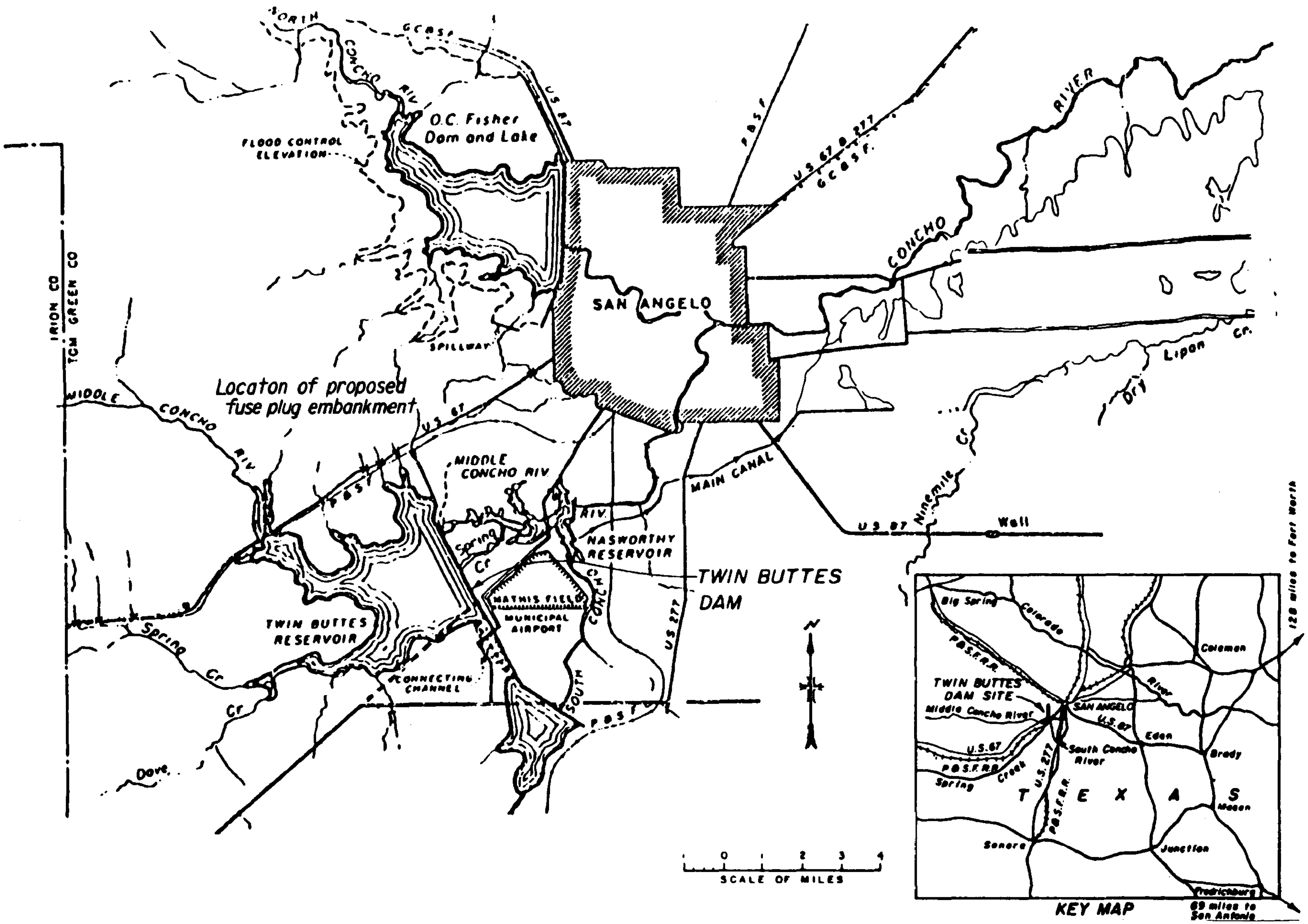
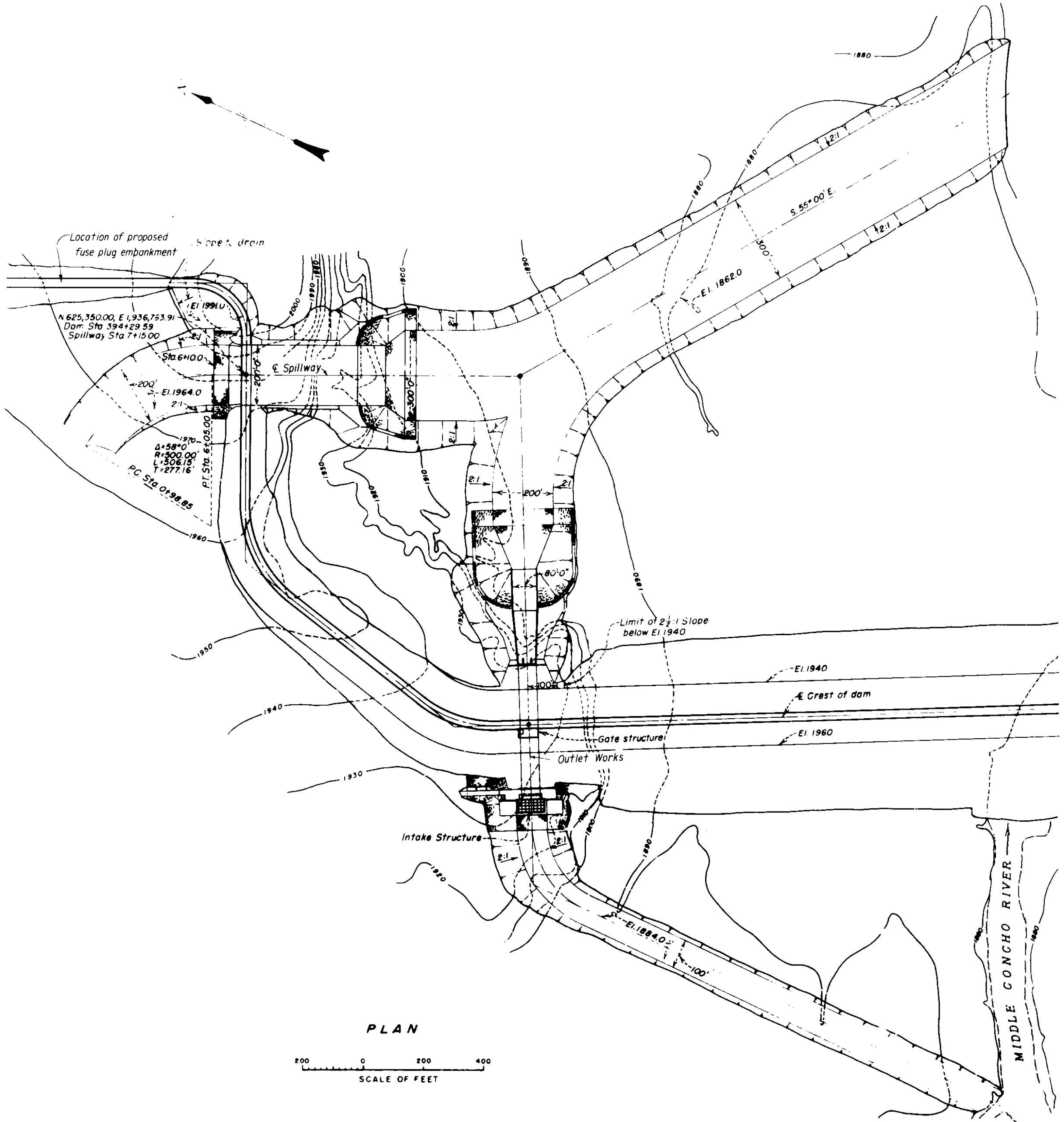
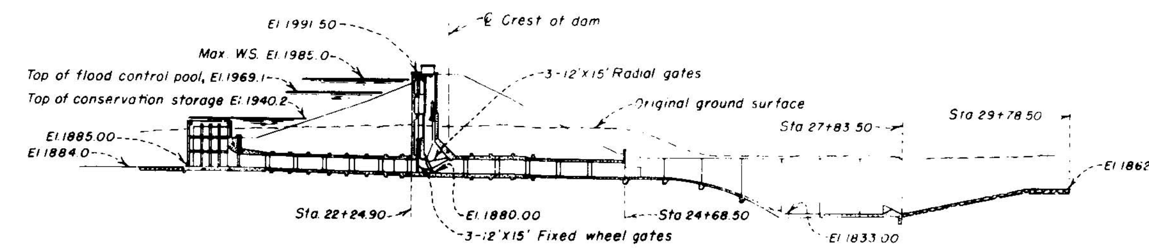


