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SOAP LAKE SIPHON

by ROBERT SAILER

Denver, Colorado
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Engineering Monographs

No. 5

SOAP LAKE SIPHON

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FRONTISPIECE - Crossing the lower end of the Grand Coulee by the West Canal required construction of the Soap Lake Siphon. The siphon begins on the east side of the depression (lower center), crosses at the north end of Soap Lake, and climbs the bench to the west.

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INTRODUCTION

Soap Lake Siphon, now under construction by the Bureau of Reclamation, is part of the West Canal of the irrigation system of the Columbia Basin project. The siphon is located near the town of Ephrata, Washington, about 50 miles southwest of Grand Coulee Dam. In this vicinity, the route of the canal requires a crossing of the lower Grand Coulee, a large topographical trough, as illustrated in Figure 1. To convey the water across this trough, Soap Lake Siphon, named for a nearby lake, is being built.

The siphon is 12,900 feet long, having a design flow capacity of 5,100 cubic feet per second. The inlet and outlet legs of the siphon are 25 feet 0 inches inside diameter and are monolithically constructed of reinforced-concrete pipe designed to withstand hydraulic heads up to 100 feet. The central, or high-pressure, section, which will be under a maximum head of 225 feet, is 22 feet 4 inches inside diameter and consists of steel-lined reinforced-concrete pipe cast in place.

INVESTIGATIONS

Location of the siphon required a careful investigation of a number of alternative lines and studying construction and maintenance costs. Figure 2, showing the several routes considered, makes it apparent that a lake crossing covers the shortest distance; therefore, extensive investigations were made of the lake crossing.

A siphon pressure tunnel under the lake was first considered, but borings in the lake bed failed to reach rock at a depth of 200 feet below the water surface. Since this depth would have made the pressure head on the siphon about 400 feet, the tunnel scheme was abandoned as impracticable.

Lake Crossing

Comparative estimates were made for a steel pipe supported on concrete piers built on piles driven into the lake bed, and for a steel pipe laid on a rock fill.

Although estimates indicated that the latter type of construction would be somewhat costlier than the former, favorable consideration was given to the rock fill, both because greater advantages in operation and maintenance were anticipated, and because the estimated difference in cost was small.

Samples obtained by core drilling for foundation exploration showed that a gravel stratum about 120 feet below the water surface is overlaid by lake deposits about 90 feet thick. The lake deposits are interbedded with swampy material and grade downward into firm silt and clay. This overlying material, upon which the rock fill would have had to be placed, exhibited unstable characteristics that caused concern over the ability of the undisturbed saturated material to support the heavy loads to be imposed by the rock fill. Denison-type undisturbed samples were taken for stability tests, to measure triaxial shear and consolidation properties which were used in the calculation of stability. Tests of these samples showed conclusively that the lake-bed material overlying the gravel stratum had no measurable shear resistance and that a rock fill constructed thereon would be unstable and unsafe. For these reasons the plan of using rock-fill foundation for the pipe was abandoned.

The undisturbed samples of the lake bed material also showed that little reliance could be placed on it for either frictional or lateral support for piles. It was apparent that the gravel stratum underlying the lake bed deposits must be penetrated to provide adequate bearing for piling. The water in the lake showed a high concentration of carbonates, sulphates, and chlorides; the total dissolved solids exceed 37,000 parts per million in a typical analysis. Tests indicated that concrete piles exposed to water of this nature might deteriorate very rapidly. It was believed steel piles would suffer less damage than concrete in the lake water; but in penetrating the gravel stratum underlying the lake bed material, the piles would come in contact with fresh water. A concentration of solutions varying over the length of the pile would develop a concentration cell to the detriment of the immersed metal, the greater damage being suffered by that portion in the solution of higher concentration. Paint as a means of protection was precluded, both because of the certainty of damage due to driving the piles and the equal certainty that the lake water would remove it rapidly. It appeared that the only practicable method of preventing corrosion of steel piles would be cathodic protection, which had proven effective when used on steel pipe and steel sheet-piling. However, uncertainty remained as to the effectiveness of cathodic protection for the interior piles of the large pile clusters required for each pier, and since no adequate estimate of the first cost or maintenance costs of such an unprecedentedly large system of protection could be made, the plan of using steel piles for the lake crossing was discarded.

