LABORATORY AND FIELD INVESTIGATIONS

OF SEDIMENT CONTROL STRUCTURES AT DIVERSION DAMS

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By

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SUMMARY AND CONCLUSIONS

The model studies and investigations of field performance of sediment control structures at diversion headworks discussed in the paper have shown that the amount of bedload sediment entering a canal can be controlled to a significant extent. This can be done by arranging the entrance to the headworks and sluiceway to give favorable flow conditions for controlling the movement of bedload sediment.

Curved guide or training walls which confine and guide the flow around a curve, develop a secondary spiral current in the flow causing bedload sediment to move to the inside (convex side) of the curved channel. Constructing a curved entrance channel in proper plan with respect to the headworks and sluiceway causes the bedload sediment to move toward and out the sluiceway. The sediment control action can be obtained using curved guide walls with either intermittent or continuous sluicing flow. Intermittent sluicing flow is more efficient for removing bedload sediment than continuous sluicing flow. Field experience has shown that intermittent sluicing works very well for Superior-Courtland, Bartley, and Woodston Diversions constructed in Nebraska and Kansas. They have curved guide or training walls for bedload sediment control.

A basic principle for controlling bed sediment at an intake to a canal is to control the flow to minimize the disturbance near the channel bed in the vicinity of the intake to the canal. This basic principle was used in developing the short tunnel undersluice. The short tunnel undersluice divides the flow in two horizontal layers. Flow carrying bedload sediment goes under the horizontal roof of the undersluice and into the sluiceway. Flow diverted into the canal is that flow over the roof of the undersluice. If flows are divided properly bedload is not raised from the bed and drawn into the canal. Entrances to the canal headworks and sluiceway must be close together for the short tunnel undersluice to be most effective for controlling bedload sediment.

Hydraulic model studies were performed to develop the short tunnel undersluice structure built at Milburn and Arcadia Diversions on the Middle Loup River in Nebraska. The river has a comparatively

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uniform hydrograph and fine sand bedload sediment. Review of field operation of these diversions shows that the short tunnel undersluice structures are operating as the model studies predicted in keeping bedload sediment from going into the canals.

RESUME ET CONCLUSIONS

Les recherches sur modèles et les renseignements obtenus sur le terrain visant les structures qui permettent le contrôle des sédiments au niveau des travaux de tête, ont été discutées dans le présent article. Elles ont montré que l'on pouvait assez bien contrôler la quantité de sédiments qui entrent dans le canal. Le résultat peut être obtenu grâce à un profil spécial à l'entrée des travaux de tête et dans le canal d'évacuation qui offre les conditions les plus favorables à l'écoulement et au contrôle des sédiments charriés par le courant.

Les courbes directrices ou les murs de guidage qui dirigent et guident le flot dans les virages, créent un courant secondaire en spirale, avec pour effet le dépot de sédiments à l'intérieur de la courbe (côté convexe) dans le canal. Si l'on construit un canal à entrée courbe en fonction des travaux de tête et du canal d'évacuation, on obtiendra un mouvement des sédiments dans le lit du courant dirigé vers l'avant et la sortie du canal d'évacuation. Le contrôle des sédiments peut être obtenu en employant des murs courbes de guidage, qu'il s'agisse d'un courant d'évacuation intermittant ou continu. Un courant d'évacuation intermittant est plus pratique qu'un courant continu pour se débarrasser des sédiments. On a constaté sur le terrain qu'un courant d'évacuation intermittant réussissait très bien dans les détournements de Superior-Courtland, Bartley et Woodston, construits au Kansas et au Nébraska. On y emploie des courbes directrices et des murs de guidage pour contrôler les sédiments.

L'un des principes de base pour diriger les sédiments au niveau de la tête d'un canal consiste à contrôler le courant pour limiter les perturbations dans le lit du courant à ce niveau. Ce fût le principe employé dans la construction de courts tunnels d'évacuation: le tunnel court pour l'évacuation divise le courant en deux couches horizontales. Le courant qui transporte les sédiments va sous le toit horizontal du tunnel, puis dans le canal d'évacuation. Le courant qui va dans le canal est celui qui coule au dessus du toit du tunnel. Si le courant est divisé correctement, les sédiments ne s'élèvent pas dans le lit du courant et ne vont pas dans le canal. Les entrées du canal et du canal d'évacuation doivent être proches l'une de l'autre, pour que le tunnel d'évacuation soit efficient dans le contrôle des sédiments.

Des maquettes d'études ont été établies pour étudier la structure du tunnel d'évacuation construit au détournements de Milburn et Arcadia sur la Middle Loup River au Nébraska. Cette rivière à une charge de sédiments de sable fin répartie d'une façon assez uniforme. Les observations renouvellées sur le terrain ont montré que les structures des tunnels d'évacuation fonctionnent comme il avait été prévu sur les maquettes, et empêchent les sédiments d'aller dans les canaux.

LABORATORY AND FIELD INVESTIGATIONS OF SEDIMENT CONTROL STRUCTURES AT DIVERSION DAMS

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ABSTRACT

Laboratory model studies have been used to develop designs for sediment control structures at diversion dams. Curved guide walls leading to a headworks and sluiceway and a short tunnel separating the flow to the sluiceway and headworks are two of the sediment control methods developed and constructed on Bureau of Reclamation projects.

Field operation has shown that the percentage of coarse sediment entering the canal can be controlled by arranging the entrance to give favorable flow conditions. Curved guide walls take advantage of secondary currents to move the bed sediment to the inside of the curve and toward the sluiceway. Intermittent sluicing is used successfully with curved guide walls. A short tunnel skimming top water to the canal headworks is very successful in controlling bed-load sediment on streams that have little floating debris and trash.

The paper discusses results of several model studies of sediment control arrangements at diversion dams. Field information is used to show actual case studies of model investigations and prototype conformity.

INTRODUCTION

Control and removal of coarse sediment carried into canals by water diverted from heavy sediment-laden streams is an important part of design and operation of many irrigation projects. With the increasing demand for water and greater diversions from these streams, the importance of the problem of excluding sediment from the canals will continue to increase.

On some of the larger projects, elaborate desilting works have been built such as those on the All-American Canal which utilize settling basins and clarifier scrapers. On smaller projects, however, the cost of that type of structure cannot be justified, and simpler and cheaper means are required. The use of simple gated sluiceways and wasting part of the water have been used in many instances. Some of these structures have proven unsatisfactory and have failed to exclude the coarse sediment from the canal systems necessitating frequent cleaning of the canals. The cost of sediment removal from canals is a large item of expense for operation and maintenance on irrigation projects.

Research engineers and designers are continually searching for the most effective methods of excluding sediment from canals at head works so that the cost of canal operation and maintenance can be reduced.

Model studies performed at the Hydraulic Laboratory of the Bureau of Reclamation have developed effective methods of reducing the amount of coarse sediment entering canal headworks at diversion dams for specific projects. To develop the most satisfactory solution of a sediment control problem at a diversion usually requires a movable bed hydraulic model study. A preliminary design is first modeled and then the laboratory research engineer, in close liaison with the designers, develops the structure to give the best sediment control. Information obtained from the field and reported herein shows that where hydraulic model studies have been conducted, sediment control is much better than where model studies were not conducted.

CURVED GUIDE WALLS

Basic Theory and Development

In a channel transporting bedload sediment, a curve causes a superelevation in the flow which appears on the water surface. A higher water surface on the outside of the curved flow causes a flow circulation due to the higher head on the outside of the curve. Flow goes down on the outside or convex side of a curved channel and crosses the bottom toward the concave or inside part of the curved channel. As the flow moves across the bottom it moves the movable bedload to the inside of the curve with the flow. The theory of secondary circulation was used in developing curved guide wall structures for sediment control at canal headworks. Initial tests were made in a hydraulic model using an undistorted scale to develop the radius of curvature and the length of curve that would cause the greatest reduction of bedload going into a canal headworks. The length of curve upstream from the canal headworks was varied to determine the shortest guide walls that would still give a good reduction of bed sediment going into the canal compared to amount of bed sediment moving into the headworks with no curved guide wall sediment control structure.

A basic principle for controlling bed sediment at an intake to a canal is to control the flow so there is the least disturbance near the channel bed in the vicinity of the intake to the canal. Any disturbance or flow condition which causes bed sediment to be raised from the bed due to turbulence, vortex flow, or abrupt change on the bottom of the channel near the canal entrance can cause bed sediment to become suspended and move into the canal. An example is the vortex which formed just upstream from the headworks gate to the canal on Woodston Diversion Dam.1/

The vertical vortex action of the flow caused coarse sediment to be picked up from the channel bed allowing a higher concentration of bed sediment to be drawn through the canal gate. To stop the vortex flow, a curtain wall was installed which extended 2 feet below the normal water surface. The bottom upstream edge of the curtain wall had an 8-inch radius to reduce turbulence and losses at the entrance. The curtain wall prevented the vortex from forming and consequently reduced the amount of bed sediment going into the canal.