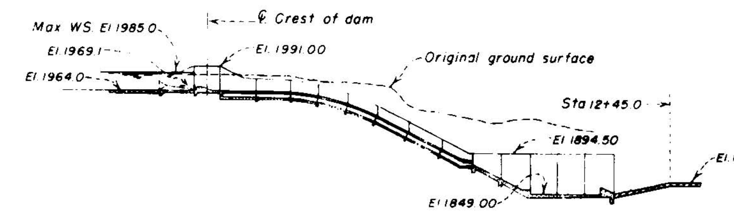
Figure 1. – Vicinity map.



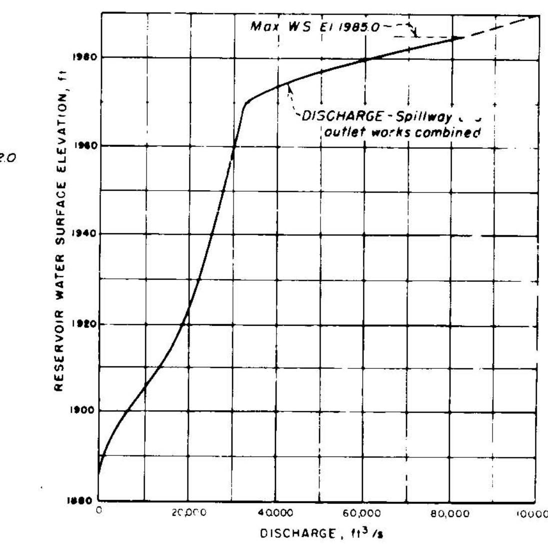


PROFILE ON ℄ OUTLET WORKS

SCALE OF FEET



PROFILE ON ℄ SPILLWAY



SPILLWAY AND OUTLET WORKS COMBINED DISCHARGE CURVE

REFERENCE DRAWINGS

DAM - GENERAL PLAN & SECTIONS - SHEET 1 OF 3 .... 825-D-7
SPILLWAY - PLAN AND SECTIONS 825-D-11
OUTLET WORKS - PLAN AND SECTIONS 825-D-15

Figure 2. – Spillway and outlet works, plans, sections, and discharge rating curves (original dam layout).

