SYNOPSIS

The Bureau of Reclamation's Tehama-Colusa Canal in the California Central Valley Project is the first known dual-purpose canal being used both as a spawning grounds for salmon and also as a conveyance structure to supply water to irrigated lands.

Water which enters the canal from the Sacramento River carries a moderate load of suspended sediment. The sand and silt sizes of this sediment will be removed in a settling basin. Seven to seventeen acre-feet of clay size sediments will pass into the canal each year and deposit in the 2-1/2-foot-thick layer of gravel (3/4 to 6 inches in diameter) placed in the bottom of 3.22 miles of the concrete-lined canal for spawning purposes.

Several gravel cleaning methods, including underdrains, water and air jets, and mechanically cleaning the gravel, were studied before the baffle gate was developed to clean fine sediment from gravel. The adjustable baffle gate is mounted on a carriage spanning the 140-foot-wide canal and is lowered into the water sufficiently to increase the velocity beneath the baffle gate to scour the gravel to the concrete canal bottom.

Model tests were made in a 25-foot-long section of a 4-foot-wide by 8-foot-deep flume in the Bureau's laboratories in Denver, Colorado, to provide a basis for designing the field size baffle gate cleaning device.

RESUME

Le canal Tehama Colusa de la Central Valley Project de Californie, construit par le Bureau de Réclamation, est, à notre connaissance, le premier canal ayant double emploi. Il sert à la fois de frayère à saumons et de moyen de distribution d'eau d'irrigation.

L'eau vient de la Sacramento River. A son arrivée dans le canal elle contient une quantité modérée de matériaux sédimentaires en suspension. Le sable et le limon sont retenus dans un bassin de décantation. Cependant de 8,640 mètres cubes à 21,200 mètres cubes (sept à dix-sept acres-pièces) de sédiments argileux se déposent chaque année sur la couche de gravier (1,8 à 16 cm de diamètre) (3/4 à 6 pouces) de 70 cm d'épaisseur (2 pieds et demi) qui recouvre le fond du canal sur une distance d'environ 4,8 km (3,22 milles).

Avant d'aboutir à la méthode d'emploi d'une vanne de déflexion pour le nettoyage du gravier, nous avons étudié des méthodes différentes, par exemple: les systèmes de drains sous-jacents, les jets d'eau et d'air sous pression, et le nettoyage mécanique du gravier. La vanne réglable est montée sur un châssis qui traverse le canal dans toute sa largeur (46,6 m environ) (140 pieds). La vanne peut être plongée dans l'eau de façon à augmenter la vitesse du courant qui passe dessous. C'est ce mouvement qui permet au gravier d'être nettoyé jusqu'au béton du revêtement.

Les essais ont été faits dans les laboratoires du Bureau de Réclamation à Denver (Colorado) sur un modèle réduit représenté par une section de radiers mesurant 8 m de longueur, 1,32 m de largeur et 2,6 m de profondeur (25 pieds, 4 pieds, 8 pieds). Ce sont ces essais qui ont fourni la base des caractéristiques pour la construction de la vanne de déflexion qui sert au nettoyage.
INTRODUCTION

The extensive effort to provide fish spawning facilities on the Bureau of Reclamation's Tehama-Colusa Canal in the California Central Valley Project exemplifies the increasing importance of secondary features of multiple-purpose water projects. Artificial spawning channels are not uncommon, but this is the first known example of a canal being used for dual purposes, a spawning grounds for fish and also a conveyance structure to supply water to irrigated land.

Tehama-Colusa Canal is part of the Sacramento Canals Unit, Sacramento River Division of the Central Valley Project in California. The canal is designed to carry 2,530 cubic feet per second diverted from the Sacramento River at the Bureau's new Red Bluff Diversion Dam located near Red Bluff, California. The upstream 3.22 miles of the concrete-lined canal will be used as a combination irrigation and fish spawning channel (dual-purpose channel). On the concrete canal bottom, 2.5 feet of 3/4- to 6-inch-diameter processed spawning gravel will be placed. The width of the canal at the gravel surface is 100 feet. Design depth, for a discharge of 2,530 cfs, is 6.59 feet for a smooth gravel bed, and is 8.25 feet when the gravel bed is covered with redds (nests made by the spawning salmon), Figure 1.