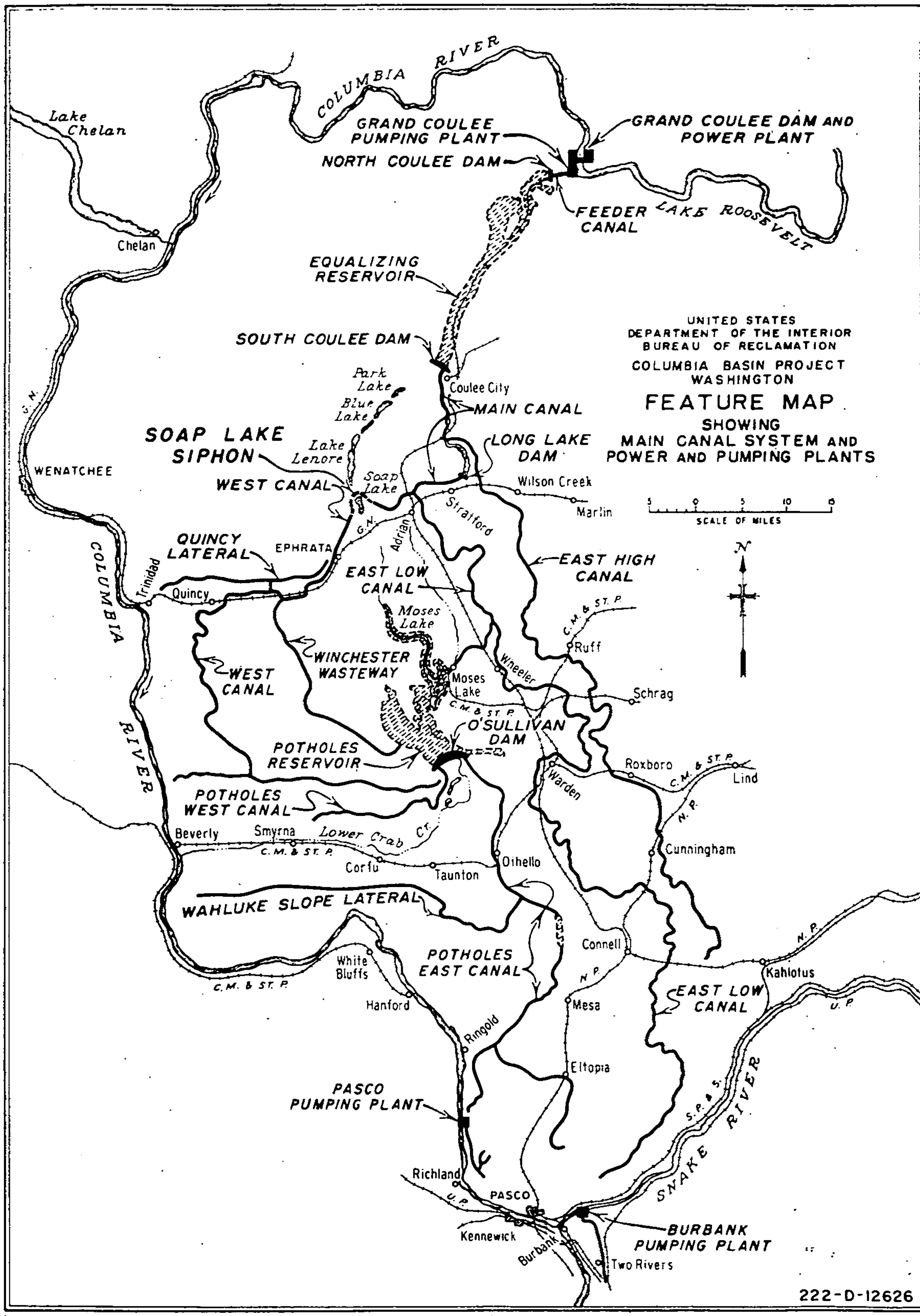


FIGURE 1 - Soap Lake Siphon is an important link in the West Canal system of the Columbia Basin project. Land to be brought under irrigation lies between the West Canal and the East High Canal, extending south to the Columbia River.

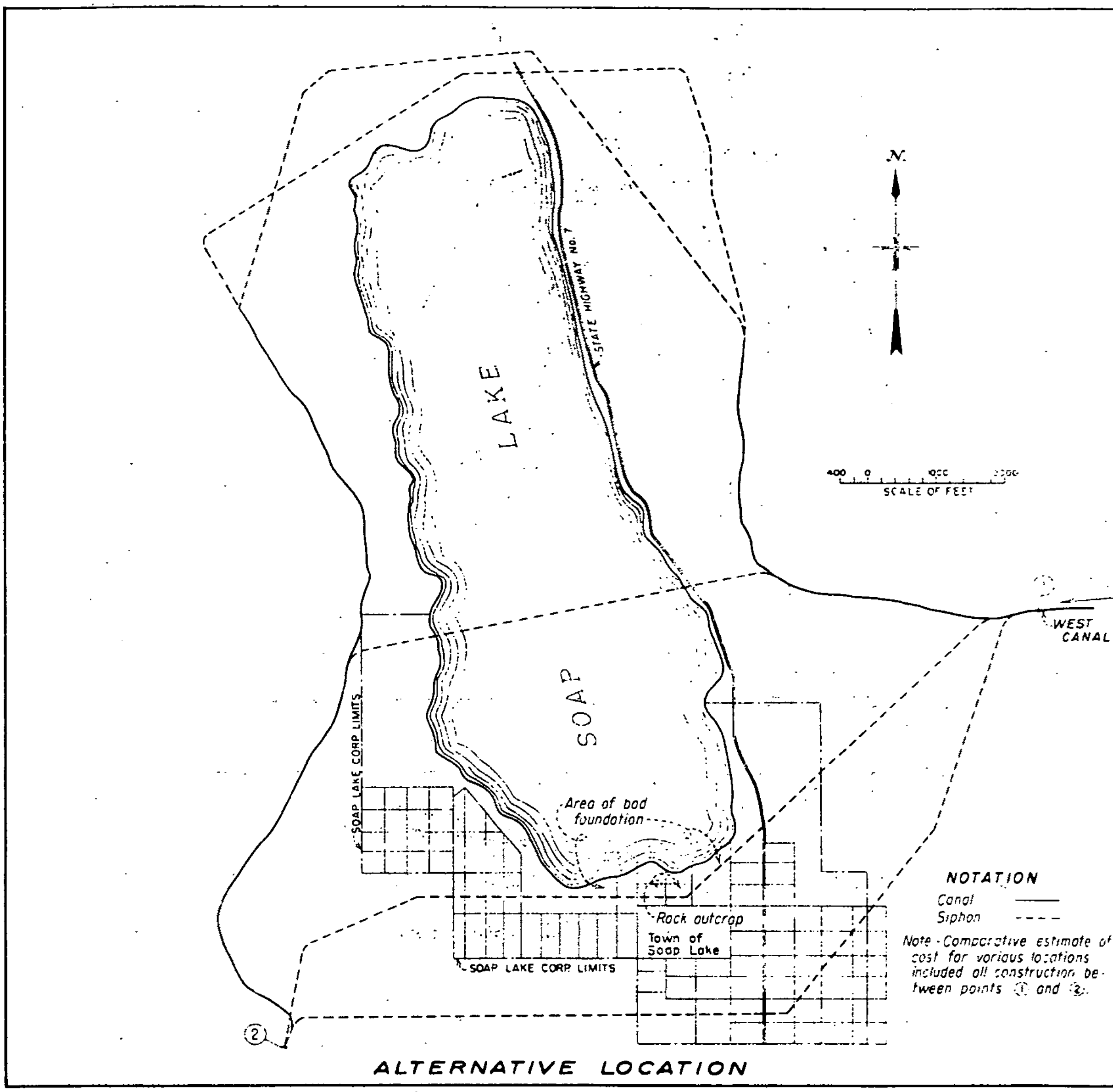


FIGURE 2 - Investigations included examination and comparative cost estimates for the location of the siphon on each of the routes illustrated here.

Cost studies were made for steel pipe supported on concrete piers carried to the gravel stratum by open cofferdam construction, but here again the question of damage to the concrete by the lake water and the uncertainty as to the efficacy of possible means of protection, as well as the high cost of such construction, caused the abandonment of this plan as well, and with it the abandonment of the idea of a siphon crossing the lake.

Final Location

Consideration was next given to constructing a siphon around either the north or the south end of the lake, although this would involve materially longer siphons. Cost comparisons showed that the line passing around the north end of the lake would be the less expensive, and this line was adopted as the location for the final design.

Of interest is the result of studies made to compare the cost of a single pipe with that of smaller twin pipes designed for the same total capacity. The studies showed that the two smaller pipes would cost about 25 percent more than a single pipe.