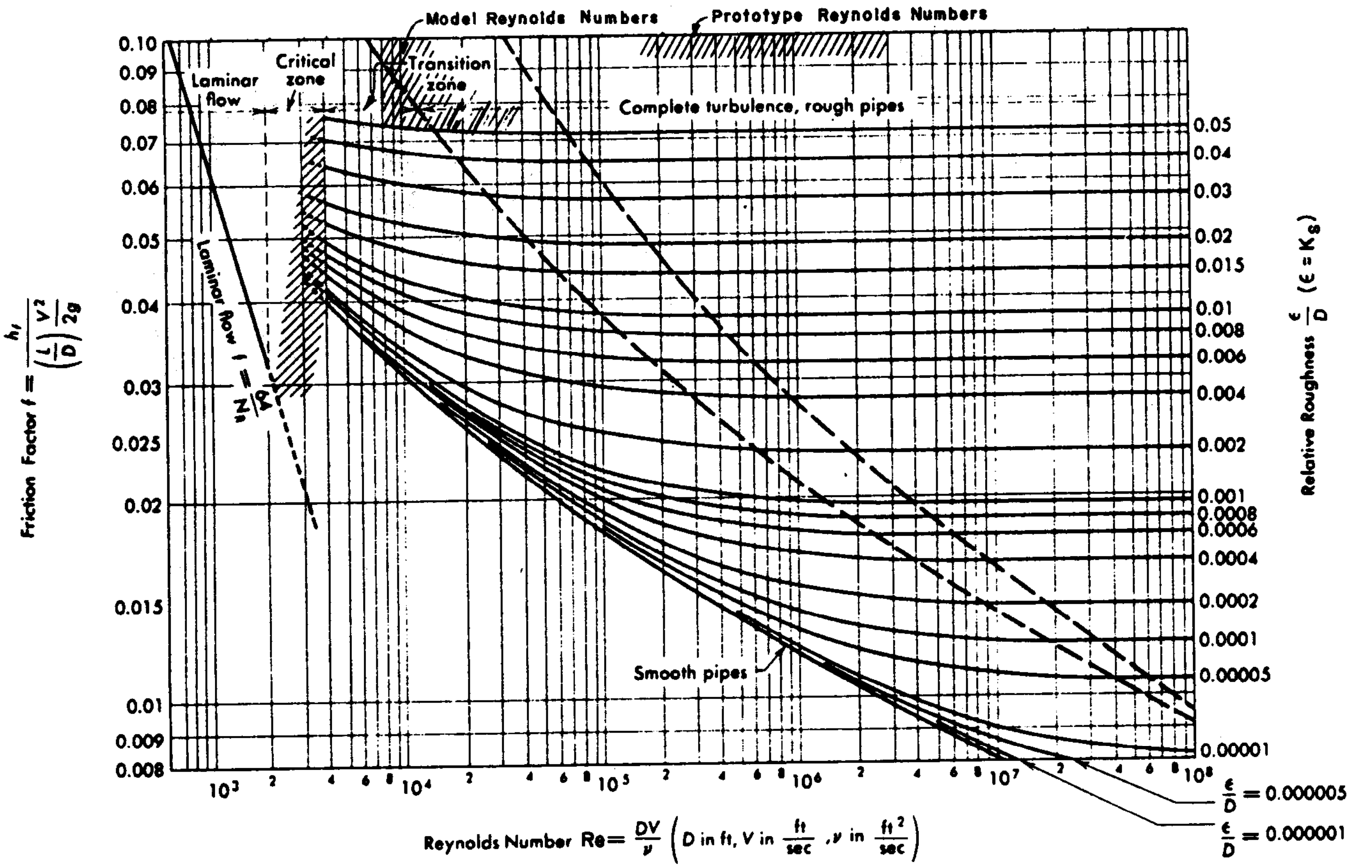


Figure 3. – The Moody diagram.

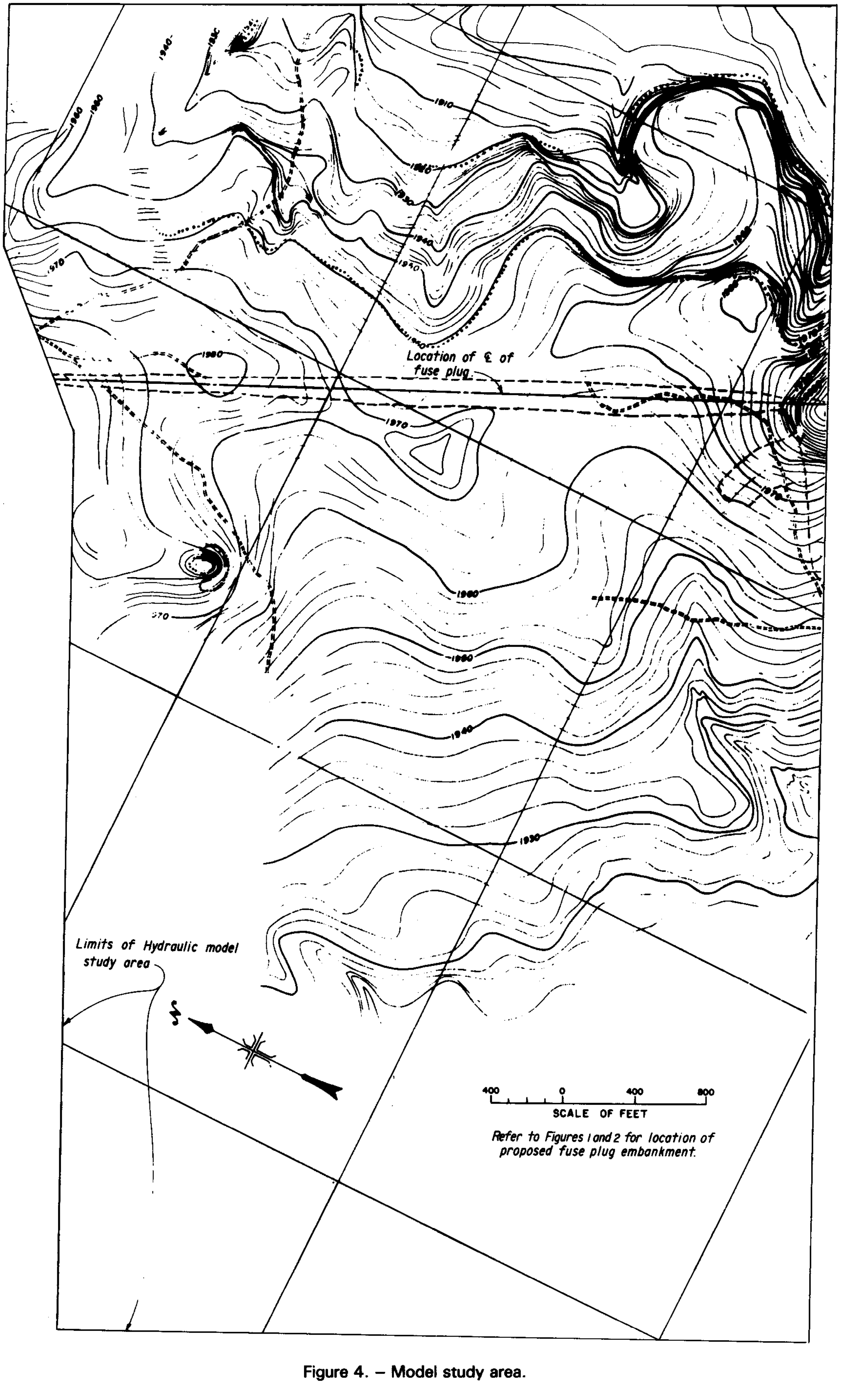


Figure 4. – Model study area.