At the end of the dual-purpose channel, 230 cfs is diverted to two parallel single-purpose (fish spawning) channels each carrying 115 cfs. The 3/4- to 6-inch spawning gravel is also placed 2.5 feet deep in these channels and water flows 1.5 feet deep over the gravel. The remaining discharge (2,300 cfs) continues down Tehama-Colusa Canal which carries water to Tehama, Glenn, Colusa, Lower Cache Creek, Solano, Yolo, and Zamora service areas for irrigation. Water in the single-purpose spawning channels discharges into Oat Creek and passes back into the Sacramento River. Adult salmon will take the same route except in the reverse direction when they come from the ocean to the spawning area in Tehama-Colusa Canal where they were hatched from eggs deposited by their parents. To start the cycle, adult salmon will be trapped at Red Bluff Diversion Dam and placed in the spawning channels, Figure 2.

This study is concerned with the 3.22-mile, dual-purpose channel in Tehama-Colusa Canal and specifically with cleaning deposited sediment from the 2.5-foot-deep spawning gravel in the dual-purpose channel, and related problems.

Upstream from the Tehama-Colusa dual-purpose channel and downstream from Red Bluff Diversion Dam, a 2,163-foot-long trapezoidal-shaped settling basin 260 feet wide on the bottom and 23 feet deep will be constructed to trap sediment. This basin traps the sand sizes and silt sizes of sediment. It is the smaller clay sizes of sediment that pass through the settling basin and which will settle in the spawning gravel. The spawning gravel must be free of deposited sediment during the time salmon eggs are in the gravel so that water saturated with oxygen can flow around the eggs continuously keeping them alive to hatch into salmon fry. Salmon eggs that do not have a continuous supply of oxygen as contained in the flowing water will die before they hatch. To make the gravel free of sediment and to provide a sediment-free resting place and hatching place for the salmon eggs, a cleaning device called a baffle gate was developed and tested in the Bureau's hydraulic laboratory for use in the Tehama-Colusa Canal.

GRAVEL CLEANING PROBLEM

To keep the problem of cleaning sediment from the spawning gravel as simple as possible and to do the job effectively, a hydraulic means, using the energy of the water in the canal, was decided as the most practicable. Preliminary studies in the hydraulic laboratory on other methods and concepts indicated this would be the most logical approach. The Fish and Wildlife Service specified that a period of 1 month, and at the maximum 2 months, would be available to clean the spawning gravel. The fall spawning period for Chinook salmon extends from October through
December, and the incubation and emergence period follows extending through April. A spring spawning, incubation, and emergence period would utilize all but one or two of the remaining spring and summer months. Therefore, it is very important that a rapid method of cleaning the gravel be used.

Previously Used Cleaning Methods

The artificial spawning channel at Rocky Reach Dam on the Columbia River is cleaned with a bulldozer having a rake mounted where the blade is usually mounted. The bulldozer can operate at normal depth (1-1/2 to 2 feet) and can agitate the gravel to its full depth with the rake. Water at a relatively high velocity and shallow depth flows through the channel during the cleaning operation, washing fine sediment from around the gravel into suspension and carrying it downstream and out of the channel.

Abernathy spawning channel near Long View, Washington, which has 3/4-inch gravel about 1 foot deep is cleaned by hand with a portable pump supplying water to a hose and nozzle. At both Rocky Reach and Abernathy spawning channels the water is shallow, 1-1/2 to 2 feet deep, whereas in Tehama-Colusa Canal the water flows deeper than 6-1/2 feet.

Windblown Sand Problem

A problem caused by coarse sand being blown into the spawning gravel by wind action has arisen on at least one artificial spawning channel. The sand size sediment will not stay in suspension in the low velocity flowing water, and therefore the normal channel flow cannot be used to clean the spawning gravels containing sediment in the sand sizes. To clean sand from the spawning gravel in a low velocity channel requires mechanically handling the gravel and separating the sand from the gravel in some manner. One method that has been used was to windrow the gravel on one side of the channel and then the other side using a dragline. High velocity water at lower depths would then flow down the excavated channel washing accumulated sediment to the end of the channel. The process was only partially successful but was very expensive. During one cleaning operation the cost was approximately $3.60 per cubic yard.

Tehama-Colusa spawning channel is constructed in an area that is completely covered with agricultural crops where sand will not ordinarily be picked up by the wind. Consequently, Tehama-Colusa spawning channel will not be faced with the windblown sand problem.