ALTERNATIVE DESIGNS

Cost studies were undertaken for a design utilizing buried monolithic concrete

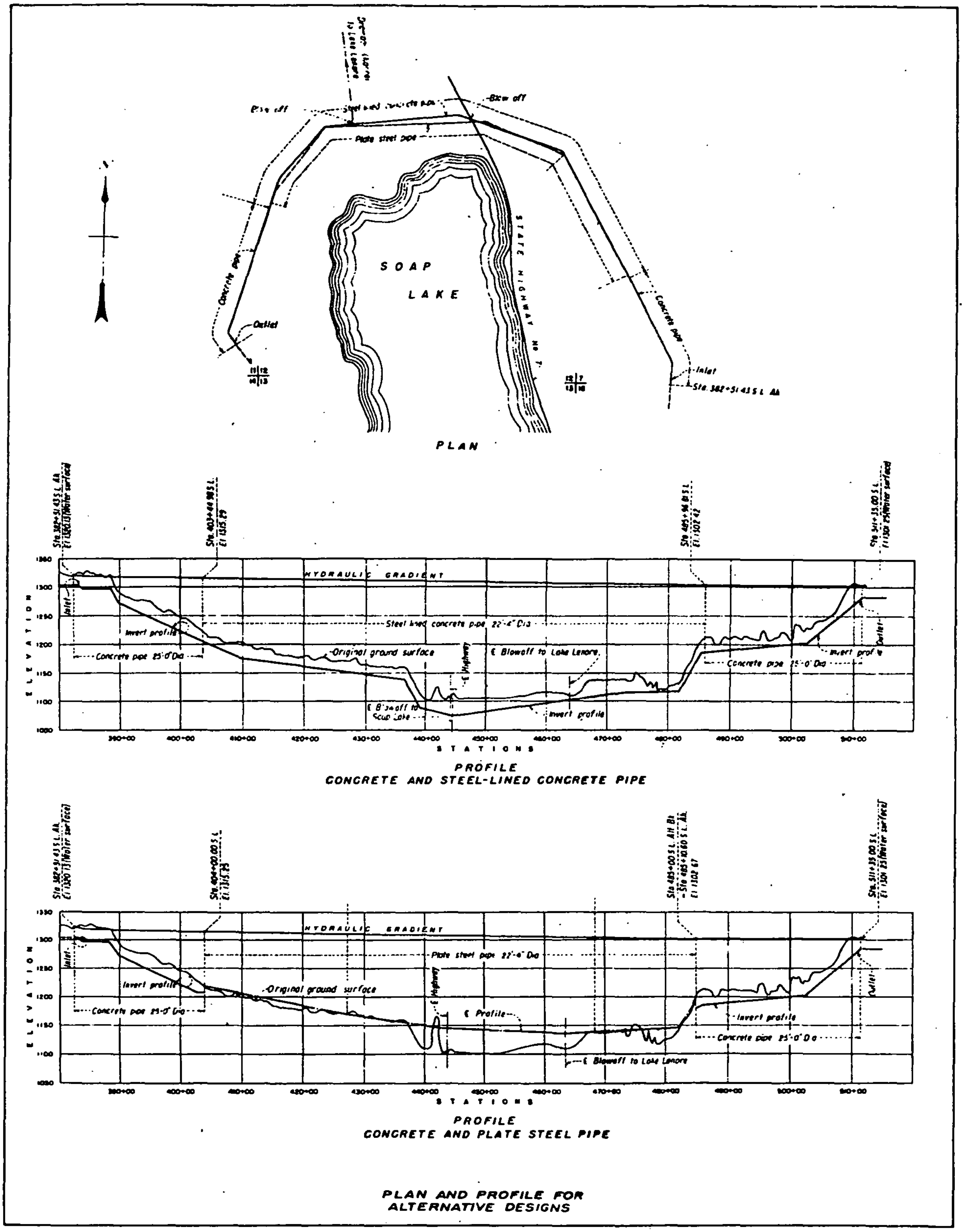


FIGURE 3 - The specifications for construction of the siphon invited bids on these alternative designs, locations, and profiles.

pipe for the inlet and outlet legs of the siphon where the hydrostatic head was 100 feet or less, and exposed plate-steel pipe in the sections where the hydrostatic head was greater than 100 feet. Such design is in accord with the general practice of the Bureau, as experience has shown that concrete pipe with relatively thin walls may lose its watertightness when subjected to internal water pressures much in excess of the equivalent of 100 feet of hydrostatic head.

In preparing the estimates it was noted that the cost of the steel pipe designed for the 100-foot hydrostatic head was nearly double the cost of the concrete pipe for the same head. This circumstance led to studies looking toward the development of a new design which would combine the low cost of concrete pipe with the watertightness of steel pipe. The result of these studies is a steel-lined concrete pipe cast in place. The thin steel liner on the inside surface of the pipe has a threefold purpose: first, it provides a watertight membrane; second, it serves as an inside form for the concrete; and third, it is an integral part of the reinforcement. Two layers of steel bars are provided as reinforcement in addition to the liner plate, the inside layer of bars being placed directly against the steel plate.

This design was presumed to be materially less costly than conventional plate-steel pipe; but because of the unusually large size of the pipe and uncertainty about the reliability of a cost estimate on this new type of construction, it was decided to prepare specifications and call for alternate bids on the conventional plate-steel pipe and the steel-lined concrete pipe.

Plan and Profile

Plans and profiles of the alternative designs are shown on Figure 3. The inlet and outlet legs of the siphon are 25-foot 0-inch inside diameter concrete pipe and are identical respectively for both designs, as alternatives were considered only for the central portion, where the hydrostatic head is greater than 100 feet. The alternative designs differ little in plan. They were made to adapt each design to the topography and foundation conditions best suited to it. Rock outcrops are ideal locations for the concrete anchor blocks necessary for the sharp bends in the steel pipe, but the sweeping, long-radius curves of the steel-lined concrete pipe require neither rock foundation nor anchor blocks. In profile, the steel-lined concrete pipe, being buried, is somewhat lower than the exposed plate-steel pipe. At the highway crossing the steel-lined concrete pipe, beneath the roadway, reaches its maximum hydrostatic head of 225 feet while the plate-steel pipe, for reasons of economy, would have crossed overhead and continued in the elevated position across the flat land north of the lake. The elevated steel pipe was designed to be supported by steel bents erected on low concrete piers.