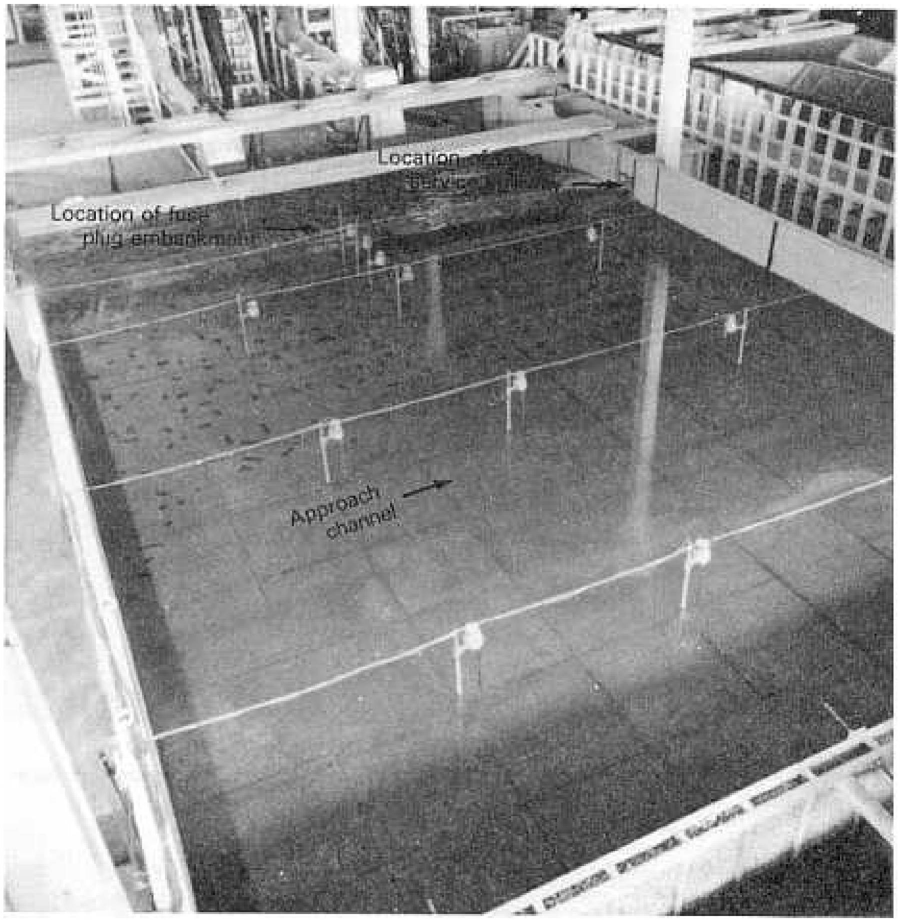


Figure 5. – Overall view of the 1:150 scale hydraulic model with simulated mesquite friction. Photo P801-D-81383

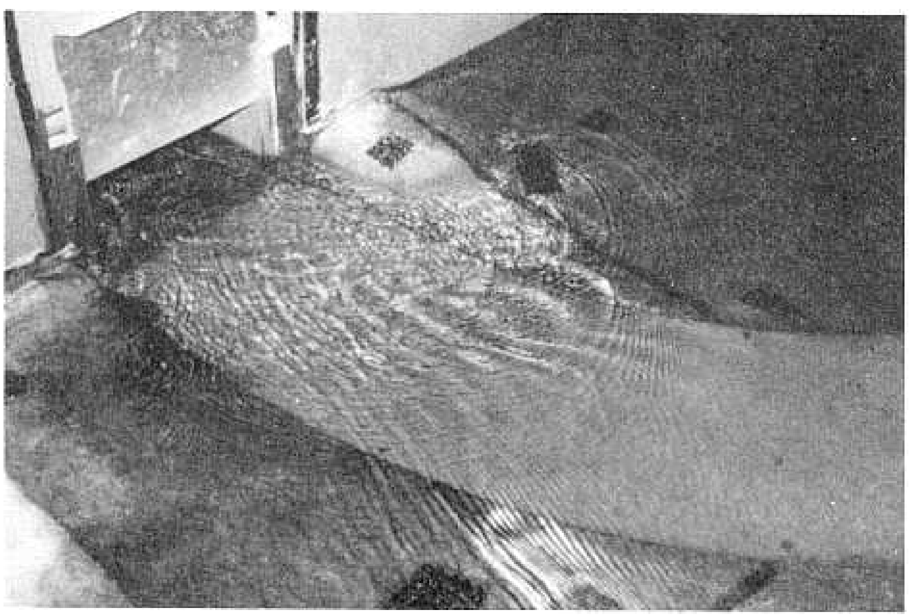


Figure 6. – Ogee spillway approach channel in model. Photo P801-D-81384

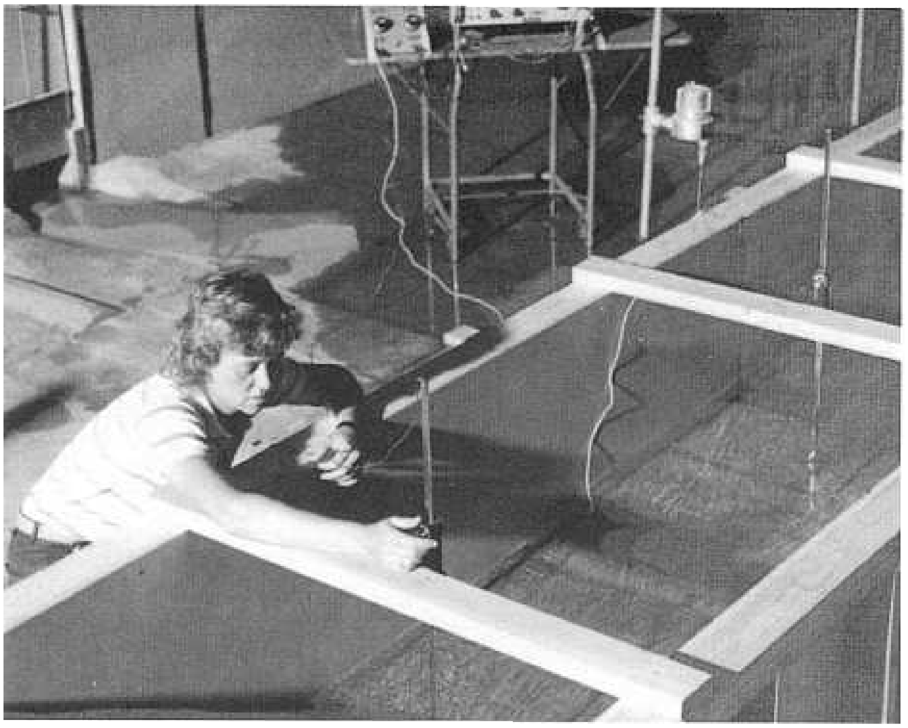


Figure 7. – Wave probability probe used with point gauges to measure water surface elevations. Photo P801-D-81385