VELOcity FIELD REQUIREMENT AND ROUGHNess VALUES FOR SPAWNING GRAVEL

Two basic requirements for salmon eggs deposited in spawning gravel are: (1) that they be protected from predators and from dislodgment from the gravel, and (2) that they have a continuous supply of oxygen during incubation and emergence. These requirements may be stated in the terms that: (1) the physical condition (size and gradation) of the gravel, and (2) the velocity field in the vicinity of the bed will be attractive to the adult salmon for their spawning activities of building redds and for depositing eggs.

For the Chinook spawning channels of Tehama-Colusa Canal, biologists of the Fish and Wildlife Service have determined that to have desirable conditions for the spawning salmon the flowing water should have a velocity within the range of 1.5 to 2.5 feet per second at a point 0.3 foot above the gravel bed and that the gravel should be in the size range of 3/4 to 6 inches in diameter. To achieve the required velocity distribution for this specified gravel bed in a concrete-lined canal requires that definite relations be established between the channel roughness (gravel bed and concrete side slopes), hydraulic slope, boundary shear and depth.
To determine what the hydraulic slope should be to satisfy the required velocity distribution above the gravel bed, the assumption was made that the expression for local boundary shear, $T_0 = yds$, would apply over the entire 100-foot-wide bed. For wide channels where the bed width is 10 times the depth or greater, the maximum tractive force on the bottom is approximately the same as the maximum tractive force on the bottom of very wide channels.\(^1\) The semilogarithmic velocity distribution equation,

$$v_y = 5.75 \sqrt{\frac{T_0}{\rho}} \log \frac{30y}{k};$$

where $y =$ distance from boundary in feet, $T_0 =$ local boundary shear in pounds per square foot, $v_y =$ velocity at distance $y$ from boundary in feet, $k =$ roughness (mean particle diameter in feet), $\rho =$ mass density in slugs per cubic foot, was related with Manning's equation,

$$\bar{v} = \frac{1.49}{n} (d)^{2/3} (S)^{1/2}$$

where $\bar{v} =$ mean velocity in feet per second, $n =$ roughness value, $d =$ depth (substituted for hydraulic radius because of the wide channel), and $S =$ hydraulic gradient.

Over the range of depths expected to occur in Tehama-Colusa Canal the relation $n = 0.032 k^{1/6}$ between Manning's roughness coefficient and mean gravel size was derived.\(^2/3/4\)

From these relationships and water requirements for irrigation, design values for Tehama-Colusa spawning channel were computed as follows: design discharge $Q = 2,530$ cfs. For a smooth gravel bed, the Manning roughness value for the gravel bed $n_g = 0.025$, Manning's roughness value for concrete side slopes $n_c = 0.015$, concrete side slopes $= 2:1$, depth $d =$ 6.59 feet, hydraulic radius $R =$ 5.76 feet, cross section area $A =$ 745.9 square feet, slope $= 0.00027$, bed width $b =$ 100 feet, mean velocity $V =$ 3.39 feet per second, and effective Manning's roughness value $n_e =$ 0.023.

Where the gravel bed is covered with reds dug by the salmon, Manning's $n$ value for the gravel bed $n_g =$ 0.040, and $d =$ 8.25 feet, $b =$ 100 feet, $R =$ 7.02 feet, $V =$ 2.63 feet per second, $n_c =$ 0.015, slope $= 0.00027$, and $n_e =$ 0.034.

The effective Manning's roughness value for the channel was computed using the formula

$$n_e = \left[ \frac{P_b n_g^{3/2} + P_c n_c^{3/2}}{P} \right]^{2/3}$$

where $P_b$, $P_c$, and $P$ are the wetted perimeter of the gravel bed, the concrete side slopes and the total wetted perimeter, respectively. The other values are as shown above.

**LABORATORY EXPERIMENTAL TESTS**

Exploratory tests were conducted in a small 2-foot-wide by 2-foot-deep by 8-foot-long flume to determine which method of various possibilities of cleaning sediment from the spawning gravel had the most promise of being successful. Prototype size gravel was placed in the flume to a depth of 1 foot. Preliminary tests were made using the following cleaning methods: (1) Water and sediment pumped into or out of the underdrains, (2) Jets using water and/or air pumped into the gravel to flush sediment, (3) A floating barge with and without baffles on its underside and having a differential head upstream to downstream of the barge, (4) A mechanical cleaning machine which would pick up the gravel from the canal bottom, wash it and lay it down again, and (5) A baffle gate method by which sediment was washed from the gravel as the gravel was moved a short distance downstream.