Each canal headworks at a diversion on an alluvial river has specific characteristics such as canal discharge, river discharge, size and gradation of bedload sediment, sediment discharge, and bed slope which differ from location to location. The basic principles described above, when considering a sediment control arrangement, are the basis for the basic layout of a curved guide wall sediment control structure at a diversion headworks.

Model Study Criteria

In conducting a hydraulic model study of a movable bed sediment problem, the basic criteria that must be satisfied to successfully represent prototype conditions is that model sediment should be transported and its movement should be similar to movement of bed sediment in the prototype with the discharge and velocities obtained in the model.

Movement of bed sediment occurs by individual coarse particles being entrained in flowing water with the particle motion being one of rolling, sliding, or jumping (saltating). This particle motion takes place on or close to the bed of the channel. It is commonly referred to as transport of the bedload or contact load.

For all of these conditions of transport, the relative specific gravity of the particle with respect to the fluid it displaces and consequently the settling velocity of individual particles is very important.

In movable bed hydraulic model studies for sediment control structures, a ratio of the settling velocity between prototype and model sediment reduced by the square root of the length ratio $(L_R)^{1/2}$ is often used to arrive at the model scale. In the Froude Model law velocity varies as the length ratio $(L_R)^{1/2}$. Figure 1 is an example of relating prototype bed sediment and model bed sediment in making movable bed model studies for Bartley Diversion Dam headworks and sluiceway.

Because of variable water discharges, it may be impractical to test a movable bed model with all the possible discharges in the headworks and

1/Numbers refer to references at the end of the paper.

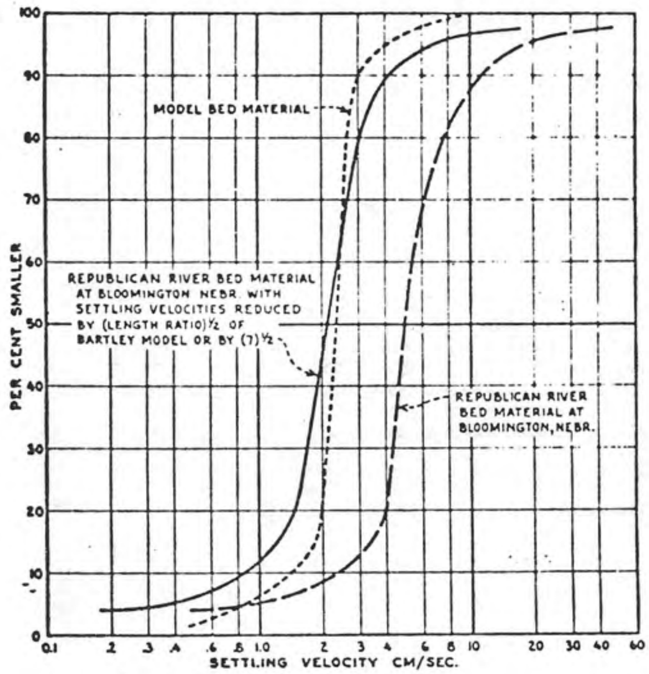


Fig. 1 - Comparison of settling velocities Bartley model studies.

sluiceways. Also, to design a sediment control arrangement that would be most effective for all possible discharges at a diversion dam with a headworks and sluiceway is usually not practical. However, on an irrigation project, the amount of drainage basin runoff that is available for the irrigation project and the amount of runoff that will be available for discharge through the diversion dam sluiceways is determined as part of the planning for the project.

TYPICAL MODEL STUDIES AND PROTOTYPE CONFORMITY - CURVED GUIDE WALLS

The first series of tests of curved guide walls which resulted in sediment control arrangements using curved guide walls constructed in the field were performed for Superior-Courtland Diversion Dam, headworks, and sluiceway on the Republican River in Nebraska.2/

Superior-Courtland Diversion Dam, Headworks, and Sluiceway

A model study of this diversion works was made to develop the headworks design that would cause the highest percentage of bedload to be carried through the sluiceway. The index used to indicate the performance effectiveness was the ratio of the concentration of the sand in the water passing through the sluiceway to concentration of sand in the water passing through the headworks, C_s/C_h. A 1:15 undistorted model was used which included an area sufficient to cover one-half of the diversion weir, the Courtland Canal headworks and sluiceway, and approximately 400 feet of the upstream river channel. The general layout of the diversion dam is shown in Figure 2.

Although the model was built to an undistorted scale, it was realized that in order to get sufficient movement of sand through the model, either the discharge or the slope scale would have to be increased. The discharge was set according to the Froude similitude requirements and the slope was allowed to build up to that required to move the sand fed into the model. This caused a slope greater than that derived from the Froude similitude relationship for an equilibrium sediment transportation condition.

It is of interest that the average slope of the riverbed in the vicinity of the Superior-Courtland Diversion site prior to construction was approximately 0.00076, and that the slope of the river approach in the model when equilibrium sediment transportation conditions were reached was approximately 0.0076. The sand used for the movable bed material was obtained from a loosely cemented sandstone broken down in a hammer mill, giving a sand with a median diameter of approximately 0.2 millimeter with 90 percent