Plate-steel Pipe

The plate-steel pipe was designed with an inside diameter of 22 feet 4 inches (as was the steel-lined concrete pipe), with the shell thickness varying from a minimum of 5/8 inch to a maximum of 1-3/8 inches. Supports, consisting of stiffener-ring girders, steel bearings, and reinforced-concrete footings, as shown in Figure 4, were provided at 100-foot intervals. Massive reinforced-concrete anchors founded on rock were provided at bends. Longitudinal movements due to expansion and contraction were made possible by sleeve-type expansion joints spaced 500 feet apart between bends. All of the features of the plate-steel pipe were designed in accordance with the standard practice of the Bureau for this type of construction.

Savings Possible with Steel-lined Pipe

Specifications No. 2411, for the construction of Soap Lake Siphon, were prepared with alternative designs for steel-lined concrete pipe and plate-steel pipe, and bids on the alternative designs were opened November 16, 1948. The low bid for all features of the siphon, including the inlet and outlet, totaled \$7,614,729. On the basis of the low bid, plus the cost of cement and aggregate furnished by the Government, the cost of the central portion of the siphon constructed of buried steel-lined concrete pipe was estimated to be \$5,398,000, while the cost of the corresponding portion constructed of exposed plate-steel pipe was estimated at \$7,761,000. Thus, the construction of the siphon using steel-lined concrete pipe was estimated to save \$2,363,000. In addition to this saving in first cost, the fact that the steel-lined concrete pipe is buried will eliminate certain maintenance costs, such as maintaining the exterior paint, which would have been necessary had the plate-steel pipe been used. These savings on maintenance, estimated to amount to \$360,000 over a period of 40 years, increase to \$2,723,000 the saving possible by the use of steel-lined concrete pipe. In view of this impressively large saving, the use of steel-lined concrete pipe is being studied by the Bureau of Reclamation for use not only as high-pressure pipe for canal siphons, but as an alternative design for plate-steel penstocks and outlet pipe for dam and power plant work.

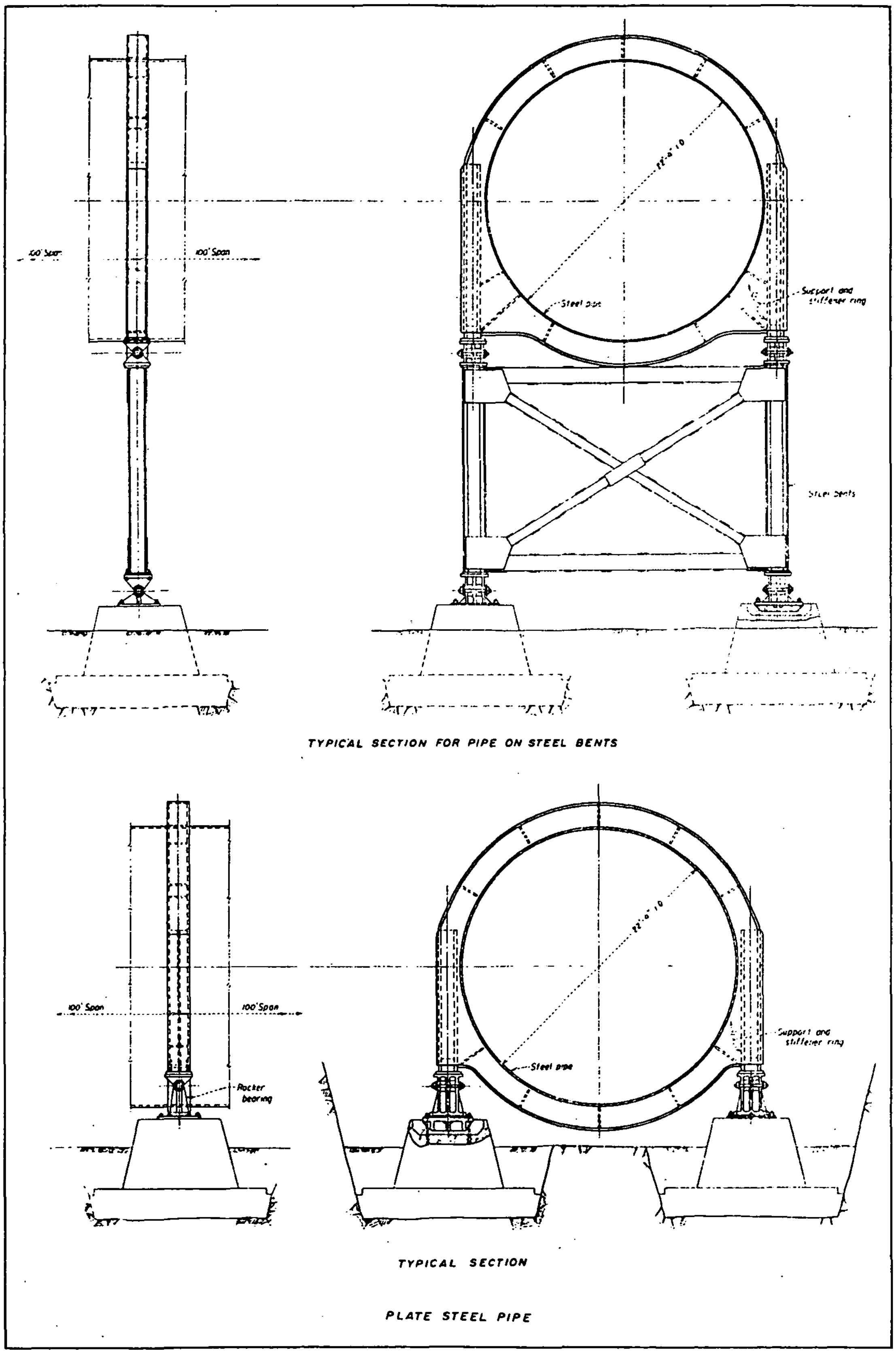


FIGURE 4 - The plate steel pipe for which bids were asked in the alternative specifications was designed in accordance with usual Bureau of Reclamation practice.

DESIGN OF PIPE

This description covers both the concrete and steel-lined concrete pipe used in the construction of Soap Lake Siphon. All of the features are described only briefly if the designs are in accordance with standard practice, but are treated in more detail if of special interest or of new design.