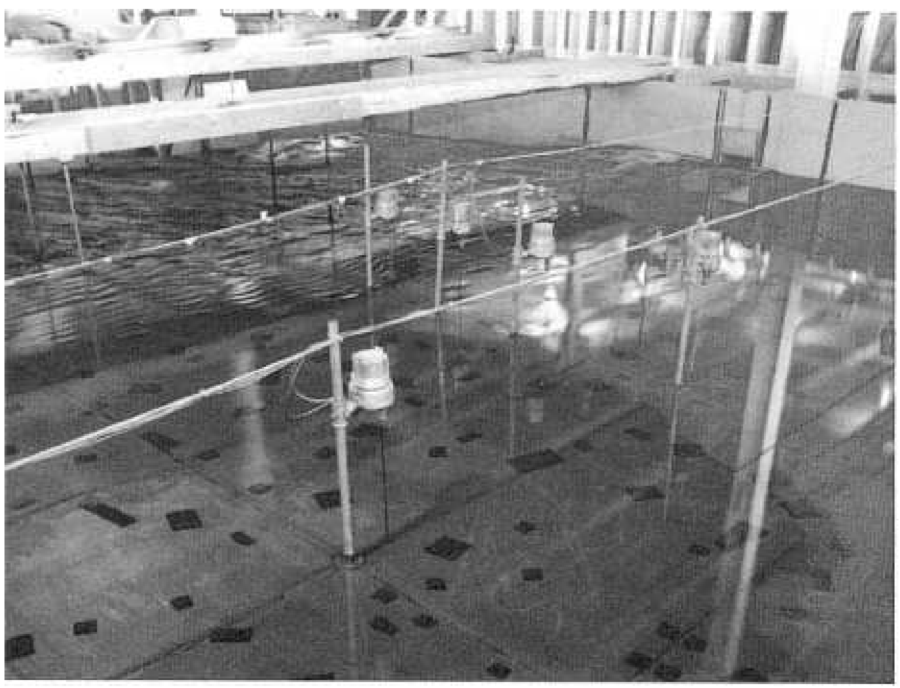


Figure 8. – Capacitance wave probes used in the large hydraulic model to measure water surface elevations. Photo P801-D-81386

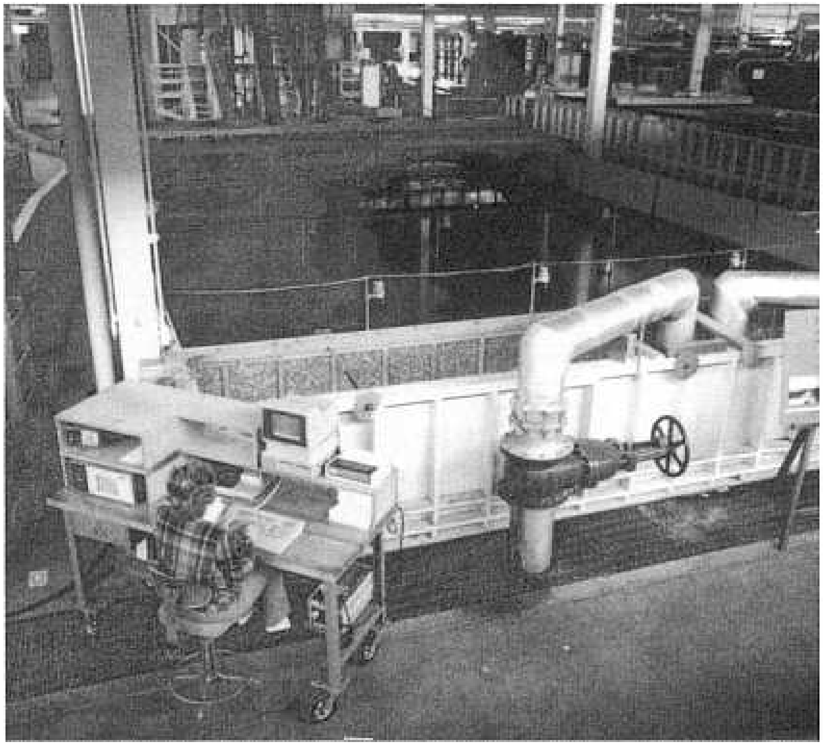


Figure 9. – Data acquisition system including HP 9816 computer. Photo P801 D-81387

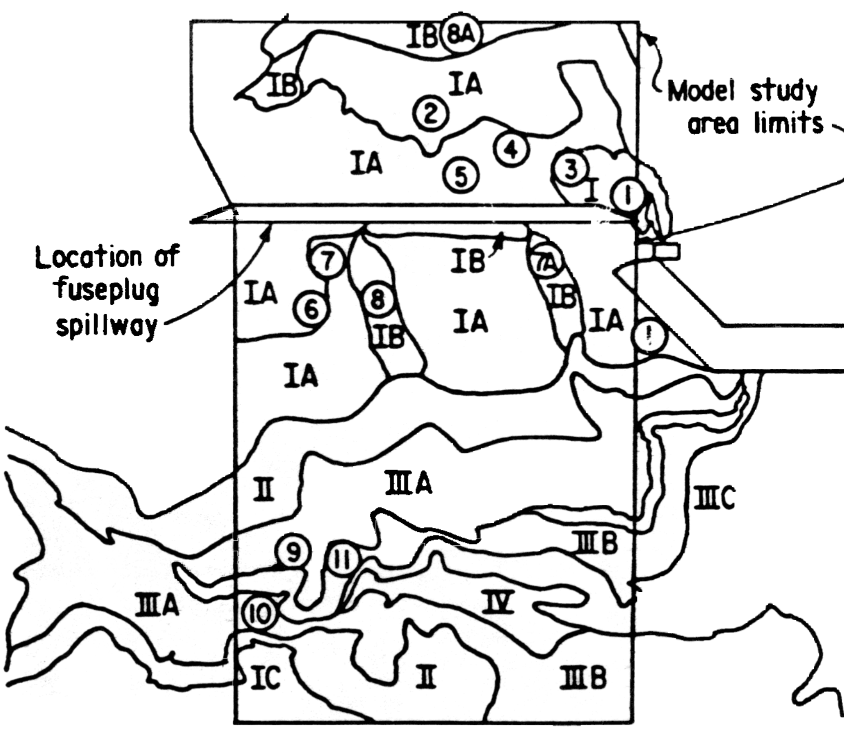


Figure 10. – Vegetation survey map of the study area. (See text for legend.)