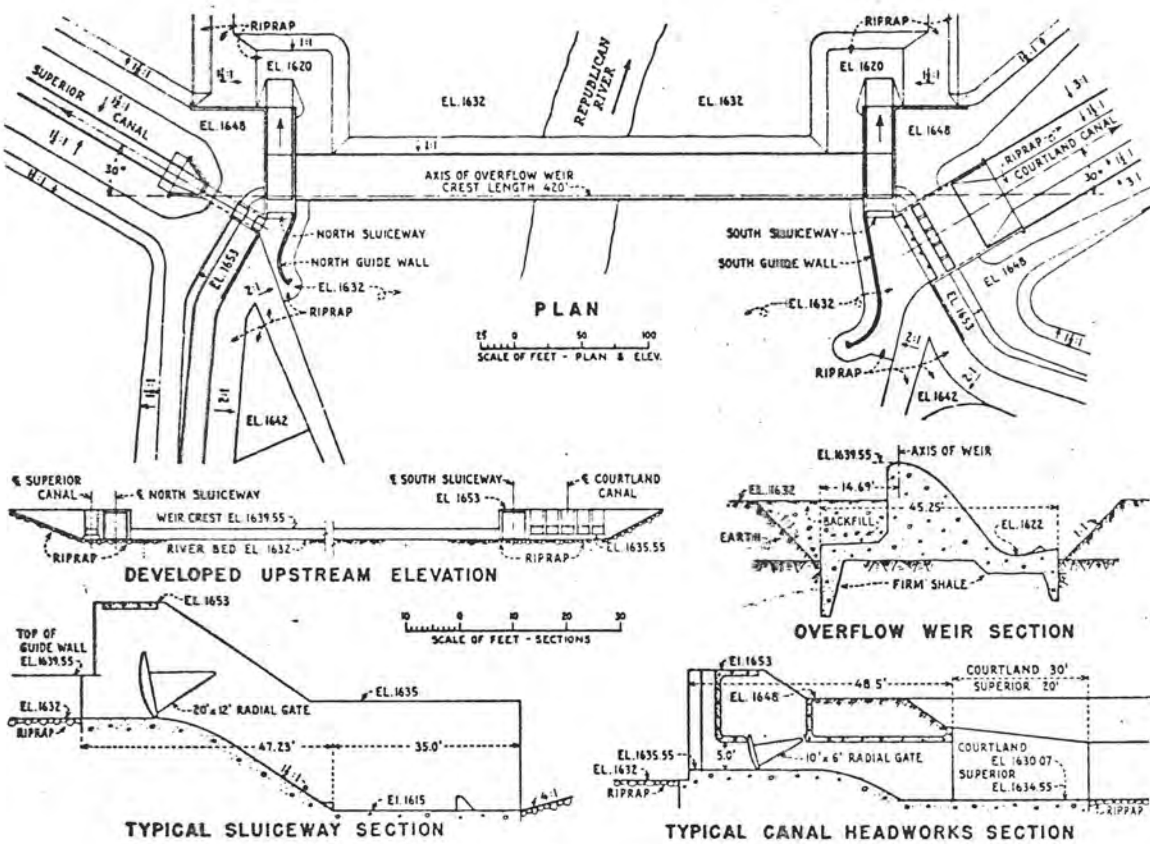
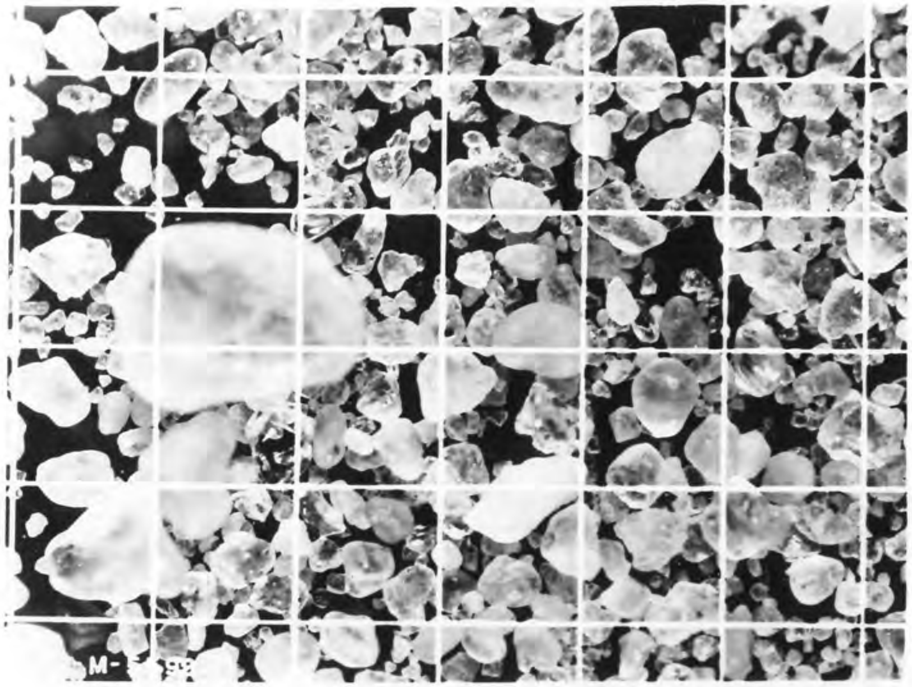
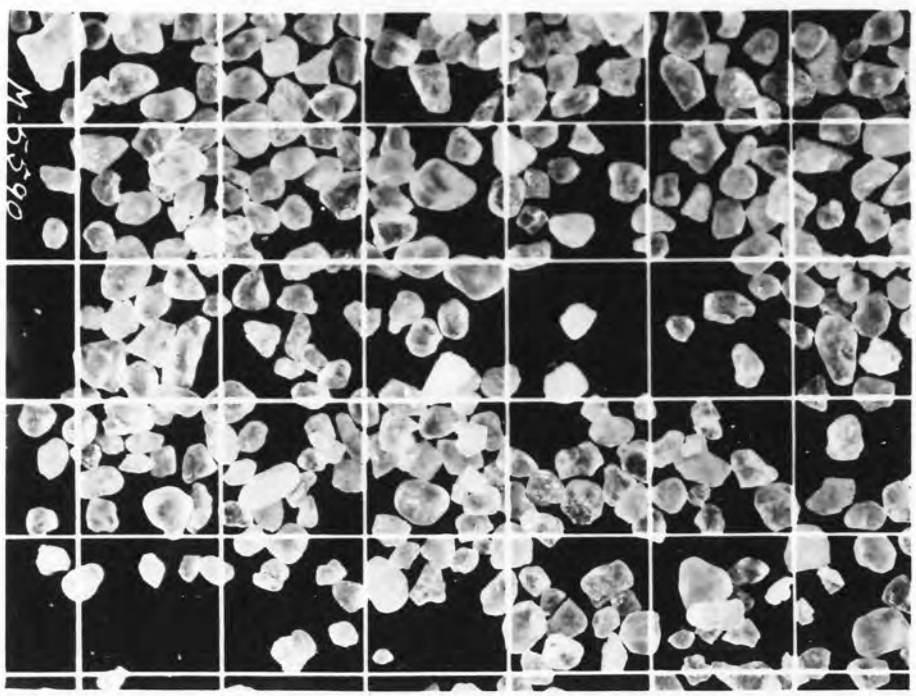


Fig.2 - Superior-Courtland Diversion Dam.



A. Republican River sand



B. Model Sand

Fig. 3

PHOTOMICROGRAPHS OF MODEL AND PROTOTYPE SANDS
GRID SPACING 1 mm.

retained between the No. 40 and No. 100 US standard screens (0.42 mm to 0.15 mm). Figure 3 shows photomicrographs of the model sand and the washed Republican River sand. Size comparisons can be made from the 1-mm rectangular grid shown on the photomicrographs.

In the Superior-Courtland model studies, the main requirement for the model sediment was that it move similarly to the bed sediment of the prototype with the discharge and velocities obtained in the model. This requirement was satisfied by the sediment described previously.

A 10-year operation study which included the riverflow, storage capacity, and diversions of the Republican River drainage area was made on the basis of complete development of the proposed irrigation systems. The operation study gave the monthly average discharge through the headworks and sluiceway of Courtland Diversion. From this analysis, a standard discharge of 600 cfs for Courtland headworks and sluiceway was chosen for the model study, with 400 cfs going through the headworks and 200 cfs through the sluiceway. The design capacity of Courtland Canal is 751 cfs. However, this maximum discharge occurs over very short periods.

Studies of the only sediment data available at the time, on the Republican River near Bloomington, Nebraska, 80 miles upstream from the damsite, indicated that the bedload amounted to 0.165 percent of the water discharge by weight. For the standard river discharge chosen for the model study, 600 cfs, the bed sediment load amounted to approximately 1-1/4 acre-feet per day. In model terms the sand feed amounted to 0.0173 lb per sec for the same sediment concentration as the prototype.

Samples of water and sand flowing through the headworks and sluiceway were taken at regular intervals by passing a collecting trough across the width of the falling nappes at the end of the headworks and sluiceway. The concentrations by weight of sand to water were quickly determined for both headworks and sluiceway and the concentration ratios were easily computed. Concentrations of individual samples from the headworks and sluiceways varied considerably because of the shifting approach channel. This action is typical of the flow in the Republican River. By taking the time average of concentrations over a comparatively long period, equilibrium sediment transportation conditions could be determined.

Preliminary Design - Courtland Headworks

An initial test was made with the sluiceway and headworks arranged as shown in Figure 2 without the guide walls. The model was operated until equilibrium sediment transportation conditions were reached. Samples were then taken from the water and sand passing through the headworks and sluiceway. The average of concentrations shown by samples taken at equilibrium conditions gave a ratio of sediment concentration in the sluiceway to the concentration in the headworks, C_s/C_h of 0.682. Normal water surface elevations of 1639.0 feet, 0.5 foot below the spillway crest, were maintained for all continuous sluicing tests.

Several guide wall and skimming weir arrangements were studied in the model. Each of these arrangements is shown in Figure 4. Table 1 shows the results of the tests giving a concentration ratio of C_s/C_h for each arrangement tested. Changes 1, 2, and 3 include walls which were all attached to the headworks of the upstream part of the structure, and they gave results which were not as good as the preliminary design.

A guide wall extending upstream from a point between the sluiceway and the overflow weir was installed to a predetermined curve. The guide wall curved the flow, inducing a secondary current which caused the bed material to move toward the inside of the curve. Change 4, Figure 4, shows this curved guide wall arrangement. A ratio of sediment concentration C_s/C_h for this curved guide wall arrangement was 6.629. Most of the previous tests indicated that the guide wall, as used in Change No. 4, was the most satisfactory in the solution of the problem. From observations made on a number of tests, it appeared necessary to make the channel between the guide wall and the headworks as narrow as possible. Curving the flow with a guide wall caused a secondary current to move the bed material to the inside of the curve only when there was enough excess head on the outside of the curve, due to centrifugal force, to activate a strong secondary current. Therefore, it was desirable to have as high a velocity as possible without picking up an excess amount of bed material into suspension. With normal canal depth maintained below the headworks, the width of the approach channel was determined for maximum diversion requirements.

For diversions less than the canal design capacity of 751 cfs, it was possible to operate the headworks with part or all of the gates partially open. The model tests were made with all five headworks gates opened equally until the best approach arrangement was determined and then tests were made in which gate openings for the five head gates were varied to effect a nonuniform velocity distribution in the headworks approach. Several combinations of gate openings for the head gates were tried but the tests with uniform gate settings gave the minimum sediment entering the canal.