General Description

The alinement and profile of the final design of the Soap Lake Siphon are shown on Figures 5 to 8, inclusive. Beginning at the inlet end, the siphon includes a number of items of construction, which are described in sequence. A gravel trap 60 feet long is followed by an open and closed transition with an over-all length of 130 feet. The inlet leg of the siphon, made of monolithically constructed reinforced-concrete pipe, is 25 feet 0 inches in inside diameter and 1,910 feet long, extending to a point where the hydrostatic head is 100 feet. At that point a section 25 feet long reduces the inside diameter from 25 feet to 22 feet 4 inches. The central portion of the siphon is a steel-lined reinforced-concrete pipe, 8,264 feet in length and 22 feet 4 inches in inside diameter. The central portion connects to an enlarger section 25 feet long, in which the diameter is increased to 25 feet. This is followed by the outlet leg, consisting of a concrete pipe 2,413 feet long, of the same diameter and construction as the inlet leg of the siphon. A closed and open transition, 136 feet long, leads to the lined canal of trapezoidal cross-section.

It should be mentioned that at the point where the steel-lined concrete pipe joins the enlarger section the hydrostatic head is 110 feet. While this is somewhat greater than is considered desirable for unlined concrete pipe, a natural bench existed at that level, and it was felt that the increased cost of constructing a portion of unlined concrete pipe at the greater head would be offset by the savings effected by placing the enlarger section on the bench.

At bends in the line, whether horizontal or vertical, long radii are used, so that the construction of special anchor blocks is unnecessary.

Hydraulic Design

Hydraulic design of the siphon conformed to usual practice of the Bureau of Reclamation and was based on the following:

1. Friction loss in concrete pipe: Kutter's formula, using friction coefficient n = 0.014.

TABLE I

Section	Discharge, cfs	Diameter	Area, sq ft	Velocity, ft/sec	Hydraulic radius, ft	Friction	Slope
Canal	5,100	-	1,026.64	4.97	10.57	.014	.0001
Concrete pipe							
Free flow	5,100	25'-0"	435.56	11.71	7.60	.014	.0009
Pressure	5,100	25'-0"	490.88	10.39	6.25	.014	.0009
Steel-lined concrete pipe or plate-steel pipe	5,100	22'-4"	391.74	13.02	5.68	.34	.00146

On the above assumptions the total frictional head loss through the siphon is as shown in Table II.

2. Friction loss in steel-lined concrete pipe or in plate-steel pipe: Scobey's formula, using friction coefficient k = 0.34.

3. Losses at inlet transition and reducer: 1.1 of the difference in velocity head.

4. Recovery at enlarger and outlet transition: 0.8 of the difference in velocity head.

5. Bend losses in accordance with Figure 9.

The hydraulic properties are shown in Table I and Table II.

Gravel Trap

Sand, gravel, and rock fragments ravelling from the slopes of cuts may fall into the canal and some of this material may be transported by the water along the bottom of the canal until it enters the siphon. If it were permitted to enter the pipe, this extraneous heavy material would probably collect at the low point and would require removal from time to time. Experience has shown that gravel and rock carried along by the water are not normally detrimental to concrete pipe. However, the same material in a steel pipe will damage or completely abrade the interior protective coating to such an extent that frequent, if not annual, repairs to the coating will be necessary. Since the steel-lined concrete pipe is no different from plate-steel pipe where interior

TABLE II

	Length, ft	Pressure head losses, ft	Velocity head recoveries, ft	Total loss, ft
Inlet	130	1.92		
Reducer	25	1.04		
Concrete pipe	4,265	3.85		
Steel-lined pipe	8,252	12.06		
Bends		1.14		
Enlarger	25		.76	
Outlet	136		1.17	
Total	12,833	20.01	1.93	18.08
Excess head provided 4-1/2%				.80
Total losses in siphon				18.88