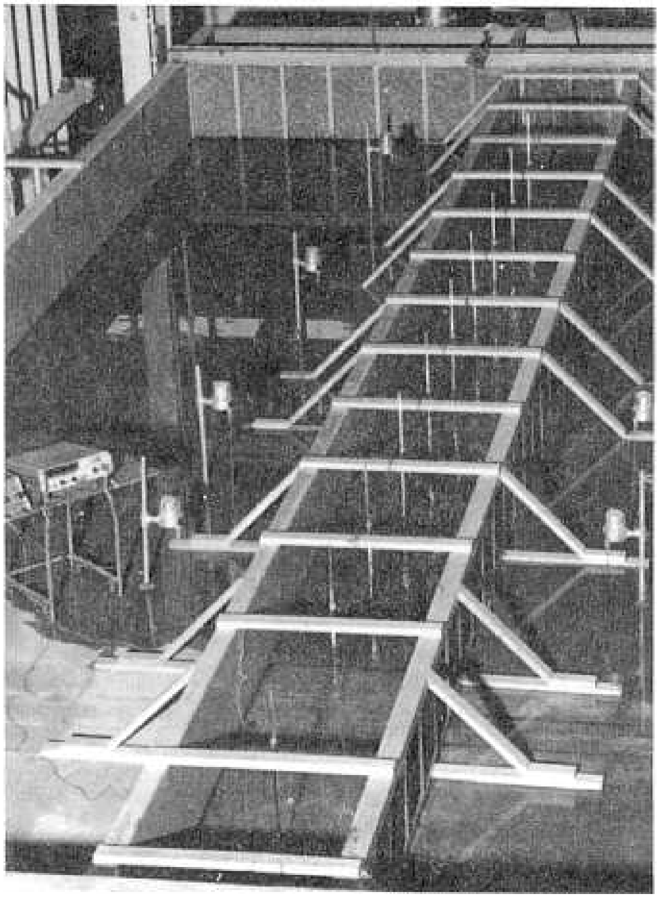


Figure   Flume inside large hydraulic model
roughness.   Photo P801-D-81388

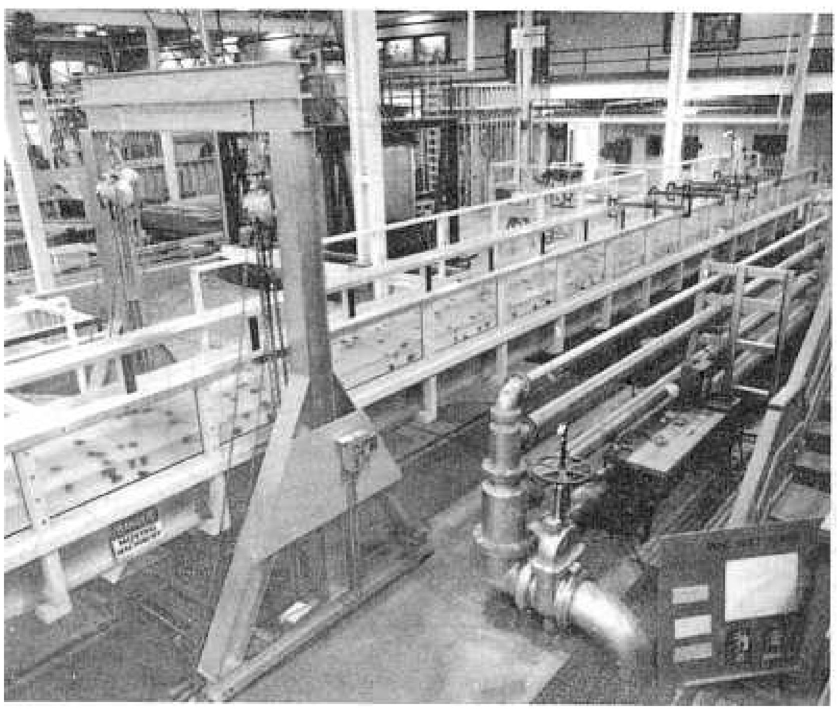


Figure 12. – Tilting flume facility   plastic   simulating   esquite
scale.   Photo P801-D-81389

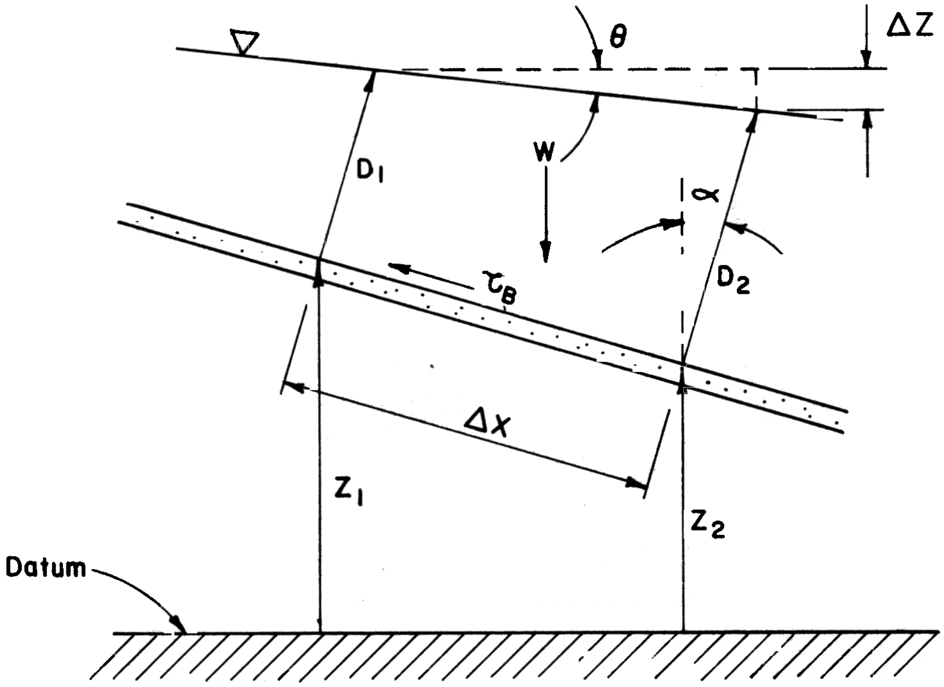


Figure 13. – Momentum balance diagram.

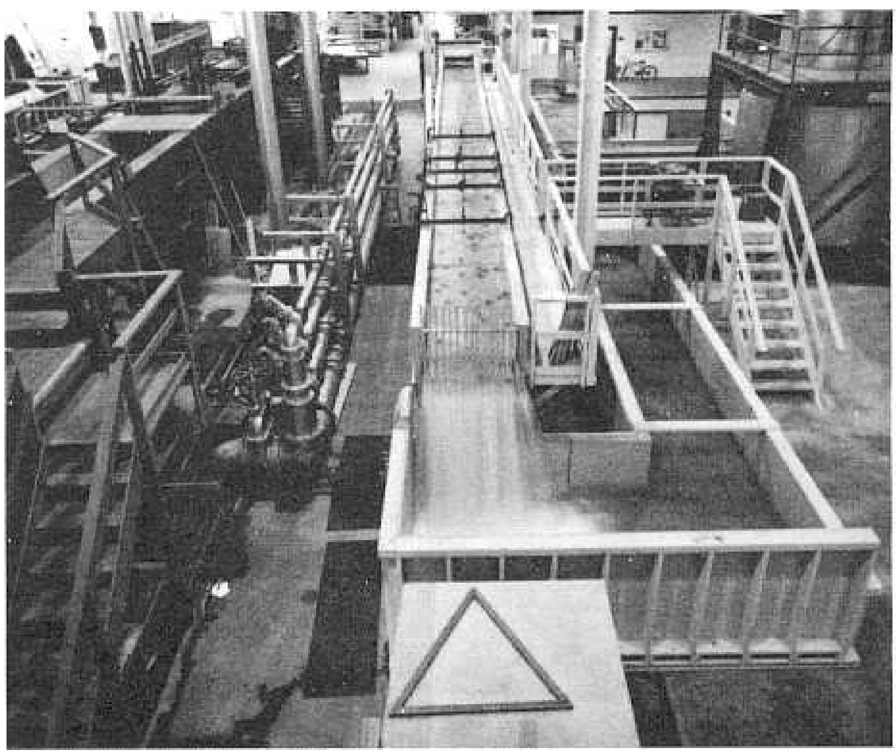


Figure 14. – Operation of the flume with plastic trees installed. Photo P801-D-81390