The arrangement shown as Change No. 7 in Figure 4 included a vortex tube extending across the face of the headworks immediately upstream from the headworks sill. A closed conduit on the end of the vortex tube discharged into the sluiceway downstream from the sluice gate. A complete run with this arrangement at the standard water discharge and sediment feed and uniform gate settings showed a C_s/C_h ratio of 7.5. A

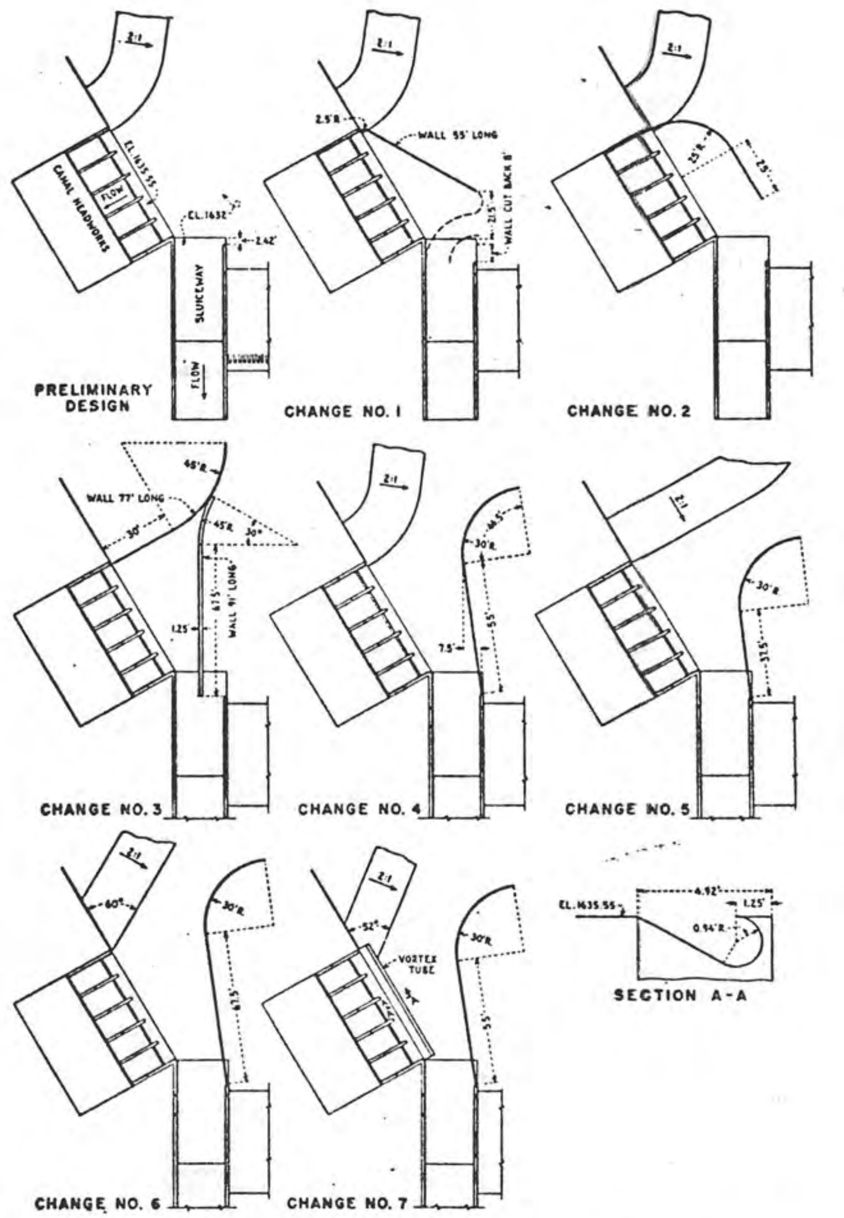


Fig. 4 Courtland headworks and sluiceway model design tests.

Table I

Designs Tested--Courtland Headworks and Sluiceway

Change Number	Length of test hr	Q_s cfs	Q_h cfs	C_s ppm	C_h ppm	C_s/C_h	Remarks
Preliminary design	27	200	400	1074	1574	0.68	See Fig. 4
Preliminary design	15	400	200	1295	977	1.33	
Preliminary design	20	200	variable	30,058	7041	4.27	During sluicing period of intermittent sluicing run
Preliminary design	20	200	400	74	104	0.71	Between sluicing periods of intermittent sluicing run
1	21	200	400	457	2116	.22	Skimming weir upstream of headworks
2		200	400				Observations showed this design not satisfactory --No data taken--See Fig. 4
3		200	400				Observations showed this design not satisfactory --No data taken--See Fig. 4
4	15	200	400	3149	475	6.63	Curved guide wall with curved embankment
5		200	400				Observations showed this design not satisfactory --No data taken
6	20	200	400	2508	489	5.13	Straight embankment at 60° angle--head gates opened uniformly
7	31	200	400	3785	361	10.5	Vortex tube installed-- sluice gate 10 ft wide
Data for Designs Tested--Superior Headworks and Sluiceway							
Preliminary design	54	40	80	37	2669	.014	See Fig. 5
1	23	40	80	311	1707	.18	Guide wall installed-- Original embankment
2	39	40	80	1247	1950	.64	Guide wall with straight embankment-- Recommended design

Description of Headings

Q_s = Average discharge through sluiceway cfs (prototype)
Q_h = Average discharge through headworks cfs (prototype)
C_s = Average sediment concentration in sluiceway ppm by weight
C_h = Average sediment concentration in headworks ppm by weight

test was then made in which the sluice gate was reduced from 20 to 10 feet in width. This arrangement gave even a more satisfactory ratio of C_s/C_h of 10.5. These last runs indicated that the vortex tube and the narrow sluice gate improved the sand distribution considerably. However, due to the necessity of passing floating debris and because of other design considerations, these two features could not be incorporated into the Superior-Courtland design.

Superior Headworks

The Superior headworks and sluiceway are on the opposite end of the diversion dam from the Courtland headworks. To test the Superior headworks and sluiceway it was necessary, in effect, to reverse the model in plan. The model of Courtland headworks was then modified to represent Superior headworks by blocking out four of the five head gates and changing the alinement of the upstream riverbank. The preliminary design of Superior headworks and sluiceway was tested using 120 cfs as a total standard discharge, with 80 cfs being passed through the headworks and 40 cfs discharged through the sluiceway. These discharges were chosen from data compiled in the 10-year operation study for the Republican River drainage discussed in the Courtland model studies. Tests on a preliminary design of Superior headworks and sluiceway gave a concentration ratio C_s/C_h of 0.014.

In view of the fact that the design was so far advanced, it was impracticable to alter the structures of the headworks and sluiceway very markedly. The recommended design for Superior headworks and sluiceway is shown as Change 2 on Figure 5. The best sediment concentration ratio obtainable with the arrangement described above was $C_s/C_h = 0.64$. This shows that considerable coarse sediment was still going into the headworks but it was a great improvement over the preliminary design. It will be noticed that a much higher concentration ratio C_s/C_h was obtained in the model study for Courtland headworks and sluiceway than for Superior model headworks and sluiceway. On the Superior study it was necessary to keep the opening between the guide wall and the river embankment equal to or greater than 20 feet, which was arbitrarily chosen at the time as the minimum for passing floating debris. Meeting this requirement necessitated lower velocities around the curved entrance channel and thereby reduced the effectiveness of the secondary current to move bed sediment to the inside of the curved channel.

Intermittent Sluicing - Superior-Courtland Diversion

Most of the model testing on Superior-Courtland Diversion concentrated on a continuous sluicing and continuous flow into the canal. Continuous sluicing was the method chosen because the 10-year operation study indicated a large quantity of water would be continuously discharging past the diversion dam to the river downstream with full diversions made to the Superior and Courtland Canals. Republic and

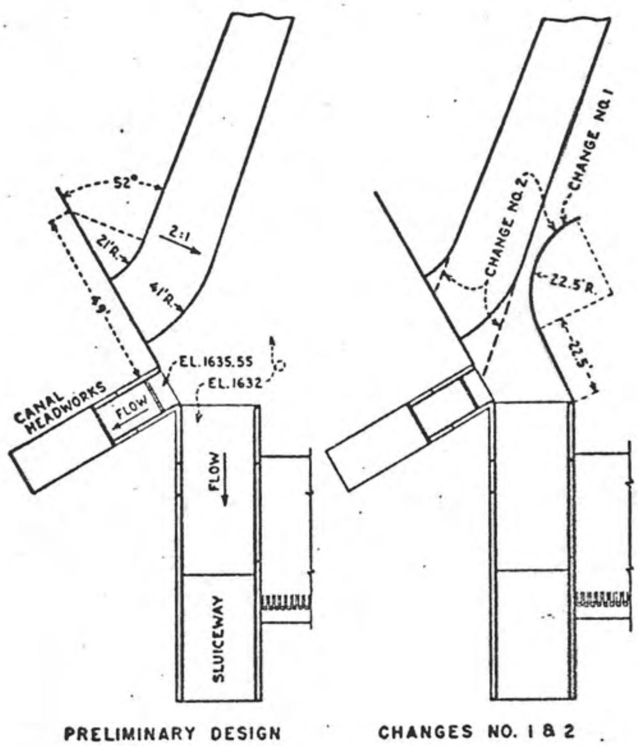


Fig. 5 Superior headworks and sluiceway model design tests.