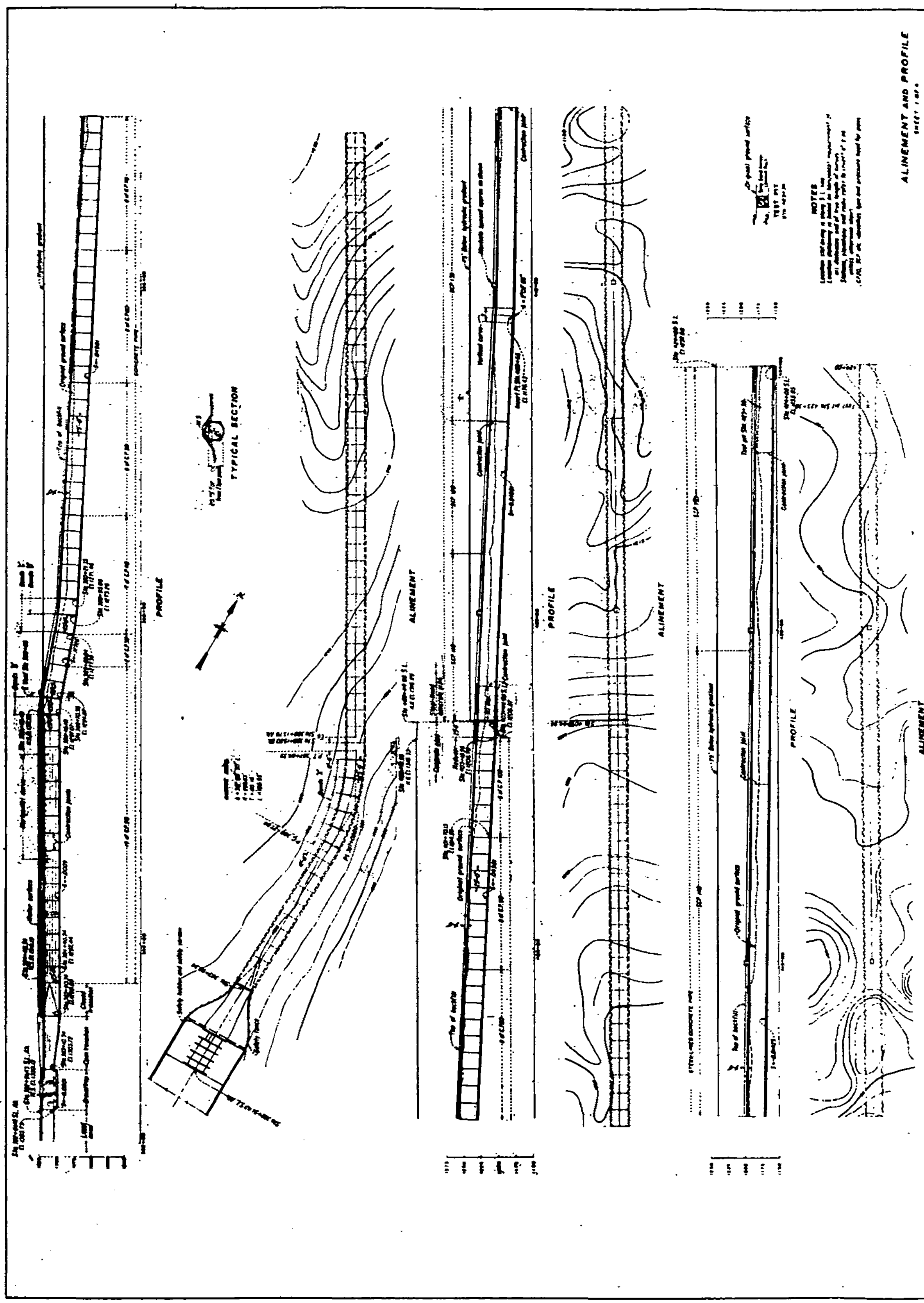


FIGURE 5 - Alinement and profile of the steel-lined concrete pipe (Sheet 1).

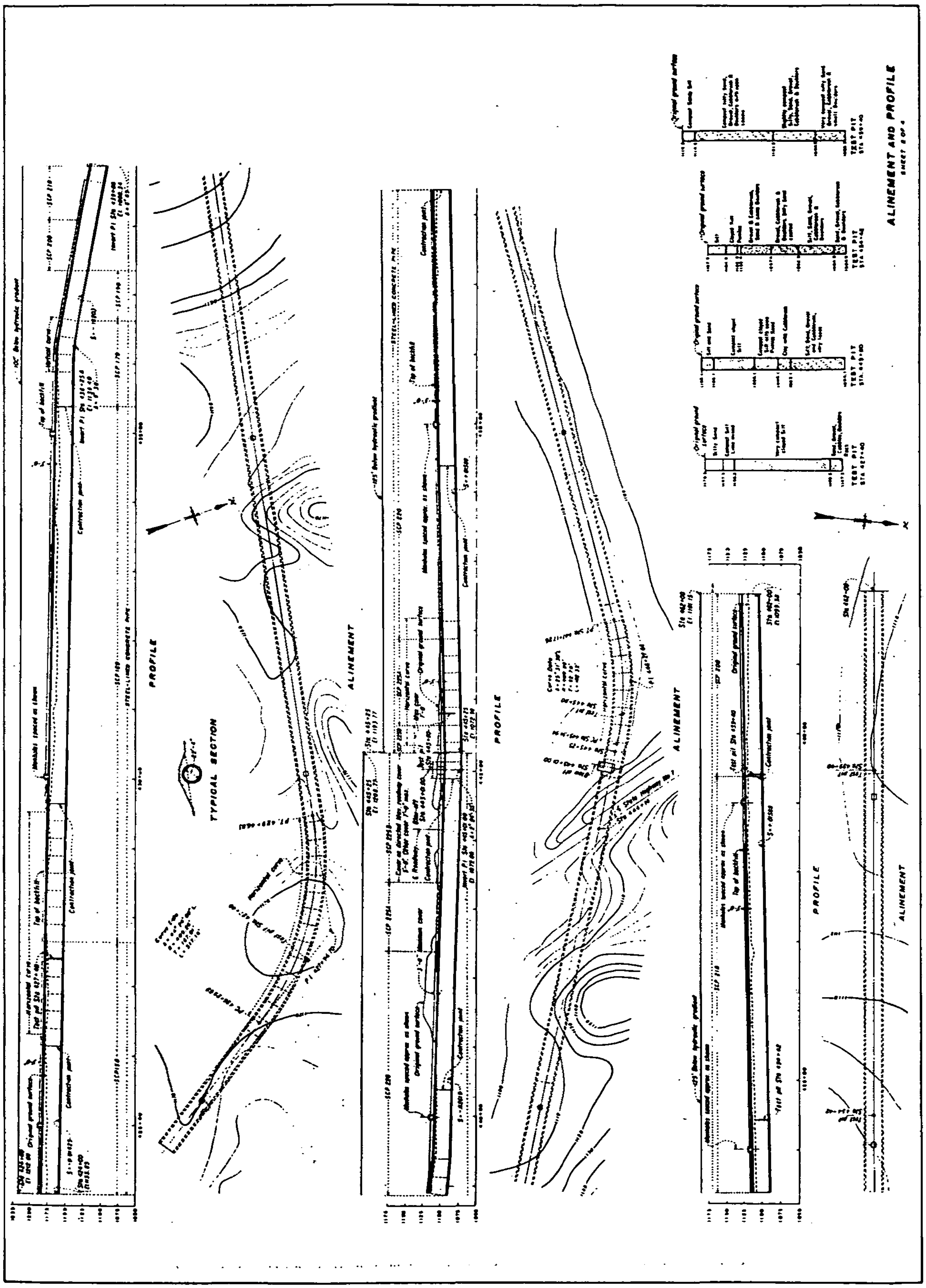


FIGURE 6 - Alinement and profile of the steel-lined concrete pipe (Sheet 2).