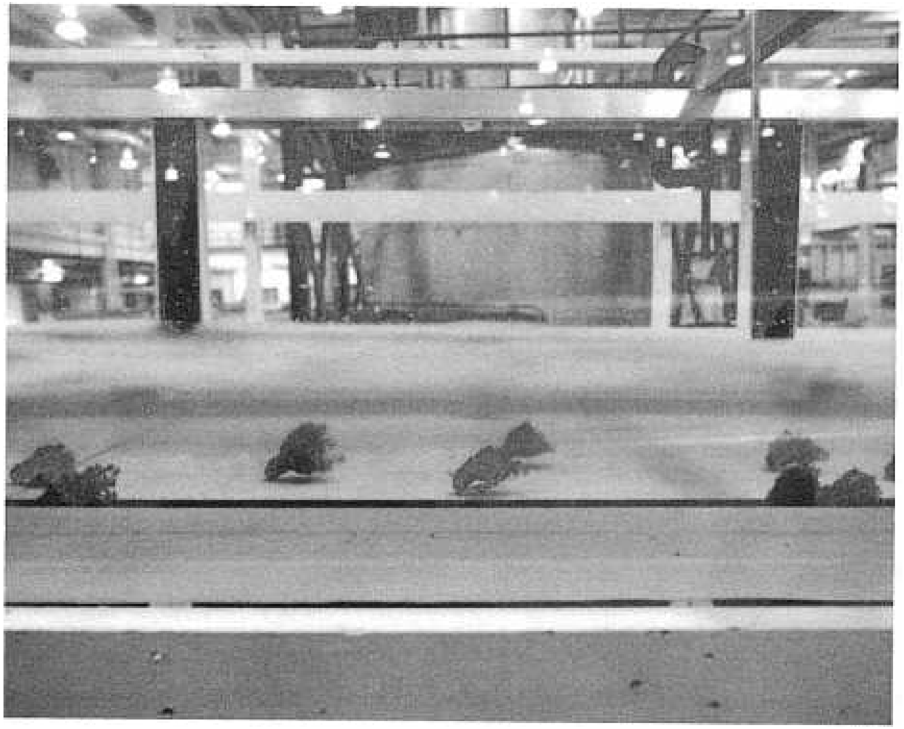


Figure 15. – Plastic trees being tested at a supercritical flow condition. Photo P801-D-81391

Figure 16. – Plastic trees being tested at a subcritical flow condition. Photo P801-D-81392

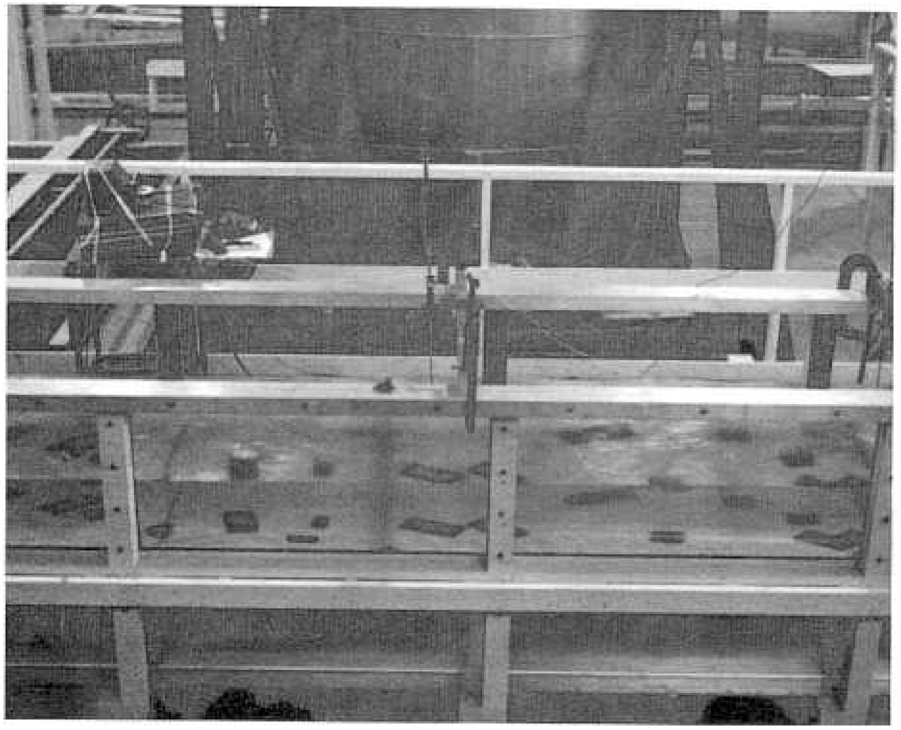


Figure 17. – Operation of the flume with outdoor carpeting installed to simulate the mesquite trees at a 1:150 scale. Photo P801-D-81393

