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Steady and Unsteady Flow Profiles in Reclamation

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Abstract

The Bureau of Reclamation owns and operates over 300 dams throughout the 17 western states. For most of these structures, tailwater measurements and steady-state water surface profile computations have been made using the PSEUDO program. Accuracy in water surface profile computations especially downstream from powerplants has been important. Small changes in differential head can mean large changes in power production and associated revenues generated. Peaking operations and flow fluctuations downstream from some dams has made flow conditions unsteady. The DWOPER program has been used to evaluate tailwater conditions under fluctuating flows at a number of sites. The STARS model was developed in Reclamation to incorporate the movement of sediment into water routing. Water surface profile computations are an integral part of the water and sediment routing process.

This paper presents case histories in the use of the PSEUDO, STARS, and DWOPER models in Reclamation to evaluate tailwater conditions. The developmental theories, varying uses, and intended purposes of the three models are discussed and comparisons of computed water surface profiles to measured data are presented.

Computational Procedures for Steady Flow Profiles

Computation of water surface profiles was a practice in Reclamation long before the advent of computers. Computations were originally completed by hand solving the Bernoulli energy equation for steady non-uniform flow along with the Manning's equation for channel roughness. Two computational methods were developed in Reclamation and simply named Method A and Method B.

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Method A is a standard step computation applicable for conditions where the flow path is assumed to be equal between cross sections for each sectional subdivision. The method is limited to relatively straight sections of river. Computational curves are developed for area and channel conveyance versus water surface elevation at each section for main channel and overbank roughness segments. The friction slope is averaged between sections. Eddy losses are computed as a fraction of the difference in velocity head between sections. The trial and error procedure sums the friction head, change in velocity head, and eddy losses to obtain an upstream water surface elevation equal to the assumed elevation.

Method B is an adaptation of Method A where reach lengths between cross sections are different. Bends in the river channel can be considered along with changes in roughness, area, and conveyance across a section. Additional curves are developed for hydraulic radius versus water surface elevation. A detailed discussion of the theory and the classic example computations for the Red Fox and Silver Fox Rivers are given by Lara (1958).

PSEUDO Program Development

In the 1960s with the development of computers, computer code for Method B was written in Fortran IV by E. Cristofano. The program was titled PSEUDO for which the author gave the acronym Prolific Synopsis of Engineering Utopia Designed Optimistically. In addition to computing standard step water surface profiles, routines were added to account for changes in discharge at a diversion or tributary, to calibrate Manning's roughness, to account for sediment accumulation, to tabulate hydraulic properties at a section, and/or to compute profiles through and over bridges and weirs (Strand, 1968).

Tailwater Study at Lake Tahoe for Bridges using PSEUDO

Lake Tahoe Dam is located on the California side of Lake Tahoe about 10 miles south of Truckee, California. The outlet works which was completed in 1913 is an 18-foot high concrete slab and buttress structure with 17 4-foot high by 5-foot wide vertical gates. Outflow passes over a protective slab before continuing downstream into the Truckee River. In 1981, the hydraulic and structural adequacy of the protective slab was under safety of dams evaluation. Tailwater studies were completed to provide the water surface profiles, rating curves, and velocity information necessary to verify that the hydraulic jump occurs and is maintained on the protective apron. The PSEUDO program was used to calculate water surface profiles from 70 to 8,000 ft^3/s. A single cross section was used at each of the bridges and located at the centerline of the bridge. Natural sections were surveyed both immediately upstream and downstream from the bridges. A main channel Manning's roughness value of 0.038 was calibrated using observed water surfaces at 70 ft^3/s. Water surface profiles at selected discharges are plotted on figure 1. The hydraulic study showed that the tailwater causes submergence of hydraulic jumps for flows of 1,000 ft^3/s and greater.

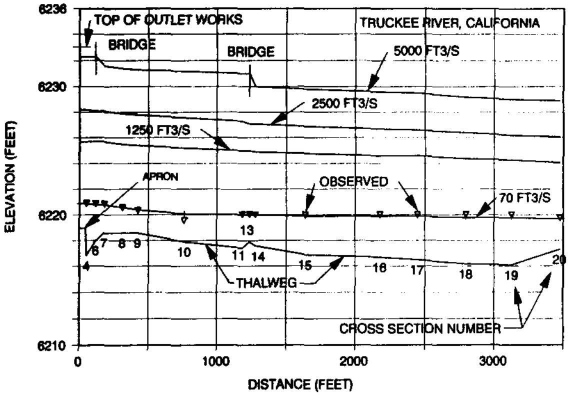

FIGURE 1. TAILWATER FOR LAKE TAHOE DAM

STARS Program Development

The standard step method is used to calculate water surface profiles in the STARS model. An upstream boundary discharge hydrograph and corresponding downstream boundary elevations are required input. From the water surface elevation at the most downstream section, calculations proceed upstream satisfying the conditions of conservation of energy, unless critical discharge occurs. The energy balance is voided when the computed water surface elevation has an adverse water slope (lower upstream elevation) or is below the critical elevation. When the computed water surface is below critical, the model raises the water surface to the critical depth. A Newton-Raphson algorithm with special checks for convergence problems is used to solve the energy balance, normal depth, and critical depth equations. Convergence is usually obtained in two or three iterations to a minimum tolerance in water surface elevation of 0.01 feet (Orvis and Randle, 1987).