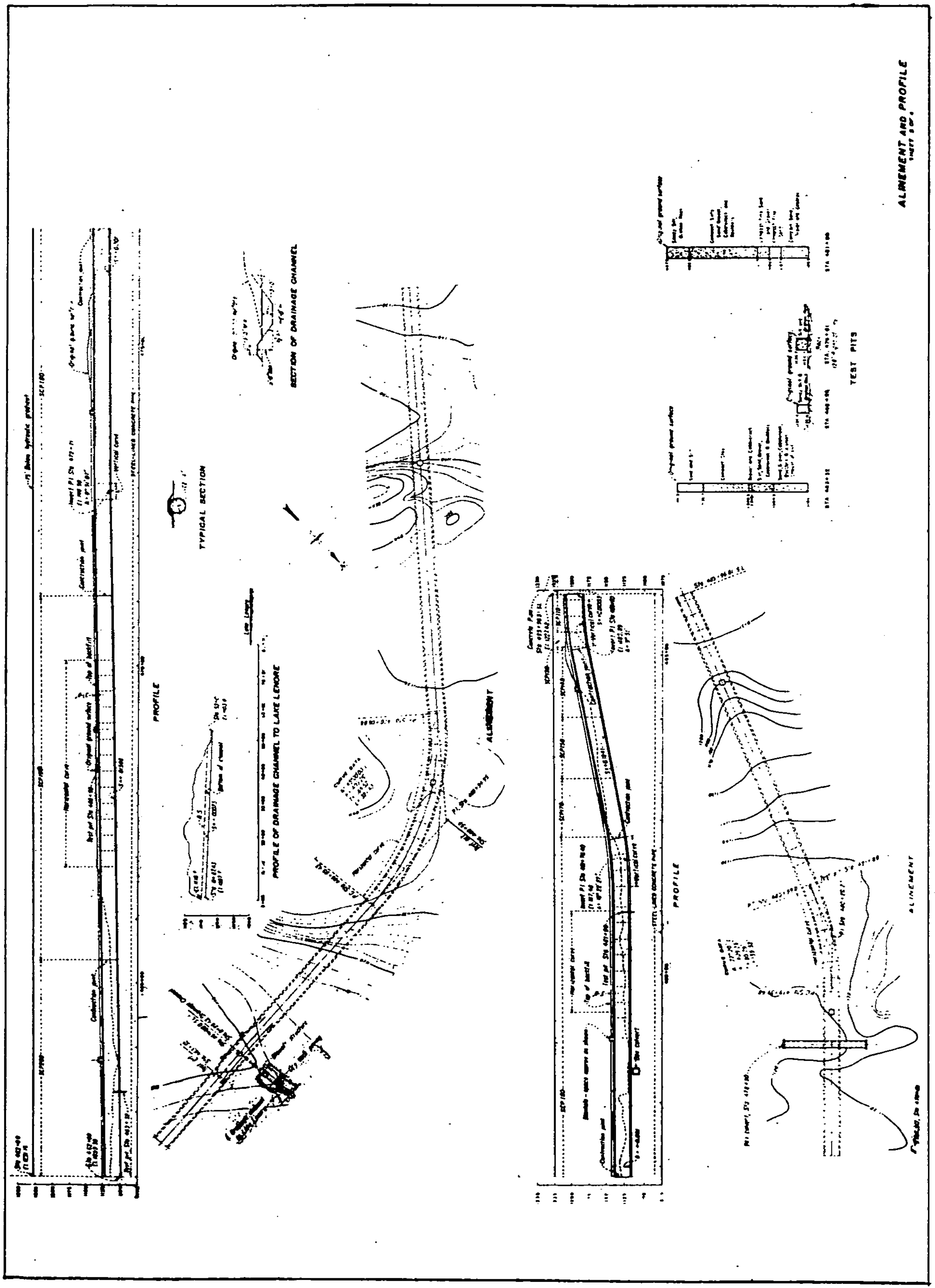


FIGURE 7 - Alinement and profile of the steel-lined concrete pipe (Sheet 3).

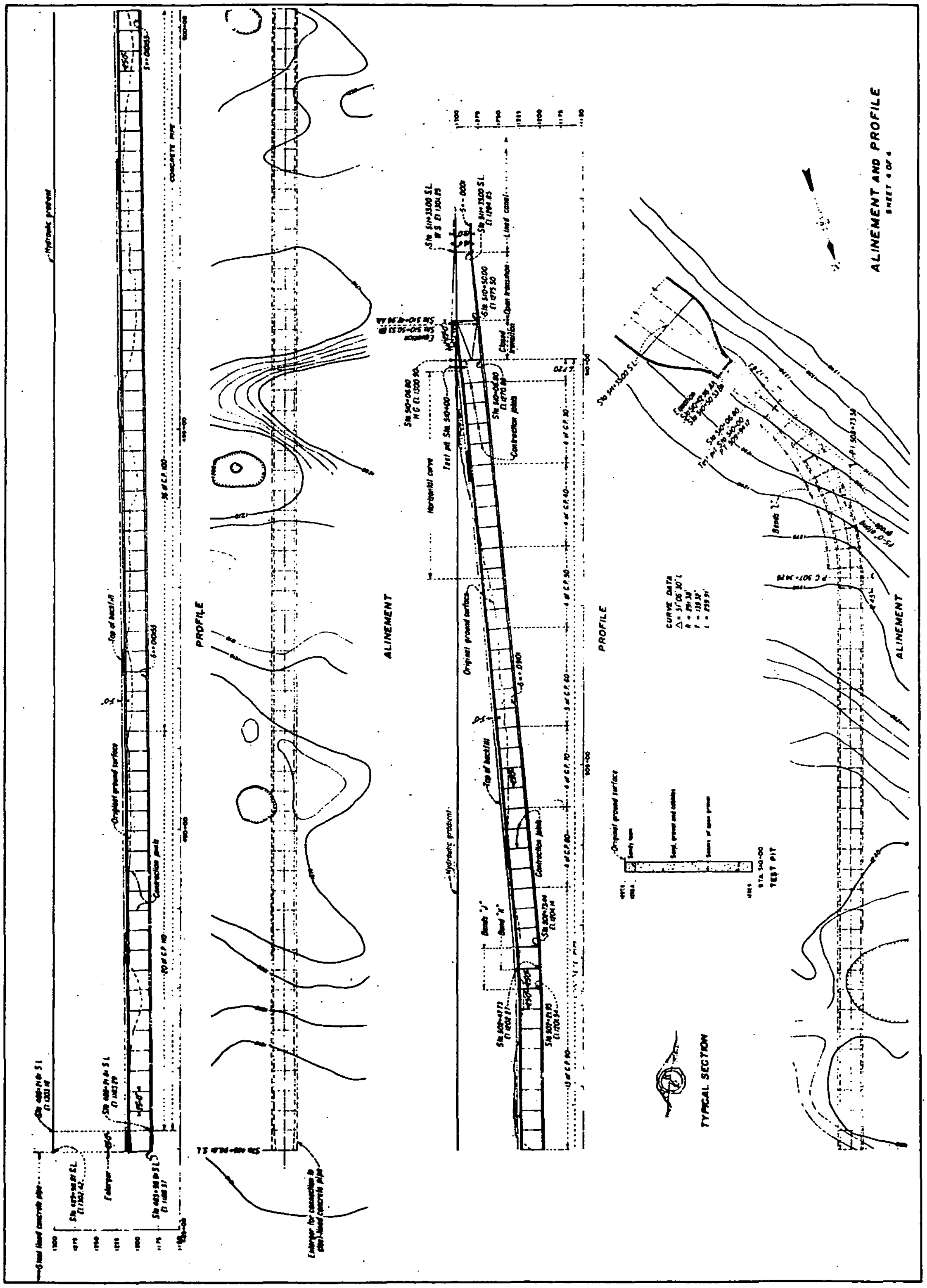


FIGURE 8 - Alinement and profile of the steel-lined concrete pipe (Sheet 4).