Figure 18. – Effect of outdoor carpeting on the flow. Photo P801-D-81394

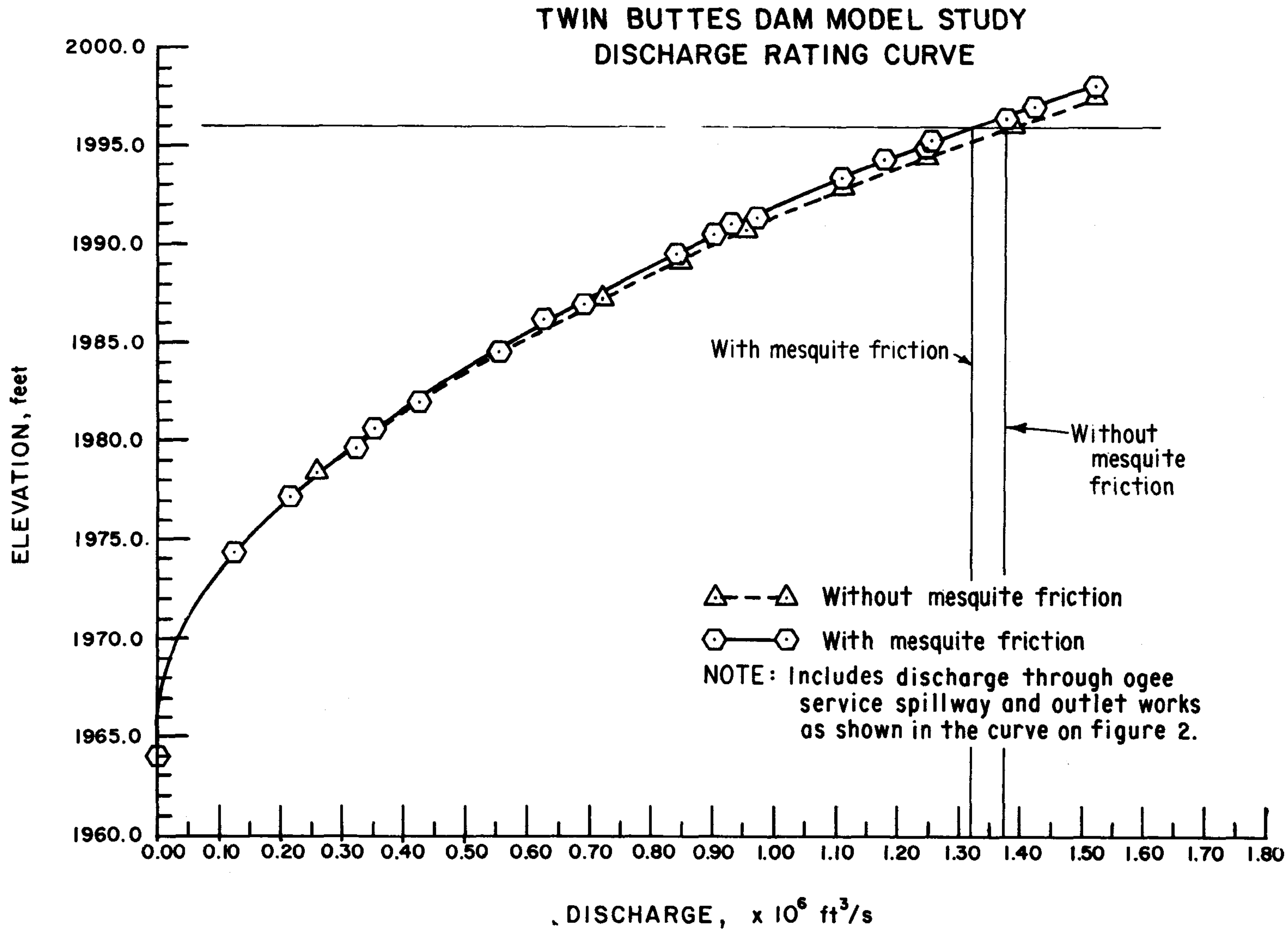


Figure 19. – Fuse plug spillway rating curves with and without mesquite friction. Twin Buttes Dam model study discharge rating curve.

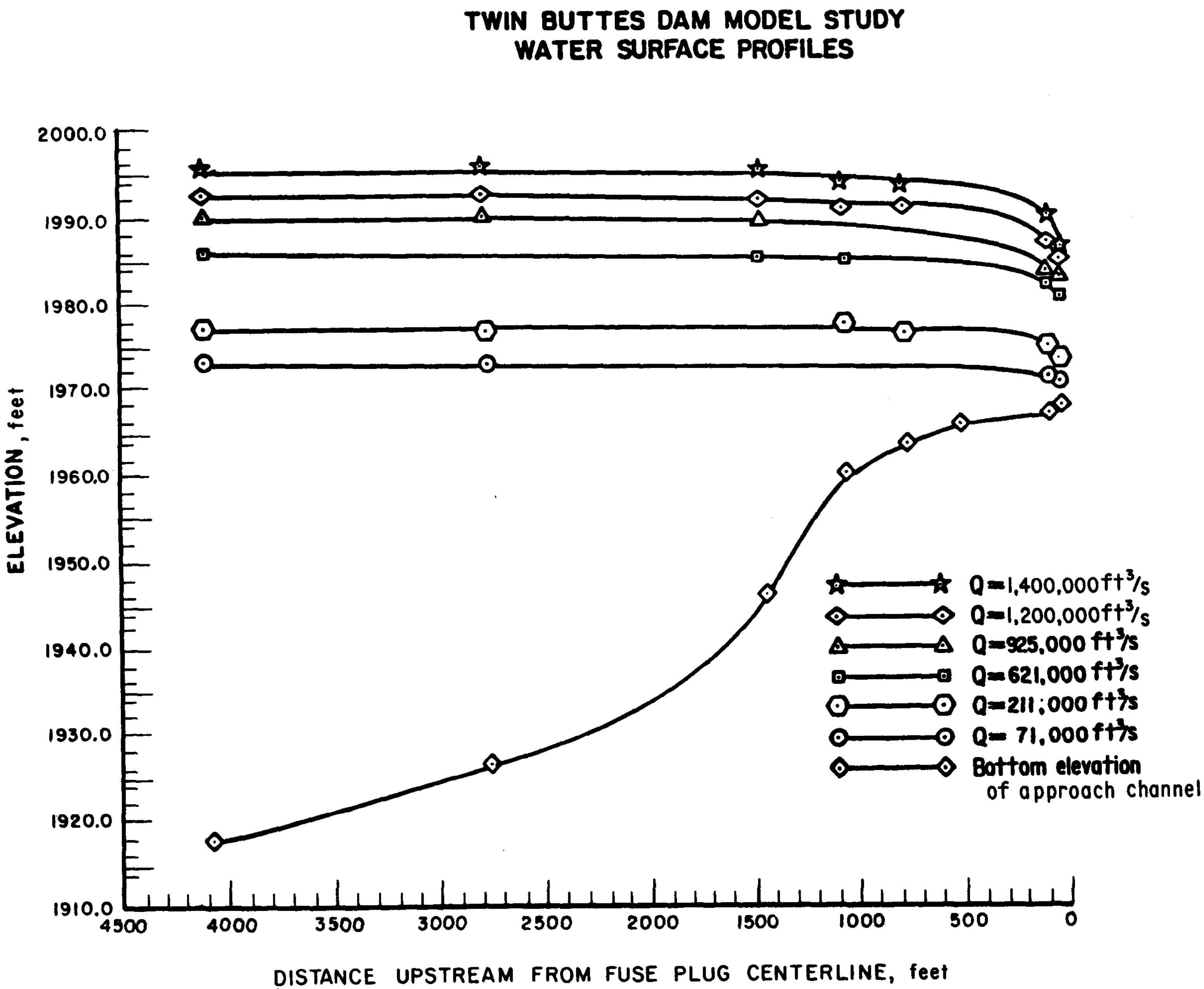


Figure 20. – Water surface profiles in approach to fuse plug spillway. Twin Buttes Dam model study water surface profiles.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-822A, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.