Scandia Diversions downstream from Superior-Courtland that were in the operation study when Superior-Courtland Diversion was designed and constructed were never authorized. Consequently irrigation flows required downstream from Superior-Courtland Diversion were reduced to zero. This made it necessary to use intermittent sluicing at Superior-Courtland to allow the minimum water to pass downstream of the diversion. A few tests were conducted on the hydraulic model in which intermittent sluicing was used to control the bedload sediment.2/ These tests showed that intermittent sluicing gave the most efficient removal of sand from water diverted to the canal. Intermittent sluicing develops a high velocity in the vicinity of the sluice gate. The resulting high tractive force readily moves the bed material.

Prototype Operation of Superior-Courtland Diversion

The project histories and engineers' inspection reports over the operating life of Superior-Courtland Diversion show that the sediment control arrangements were operating as designed and tested in the hydraulic model studies. A recent interview with the Irrigation District Manager showed that the sluice gate is operated intermittently for a short time once a day. He does this for two reasons: (1) To use a minimum amount of water for sluicing and (2) because the sediment control device operates satisfactorily with short time intermittent sluicing. Both Superior and Courtland sluiceways are operated on similar schedules. Upstream releases are controlled very closely and any excess is allowed to flow over the spillway. The hydraulic model studies showed that, for a small quantity of sluicing water available, intermittent sluicing is much more effective than continuous sluicing.

During nonirrigation seasons, the sluice gates are raised and flows are passed through the upstream storage basin to remove as much bedload sediment as possible. In years past, sluicing has been done by continuous sluicing with a smaller amount of water than recommended as a result of model studies. The change to intermittent sluicing removes much more bedload sediment to the river below. During recent years, flows in Courtland Canal have been approximately 590-610 cfs to satisfy the irrigation demand. The design capacity of Courtland Canal is 751 cfs. Superior Canal has been operated at design capacity, 139 cfs, for many years.

The District Manager said berms from some curves are cleaned every 4 to 5 years. The berms which form on the sides of the curves are a result of the fine suspended sediment. Deposits on the canal bottom due to bedload have required cleaning at intervals of 10 to 15 years. The district is happy with the operation. Hydraulic model studies showed the canals would require cleaning at much more frequent intervals with no sediment control structure.

Model Studies of Bartley Diversion Dam Headworks and Sluiceway

Continuing the sediment control studies at headworks of diversion dams, a 1:7 scale model of the headworks and sluiceway of Bartley Diversion Dam was constructed and tested.3/ This dam is also located in Nebraska on the Republican River well upstream from Superior-Courtland Diversion Dam. The plan of the Bartley Diversion Dam is shown in Figure 6. A limited time was allowed for the model study and, therefore, the scope of the study was limited. However, by taking advantage of the previous studies, a good sluicing action was obtained. The fine sand used as the movable bed material in Superior-Courtland Diversion Dam studies, previously described, was also used for the Bartley model studies. A comparison of the size analysis of the model and prototype bed material based on the settling velocities for the scale ratio of 1:7 is shown on Figure 1.

Operation of the Model

From a hydrological operation study, it was shown that 60 cfs would be required in the Bartley Canal approximately 78 percent of the time and that 37.5 cfs would be available for sluicing approximately 70 percent of the time. These discharges were arbitrarily chosen as standard for the Bartley model studies. This division of flow was varied for some of the tests. From field measurements, it was discovered that the sand bedload concentration in the Republican River at the Bartley site was 474 ppm by weight. This same concentration was used in the model study. The sand and water discharges were held constant throughout the studies. Like the previously described studies, it was found that the sediment concentrations passing through the headworks and sluiceway varied with time because of the continually shifting channel of the upstream riverbed and because the sediment approached the headworks and sluiceway in waves along the bed. To take into consideration this fluctuation, samples of the discharges through the headworks and sluiceway were taken simultaneously and at varying intervals throughout the tests. By averaging the concentrations, a time average for each test was obtained.

The preliminary design was tested in the model and a concentration ratio of $C_s/C_h = 0.13$ was obtained by sampling. This shows that the largest portion of the bed sediment was being taken into the headworks. Four changes, in which curved guide walls were installed upstream from headworks and sluiceway in addition to the preliminary design, were tested in the model. Two more changes, including tunnel entrances to the sluiceway between the guide walls, were tested. Table II gives a tabulation of all tests showing the concentration ratio C_s/C_h for each arrangement tested. It will be noted that Change 4 has a concentration ratio C_s/C_h of 6.69, and this is the highest ratio of any arrangement in which only the guide walls were added to the preliminary design.

Change 5, which includes a tunnel entrance to the sluiceway, has a higher concentration ratio than Change 4. However, because of the possibility of collecting trash on the tunnel entrance and the increased cost of the tunnel over the guide walls alone, Change 4 was recommended for inclusion in the prototype design.

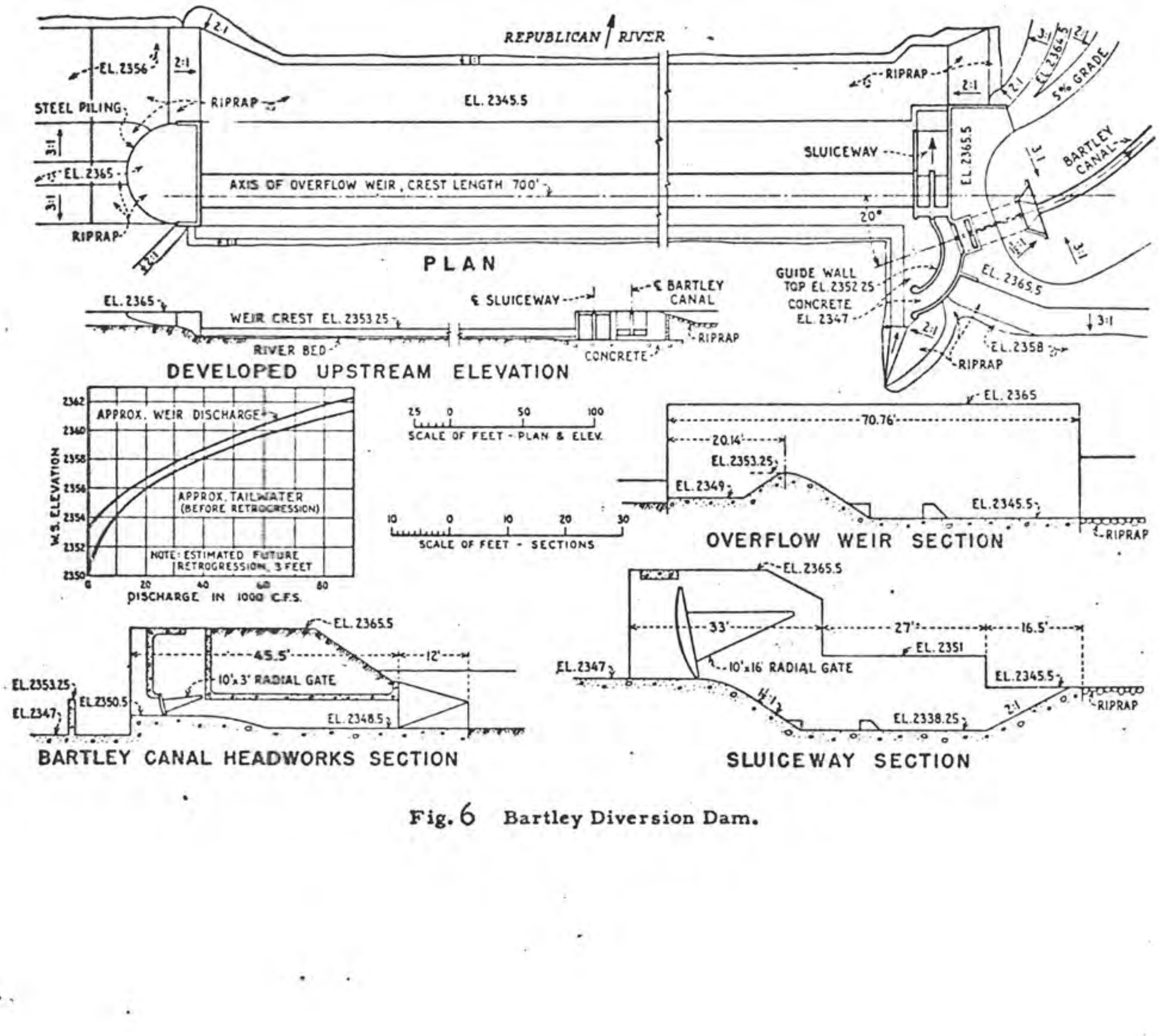


Fig. 6 **Bartley Diversion Dam.**

Table II

Designs Tested--Bartley Diversion Dam

Change Number	Length of test hr	Q_h cfs	Q cfs	C_s ppm by wt	C_h ppm by wt	C_i ppm by wt	C_t ppm by wt	C_s/C_h
Preliminary design	84	37.3	60.2	135	1020	474	668	0.13
1	51-1/2	39.5	58.0	250	603	474	463	0.41
2	34	37.8	59.7	588	367	474	455	1.60
3	24	38.7	58.8	622	389	474	481	1.60
4	49	38.8	58.7	830	124	474	405	6.69
5	6-1/2	39.5	58.0	901	115	474	427	7.83
6	24	39.0	58.5	808	168	474	423	4.81