\(^1\)Numbers refer to references listed at the end of the paper.
Tests were made in the 2-foot-wide by 2-foot-deep flume using fine sand, clayey soil, and commercial silica flour deposited in the gravel. Tests showed that the fine material could be washed from the gravel but only at a very slow rate; for example, using silica flour with a head differential of 0.80 foot (which is a maximum head across the baffle before gravel begins to move), the fine sediment would wash out of a semicircular volume of gravel 1 foot deep in approximately 10 minutes with the baffle gate stationary. To wash fine sediment out of the spawning gravel in the time allowable to clean the prototype gravel, it would be necessary to move individual gravel particles with a high velocity flowing around each gravel particle.

Tests in Large Flume

After results of testing in the 2-foot-deep by 2-foot-wide flume showed that a baffle gate method of cleaning the gravel was the most practical, this method was pursued in a large laboratory flume 4 feet wide by 8 feet deep by 80 feet long. A 20-foot-long section of the large flume was made 2 feet wide in which 2-dimensional sectional model tests were continued. The flume width was reduced so the amount of gravel to be handled would be smaller and greater depths could be achieved for the capacity of the pumping system (about 26 cfs).

The baffle gate in the flume consists of a piece of 3/4-inch plywood mounted vertically on a movable carriage so that it could be lowered into the flowing water. The baffle gate partially and temporarily restricts the normal flow of the water causing it to flow under the bottom of the gate at a velocity higher than the usual channel velocity.

Prototype gravel with gradation limits as follows was used in the 1:1 scale model tests:

<table>
<thead>
<tr>
<th>Sieve size, U.S. standard square mesh, inches</th>
<th>Percent by weight passing individual sieve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largest allowable</td>
<td>Smallest allowable</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
</tr>
<tr>
<td>1-1/2</td>
<td>15</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3/4</td>
<td>0</td>
</tr>
</tbody>
</table>

These limits of size gradation were satisfactory to the Bureau of Sport Fisheries and Wildlife requirements, and adequate quantities are available in one or more of the gravel sources near Tehama-Colusa Canal spawning channel.

Scour of Gravel with Baffle Gate

To develop relationships between the variables of discharge, position of gate above gravel bed, depth of scour, and differential head across the gate, tests were made with the baffle gate stationary and varying the discharge and the vertical position of the gate. Tests were made with prototype size gravel in the 8-foot-deep flume up to the capacity of depth and discharge of the flume and the water circulation system. Depths of approximately 4 feet above the gravel bed for a discharge of about 21 cfs could be obtained with the 1:1 scale tests. To make tests in which full prototype depth could be modeled, the scale was reduced to 1:2 based on the Froude model law. Because movement of the gravel depended primarily on velocity of flow under the gate and individual grains projecting into the flow, the size of gravel was also reduced, scaled on the basis of diameter. Tests at 1:1 and 1:2 scales gave similar results.

Tests using 1:1 scale were made with the lower edge of the baffle gate 1/2 foot above the gravel bed, level with the bed, and 1/2 foot below the gravel bed. Spawning gravel will be placed 2-1/2 feet thick on the concrete bottom in the prototype. This same depth of gravel was used for all scour tests in the 1:1 scale model.

Tests were made to relate the depth that the gravel would be scoured to two variables. (1) The position of the lower edge of the baffle gate above the gravel,
and (2) the differential head across the baffle gate, Figure 3. A differential head of approximately 1-1/2 feet for all discharges tested was required to scour the gravel to the canal concrete bottom continuously as the baffle was moved upstream. Tests were made with the baffle gate moving upstream to simulate the action visualized for the prototype operating in the full-sized canal.

At the beginning of the cleaning operation, the baffle gate is lowered until a transverse channel is dug into the gravel and the removed gravel is mounded downstream on the original gravel surface. The baffle gate is then moved slowly upstream (1 to 2 feet per minute) and gravel layers are peeled off the upstream face of the depression scoured in the gravel and deposited on the downstream face of the depression. In this process, individual particles of gravel are moved rapidly and the sediment around the gravel particles is washed into suspension and carried downstream with the flowing water.