The second distinguishing feature of the STARS model is the ability to compute hydraulics for streamtubes. The streamtube approach divides the flow into equal segments of conveyance and discharge. The total conveyance, summed from increments between individual coordinate points, is divided by a user supplied number of streamtubes. The lateral streamtube boundaries are located by interpolating between cross-section points.

Water Surface Profiles for the Grand Canyon

The first stage of the STARS modeling efforts on the Colorado River in the Grand Canyon was to compute water surface profiles with a fixed bed model to calibrate initial cross section data. The STARS model computed a continuous water surface profile for 225 miles of the Colorado River in the Grand Canyon. A Manning's roughness of 0.035 was calibrated and selected for the reaches downstream from Lees Ferry. The important parts of the profile are the reaches of river between the rapids and the drop in water surface through the rapids. Cross sections were carefully located at the bottom and crest of a rapid requiring no additional cross sections to represent geometries within a rapid. The objective in calibrating the cross section data was to determine the best possible geometric and hydraulic data for use in computing sediment transport and sand movement. Water surface elevations were surveyed at a number of rapids in 1985 at discharges of 18,800 and 27,600 ft^3/s (Randle and Pemberton, 1987). A typical profile showing the close agreement between computed and observed water surfaces for the reach above National Canyon to above Diamond Creek is presented as figure 2.

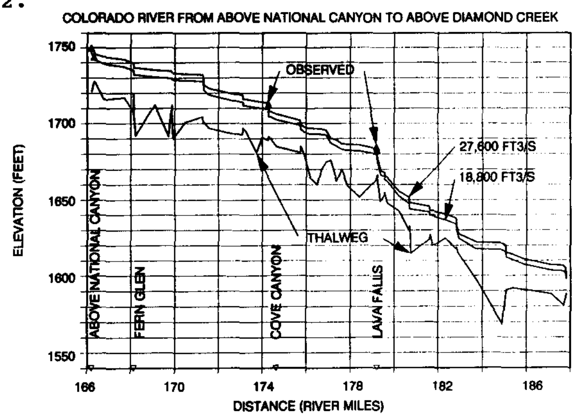

FIGURE 2. WATER SURFACE PROFILES IN THE GRAND CANYON

Theoretical Background for Unsteady Flow Profiles (DWOPER)

In the early 1970s, the National Weather Service Hydrologic Research Laboratory began developing the dynamic wave routing model now known as DWOPER (Fread, 1978). With increasing need to perform unsteady flow analyses for planning studies and river operations, Reclamation tested and adopted the DWOPER model (Randle, 1984). Powerplant releases during peaking operations at large dams fluctuate the downstream tailwater enough to classify the discharge as gradually varied unsteady flow. The basis for computations of unsteady water surface profiles in DWOPER is an implicit finite difference solution of the St. Venant partial differential equations of flow.

Water Surface Profiles Downstream from Grand Coulee Dam

A special flow regulation occurred at Grand Coulee Dam from May 21 through May 23, 1975 to simulate a power peaking operation. During this period, water surface elevations were recorded at various gaging stations along the 50-mile reach to Chief Joseph Dam. The transient flow tailwater conditions were of a concern for power production and riverbank stability in the 6-mile reach immediately downstream from Grand Coulee Dam. A sensitivity analysis completed in 1983 showed the importance of having cross section data which accurately define the volume of the channel, properly consider the expansion and contraction losses, and appropriately define the boundary conditions. Reasonable results for stage and discharge hydrographs were obtained at various intermediate points using a predetermined roughness coefficient of 0.037 and expansion and contraction loss coefficient of 0.5 and 0.1, respectively. Figure 3 compares the observed and computed stage hydrographs at River Mile 592.542 which is about 4 miles from Grand Coulee Dam.

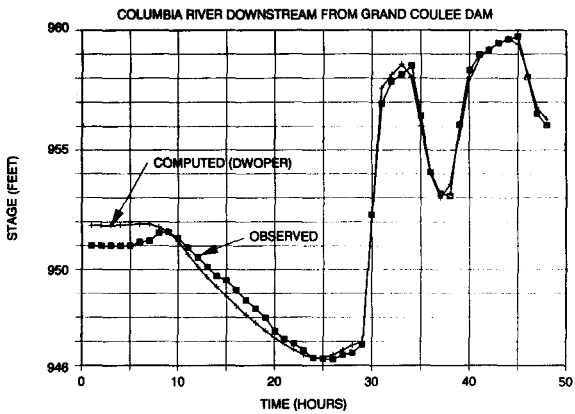

FIGURE 3. STAGE HYDROGRAPH AT RIVER MILE 592.542

Discharges at the observed site ranged from about 110,000 to 228,000 ft^3/s while discharges at Grand Coulee Dam ranged from 22,000 to 443,000 ft^3/s during the same 48-hour period (Blanton, 1976).

Conclusions

The PSEUDO, STARS, and DWOPER computer models have been successfully used in Reclamation to produce accurate water surface profiles or stage hydrographs for tailwater conditions at dams. The PSEUDO program was designed to be applied to steady-state fixed bed conditions and can be used to evaluate tailwater conditions with bridges or weirs. PSEUDO results showed reasonable agreement between observed and computed tailwater elevations for the Truckee River downstream from Lake Tahoe Dam. The STARS program was designed to compute numerous water surface profiles through a moveable bed simulation. STARS computed water surface profiles for the Colorado River in the Grand Canyon compared closely to measured data. For unsteady flow conditions, the DWOPER program has provided practicable results in a peaking power simulation for the 50-mile reach of the Columbia River downstream from Grand Coulee Dam.

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