Description of Terms

Q_s = Average discharge through sluiceway cfs (prototype)
Q_h = Average discharge through headworks cfs (prototype)
C_s = Average sediment concentration in sluiceway ppm by weight
C_h = Average sediment concentration in headworks ppm by weight
C_i = Concentration of sediment added to model ppm by weight
C_t = Average concentration of sediment discharged from model ppm by weight

A sketch of all the changes tested in the model, as well as the recommended design, are shown on Figure 7. The results of Bartley model tests show the improvement in sediment distribution by using the curved streamflow principle to cause the bedload to move to the inside of the curve. The sediment was moved toward the sluiceway and excluded from the headworks. The difference in elevation between the headworks crest and the sluiceway crest of 2.3 feet, the headworks crest being higher, was of definite advantage in keeping the sediment out of the headworks.

Intermittent sluicing tests were conducted and showed that much greater quantities of bed sediment per unit quantity of water sluiced could be moved to the river downstream than by the steady continuous sluicing operation.3/ The sluice gate was raised and the discharge allowed to increase to a maximum for the water level in the pool upstream. For intermittent sluicing the concentration ratio C_s/C_h reached as high as 27.5. As the sand, accumulated between the guide walls, is washed out the concentration reaches a peak then reduces. The concentration ratio C_s/C_h remained above the value for continuous sluicing for about 20 minutes model time. The intermittent sluicing method proved the most efficient for reducing, to a minimum, the amount of sand going into the canal.

Prototype Operation of Bartley Diversion

A review of the project histories, inspection reports, and discussions with the Irrigation District Manager indicates the sediment control structure is operating satisfactorily at Bartley Diversion Dam. Bartley Diversion is in a different district than Superior-Courtland Diversion Dam. At Bartley the sluice gates are operated intermittently the same as at Superior-Courtland except one of the two 10-foot sluice gates is opened every third day. The intermittent sluicing procedure is used to save water and the bedload sediment approaching the headworks is removed adequately. A settling basin below the canal headworks requires cleaning at 2-year intervals. Analysis of sediment deposited in the settling basin shows coarser bedload material only in the upstream part of the basin. The finer material transported in suspension makes up the remainder of the sediment deposit in the settling basin.

During the irrigation season no releases are required to pass Bartley Diversion Dam and the releases from Trenton Storage Dam upstream are made to satisfy only the demand on Bartley Canal. A small excess for safety between sluicing periods is allowed to flow over the spillway.

During nonirrigation periods (wintertime) both 10-foot sluice gates are raised and flows from upstream are used to sluice sediment stored in the pool upstream from the diversion dam.

A schedule of operation of the headworks and sluice gates in the field was developed as experience was gained by the operators. Opening the one 10-foot sluice gate located at the downstream end of the two parallel

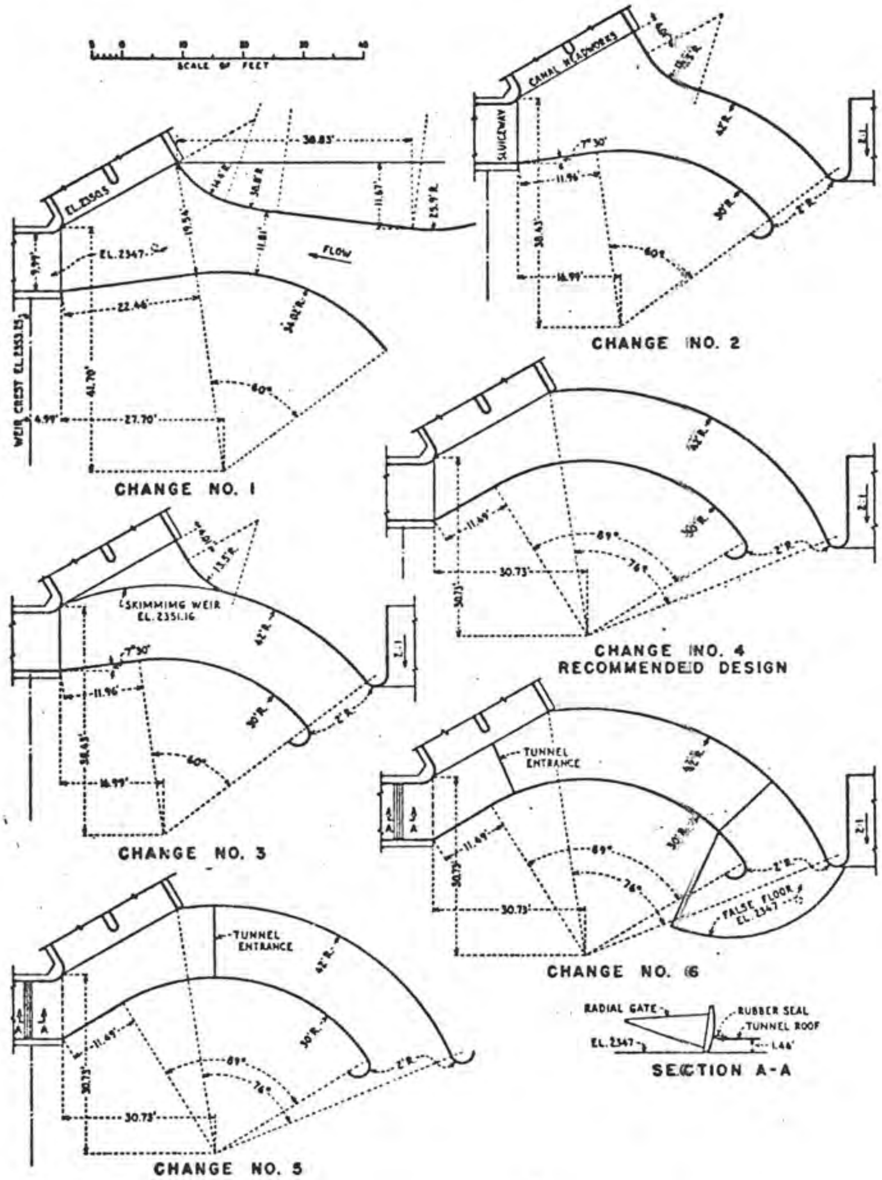


Fig. 7 Bartley Diversion Dam model design tests.

training walls for a period of 30 to 45 minutes every third day proved to be the best method of reducing, to a minimum, the coarse bedload sediment going into the settling basin and canal downstream.

CAMBRIDGE DIVERSION DAM AND HEADWORKS

Cambridge Diversion is about 15 miles downstream from Bartley Diversion on the Republican River in Nebraska. The riverbed material has a gradation similar to the riverbed material at Bartley and Superior-Courtland Diversions, and the river slope at the Cambridge Diversion is comparable to river slopes at the other two diversions.7/

Cambridge Diversion Dam was designed and constructed without a sediment control structure. Hydraulic model studies were not made to show how a sediment control structure could reduce the amount of bedload sediment going into the canal.

Review of the project histories and engineers' inspection reports, and discussions with the District Manager of Cambridge Canal shows that the upstream reach, just below the headworks, has been cleaned frequently to remove the coarse bedload sand.

The amount of sand entering the four gates at the headworks became so large that a single guide wall upstream of the gates was constructed to help control the sediment load. The wall was designed and constructed without the benefit of hydraulic model studies. The wall did not help the sediment problem and was removed in a very short time.

Other attempts have been made to reduce the coarse sediment going into the Cambridge Canal. The water surface in the pool upstream from the headworks and sluiceway was raised by raising the spillway crest about one-half foot. Stoplogs were placed in the bottom of each of the four canal gate slots to raise the bottom of the canal intake. The raised pool and stoplog changes have not had time to be tested and determine their effectiveness.

Hydraulic model studies, preferably during initial design, to develop a sediment control structure at a diversion is a much better approach to solving a movable bed sediment control problem than designing without the benefit of a hydraulic model study.

SHORT TUNNEL UNDERSLUICE

Basic Theory and Development

Under the section on curved guide walls, a basic principle mentioned for controlling bed sediment at an intake to a canal is controlling the flow to minimize the disturbance near the channel bed in the vicinity of the intake to the canal. This basic principle was used in developing the short tunnel undersluice. Again, as in the curved guide wall method of sediment control, sediment carried as bedload is what is considered here. Many skimming weir type of structures have been used to control bed sediment and divert it away from a canal intake. Too often, a vertical skimming weir is not effective because water drawn into a headworks over a skimming weir picks up heavy sediment from the bed and carries it over the vertical weir and into the canal.