The relationship between scour depth of the gravel under the gate, and discharge was found to be linear. A relationship describing flow under the baffle gate was developed which has the form of the submerged orifice equation,

\[ Q = CA \sqrt{2gh} \]

where \( Q \) = discharge under the gate, \( A \) = area under the gate through which water flows, \( h \) = differential head across the gate, \( g \) = acceleration of gravity, and \( C \) = dimensionless coefficient.

The upstream and downstream depths do not appear in the equation because they do not affect the performance of the baffle gate cleaning device in the range of depths tested (3.3 to 8.1 feet). All of the tests made with full size and 1/2 size gravel showed that the baffle gate worked very well in scouring and washing the sediment out of the gravel. Fine uniform sand (0.2-mm mean diameter) was used to represent the fine deposited sediment in the scour tests. All the sediment scour tests showed that the fine sand was readily washed out of coarse gravel and up into the flowing water. The vital and indispensable feature of the baffle gate system was that it moves the gravel and in doing this the action of washing the sediment from the gravel is rapid and positive.

**VELOCITY BARRIER FOR SMALL FISH**

The Fish and Wildlife Service was concerned with the problem of crowding (moving) small fish out of the dual-purpose spawning channel and asked that the baffle gate sediment cleaning apparatus be used for this purpose if possible. An average velocity field of 5 feet per second or greater under the baffle gate was required to prevent the small fish from penetrating the velocity barrier.

Hydraulic tests were made in the large flume to determine the velocity field that could be maintained under the baffle gate without causing the gravel to move. Velocities were measured in a vertical plane 2 feet downstream from the baffle gate. Tests at scales of 1:1 and 1:2 using the Froude model law to scale all values, including the size of the gravel, were made for prototype discharges of 750, 1,300, 1,800, and 2,400 cubic feet per second. Vertical velocity distributions were measured with the baffle gate raised to various positions above the gravel bed. The results showed that a mean velocity under the baffle gate of 5 feet per second and greater could be maintained without scouring the spawning gravel.

Previous tests using dye to trace flow lines through the gravel showed that water at rather high velocities flows in a curved path under the baffle gate and penetrates the gravel. The relatively high velocities through the gravel which continue to occur as the baffle gate moves downstream will cause the small fish to move out of the gravel and on downstream.
CONCLUSIONS

Hydraulic flume tests for Tehama-Colusa Canal spawning gravel showed that the developed baffle gate method of cleaning fine sediment from 3/4- to 6-inch-diameter spawning gravel is the best cleaning device yet investigated. Underdrains, water and air jets, and a floating barge with and without baffles extending down under the barge were tested but were not satisfactory to do the job of cleaning the gravel in the time available. The baffle gate is lowered into the flowing water sufficiently to produce a high velocity beneath the gate. The high velocity flow scours the gravel to the concrete floor and moves the gravel downstream a short distance. The gravel is then laid back down with little sorting.

A differential head of 1-1/2 feet across the baffle gate is required to scour the 2-1/2-foot-deep gravel layer to the concrete canal bottom. As the gravel is moved, fine sediment is washed from the gravel particles up into the water flowing above the gravel. Figure 4 shows an artist's conception of the prototype machine.

Tests showed that the gravel cleaning machine can also be used to dig resting pools for the spawning salmon and for creating a 5-foot-per-second average velocity barrier to force small fish to move downstream and out of the canal.

REFERENCES

3. Hebert, D. J., "Hydraulic Design of a Channel Adapted to Use as a Salmon Spawning Facility," paper presented at ASCE, Hydraulics Division Conference, Tucson, Arizona, August 1965
Figure 1. As the Chinook Salmon dig their redds (nests) in the spawning gravel the hydraulic roughness is increased from $n = 0.025$ to $n = 0.040$.

Figure 2. Tehama-Colusa Canal water is diverted from the Sacramento River at Red Bluff Diversion Dam. The dual purpose (irrigation and salmon spawning) channel is located at the head end of the canal, downstream from a settling basin.
Figure 3. Operating conditions of the baffle gate cleaning device, Tehama-Colusa spawning channel.

Figure 4. Artist's conception of the prototype baffle gate cleaning device for Tehama-Colusa spawning channel.