The short tunnel undersluice places the diverter which excludes sediment so that it divides the flow in layers. The flow carrying bedload sediment goes under the horizontal roof of the tunnel and into the sluiceway. Flow diverted into the canal is the layer which flows over the top of the tunnel. If the flows are divided properly, none of the bedload sediment is raised from the bed and drawn into the canal. The short tunnel undersluice minimizes the flow moving the bed sediment on or near the bed until it is in the tunnel and on its way to the sluiceway and river downstream.

For the short tunnel to operate properly, the entrance to the canal and the entrance to the sluiceway must be fairly close together and at an angle such that the flow will head directly into the canal and sluiceway. Many years ago, it was a common practice to have the headworks and sluiceway at right angles to each other. This was changed so that the right angle was reduced by 20^o to 30^o wherever the terrain and structure layout would allow it.

To be sure of obtaining the flow conditions that would be found in the Milburn Division prototype, a hydraulic model study was used to develop the short tunnel undersluice.4/

Model Study of Milburn Diversion

Because the position and shape of the size analysis curve of available model sand was very close to the size and shape of the prototype, sand settling velocity was not used as a prime criteria. The model sand had a mean diameter of 0.2 mm and was very uniform. The mean diameter of the prototype sand was 0.25 mm and was also very uniform.

A model scale of 1:16 model to prototype was chosen for Milburn model study. This was the first time a short tunnel was used as an excluder at a small diversion dam.

During all of the studies the model was operated at normal water surface elevation upstream from the diversion dam. The movable bed sand material in this model was fed in a dry condition from a hopper and vibratory feeder. Before taking sediment distribution data the model was allowed to operate until equilibrium sediment transport was reached. The model was allowed to establish its natural bed slope which was steeper than the prototype riverbed slope. Sand was fed so as to produce a river sediment discharge of 438 ppm by weight, the same as the prototype bedload concentration.

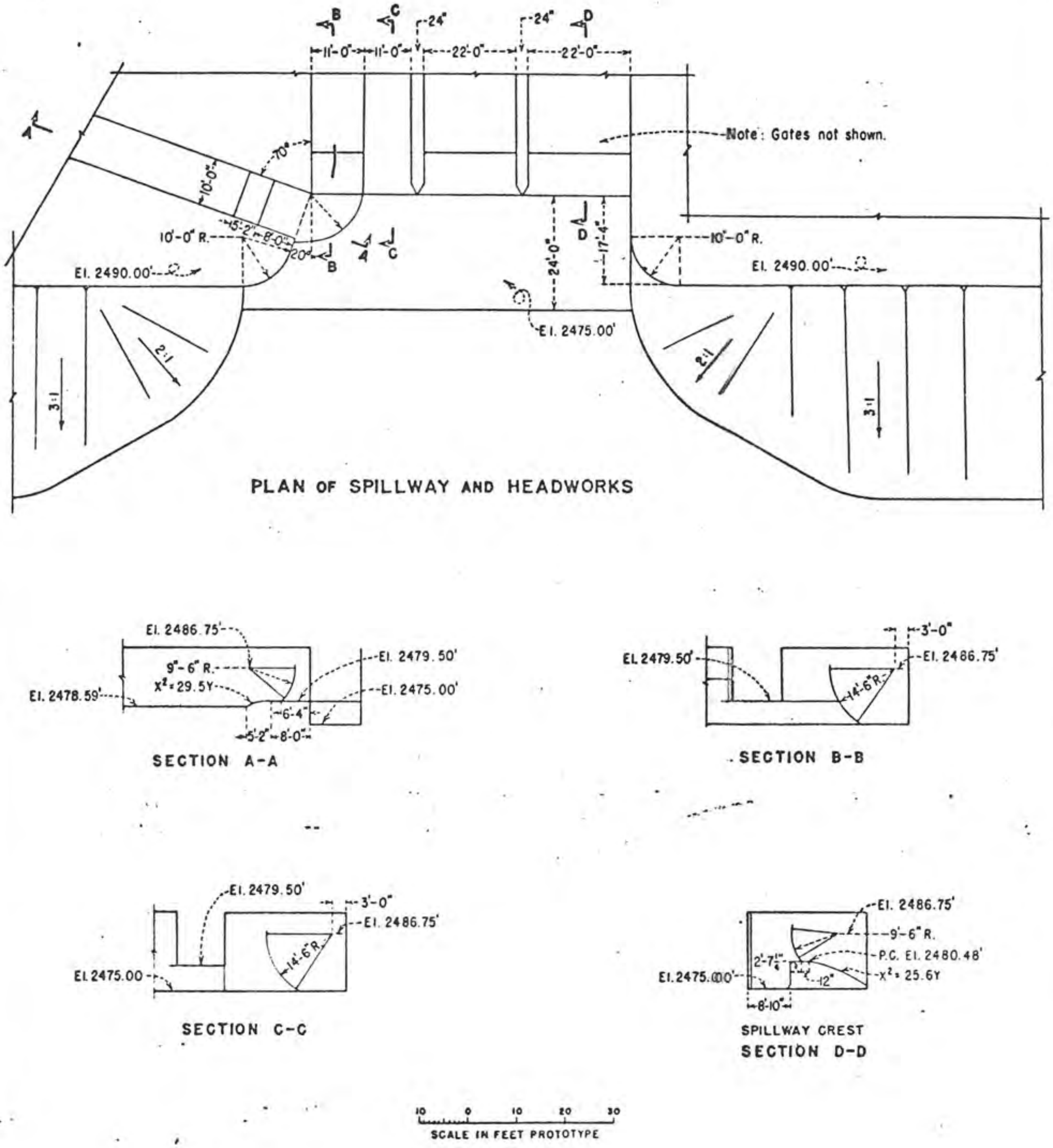


Fig. 8

MISSOURI RIVER BASIN PROJECT

MILBURN DIVERSION DAM

TUNNEL ARRANGEMENT - CHANGE II

1:16 SCALE MODEL

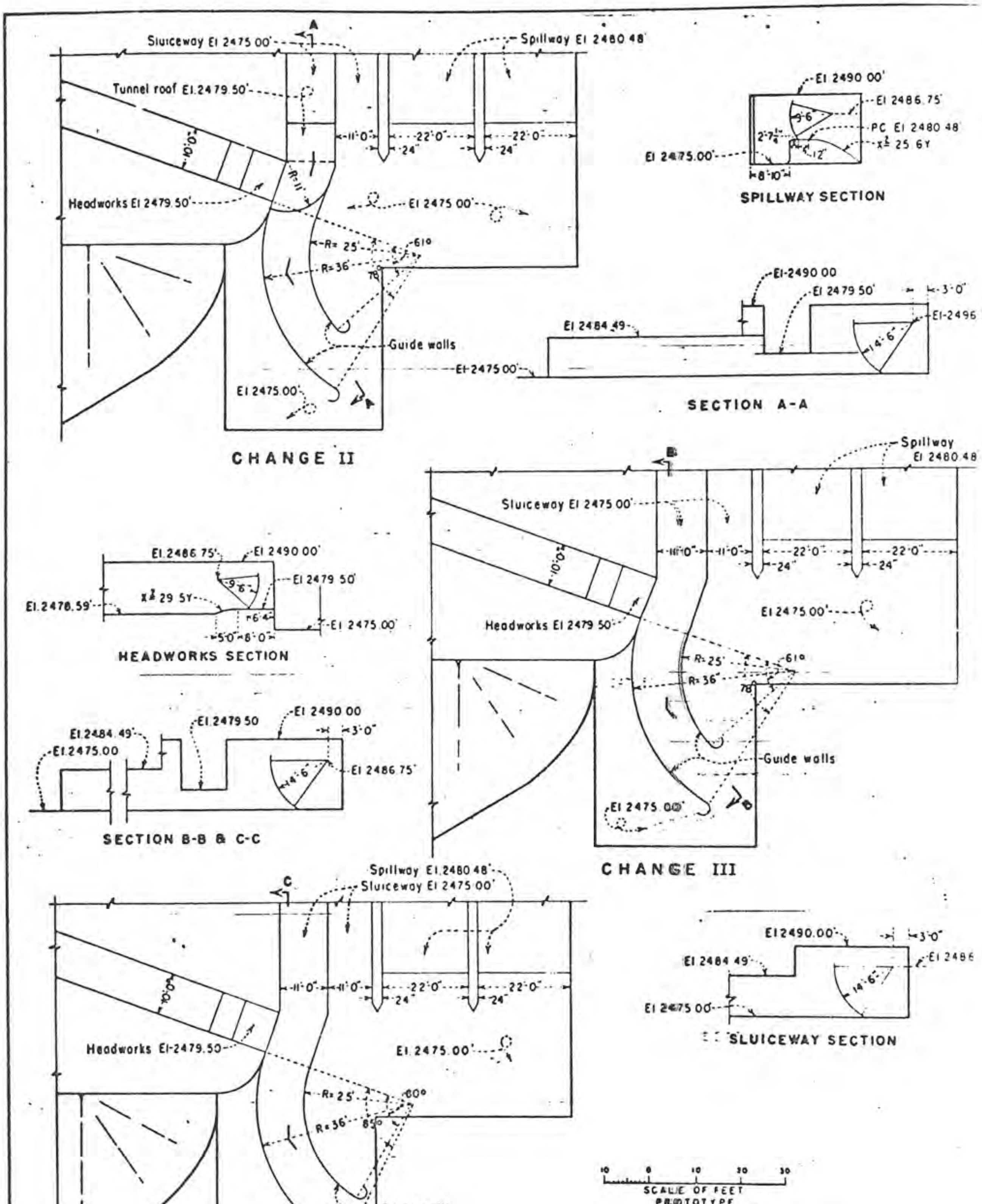


Fig. 9

MISSOURI RIVER BASIN PROJECT

MILBURN DIVERSION DAM

CHANGES II, III AND IV

1:16 SCALE MODEL

In later movable bed hydraulic model studies, sediment and water were recirculated thereby removing the need to dry and handle the sand feed by hand. Regardless of how the model is operated it is necessary to have equilibrium sand transport. The total concentration of sediment entering the model must equal the total concentration leaving the model and it must be constant.

To compare the various headworks and sluiceway arrangements, data were taken and results were expressed in concentration ratios C_o/C_h, the ratios of the sediment concentrations in the combined discharges of the headworks, sluiceway, and spillway in ppm by weight to the concentration in the headworks in ppm by weight. In addition to testing a short tunnel undersluice for Milburn Diversion, curved guide walls in combination with a short tunnel and curved guide walls alone were tested, Figures 8 and 9. The concentration ratio C_o/C_h for the preliminary design for Milburn Diversion was 0.25. The short tunnel undersluice arrangement which was recommended and constructed in the prototype gave a concentration ratio in the model study of C_o/C_h as high as 33.3, Table III. A general layout showing Milburn Diversion headworks and sluiceway is shown on Figure 10.

Prototype Conformity for Milburn Diversion

An investigation of the project inspections and histories of Milburn Diversion and discussions with the District Manager, showed that the short tunnel undersluice was controlling the bed sediment very well. The canal has been delivering from 220 cfs to the design capacity of 260 cfs each year. The upstream 3 miles of Sargent Canal have not required cleaning since it began operation in 1957, which shows that the short tunnel undersluice is keeping the bedload sediment out of the canal. It has been reported that the sizes of sediment found in suspension in the river upstream are settling out in the pool and moving as bedload into the sluiceway. Inspection of the invert of the sluiceway at Milburn has indicated wear of the concrete to the point it was repaired in 1964. Recent inspections indicate the erosion due to sand transport has worn the concrete sluice invert again to the extent that it requires repair. This indicates large quantities of sediment are being transported through the sluiceway which in turn indicates good performance of the sediment control structure and performance as the model study predicted.

ARCADIA DIVERSION - SHORT TUNNEL UNDERSLUICE

Arcadia Diversion is constructed on the Middle Loup River about 35 miles downstream from Milburn Diversion Dam which is on the same river. The canal capacity is 850 cfs. A short tunnel undersluice is used to control bedload sediment and pass the coarse sand through the sluiceway to the river downstream. The project inspections and histories and discussions with the District Manager show that the short tunnel undersluice

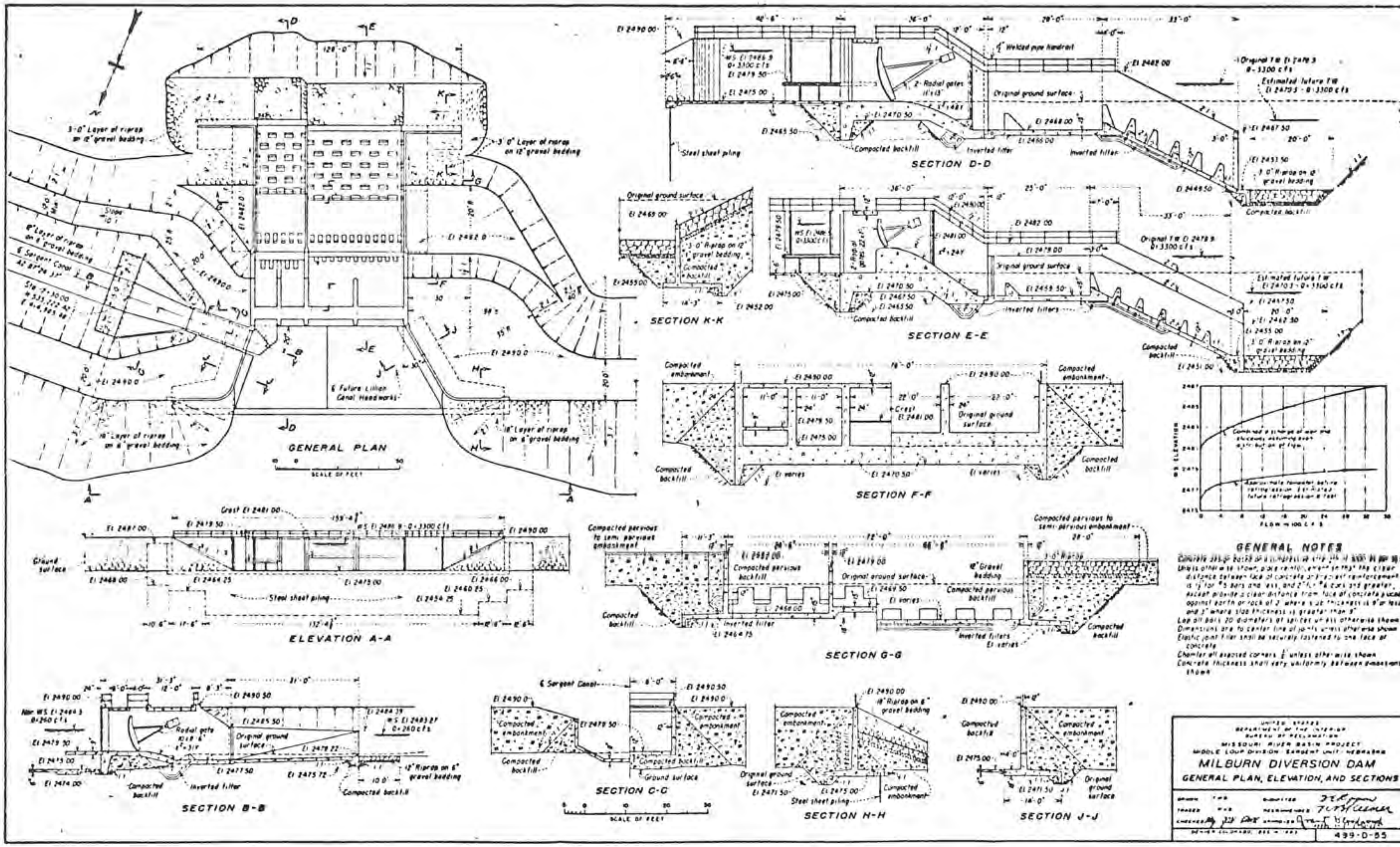


Fig. 10 Milburn Diversion Dam Headworks and Sluiceway

Table III

SUMMARY OF DATA

Model and Change	Headworks discharge cfs	Right sluiceway discharge cfs	Left sluiceway discharge cfs	Concentration ratio Co/Ch
Preliminary design	100	0	0	*0.25
Tunnel-I	102	102	102	2.7
	102	0	205	8.3
	102	0	307	33.3
	102	0	410	15.5
			average	15.0
	175	0	350	2.71
	175	0	525	4.25
	175	0	618	6.25
	175	0	175	6.80
			average	5.00
Tunnel and guide wall--II	100	100	100	0.92
Guide wall--III	100	0	200	0.44
	100	100	100	0.25
Guide wall--IV	100	0	200	0.29

*The volume of sand that entered the desilting basin was associated with the volume of water passing through headworks for calculating a hypothetical headworks concentration.

is operating very satisfactorily. In the 11 years the diversion dam has been operating, sediment deposit in the canal bottom has only amounted to about 0.1 foot. Arcadia Diversion short tunnel undersluice was designed with the results of the hydraulic model studies for Milburn Diversion as a guide.

The Irrigation District Manager and the operators are very happy with the operation of the short tunnel undersluices at Milburn and Arcadia Diversions.

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