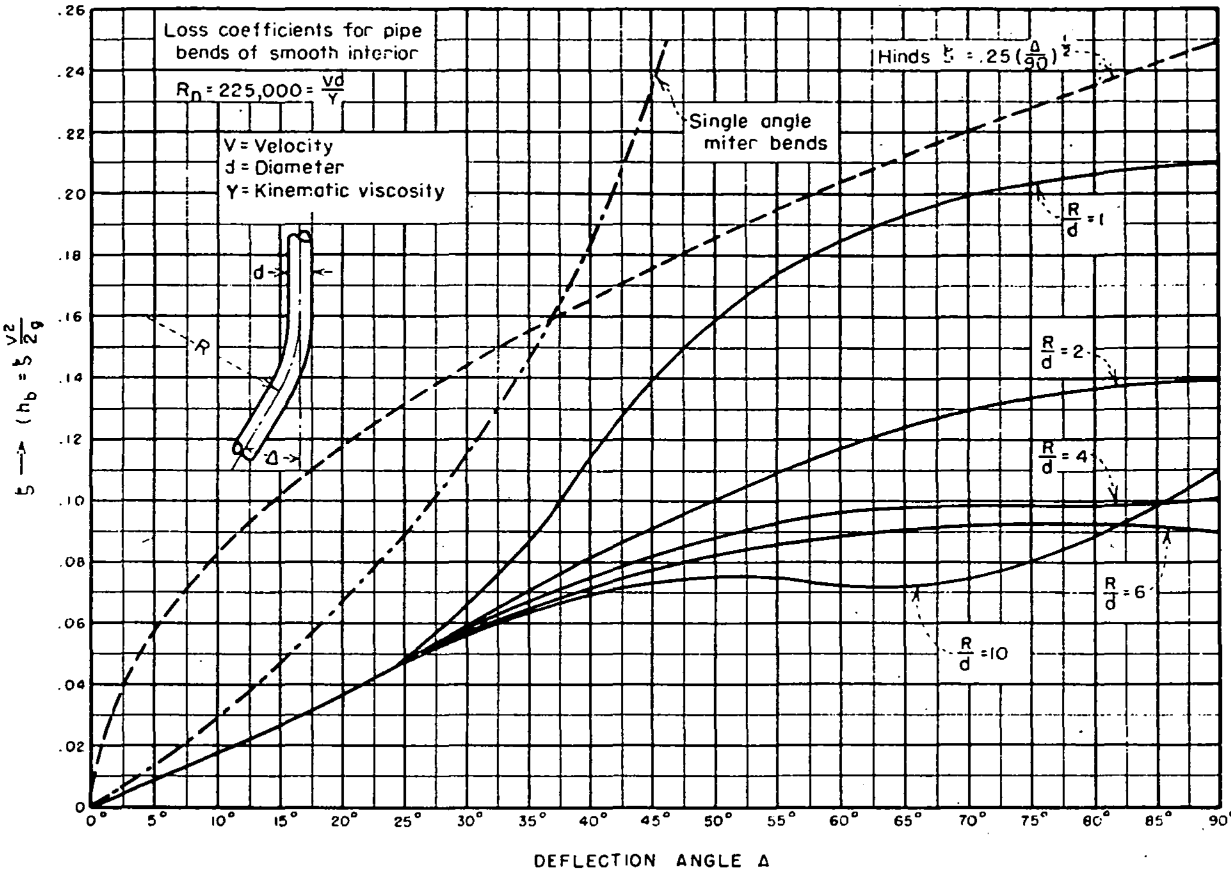


FIGURE 9 - Coefficients of bend losses for various values of R/D ratio and deflection angles up to 90°.

maintenance problems are concerned, the designers planned to prevent, insofar as possible, damage to the pipe from this source. On a structure as large as the Soap Lake Siphon, maintenance costs would be so great that the construction of a gravel trap to remove as much abrasive material as possible from the water before it entered the pipe was warranted. The size of the trap was determined arbitrarily as no data concerning the quantity of material likely to be carried by the current were available.

Figure 10 shows the gravel trap, which is of trapezoidal cross section, with the entrapment pit recessed 4 feet below the bottom of the canal. Four cross-walls divide the pit into five compartments which increase the effectiveness of trapping the transported materials. Armored seats are provided at the tops of the cross-walls for removable steel gratings, which will be installed in the future if the necessity is demonstrated.

Entrapped material will be removed, probably by power-driven mechanical equipment, between irrigating seasons. To protect the bottom and sides of the pit from the shock loads incident to this operation, the sides and bottom of the trap are formed by an 18-inch concrete slab, reinforced both top and bottom. The top layer of reinforcement is placed 4 inches from the surface for better protection of the reinforcement.

Inlet and Outlet Transitions

Both the inlet and the outlet transitions are comprised of an open and a closed section. The open section forms the transition from the trapezoidal canal section to a 25-foot square conduit, and the closed section forms the transition from the 25-foot square conduit to the 25-foot 0-inch inside-diameter concrete pipe. The open section of the inlet transition is 80 feet long, and that of the outlet, 85 feet long. The length of the closed section in each transition is 50 feet, or twice the diameter.

Concrete Pipe

The inlet and outlet legs of the siphon are monolithically constructed concrete pipe, 25 feet 0 inches in inside diameter. These legs extend from the ends of the closed transitions to the reducing and enlarging sections, where the hydrostatic head is about 100 feet, considered the upper limit desirable for low-head pipe. At the time the original estimates were prepared it was planned that a smaller diameter pipe would be used throughout the siphon. However, when final design preparation was begun, it appeared that the concrete forms being used in the construction of the Dry Coulee Siphon on the West Canal might possibly become available for use on the Soap Lake Siphon. As the Dry Coulee Siphon is a low-head concrete pipe of 25 feet 0 inches inside diameter, and because the movable steel forms for such large pipe are very expensive (reported to cost more than $50,000), it appeared advantageous to make use of these forms on the low-head portions of the Soap Lake Siphon, making the inlet and outlet legs the same diameter as the Dry Coulee Siphon.

As the total head loss for the siphon was predetermined, increasing the design diameter of the inlet and outlet legs to 25 feet reduced the head loss in those portions and permitted the use of a somewhat smaller diameter for the central, or high-head, portion of the siphon than had been originally planned. Comparative cost estimates showed that the use of a larger diameter for the low-head pipe and a correspondingly smaller diameter for the high-head pipe would result in saving nearly $100,000 over the cost of the siphon constructed with pipe having a

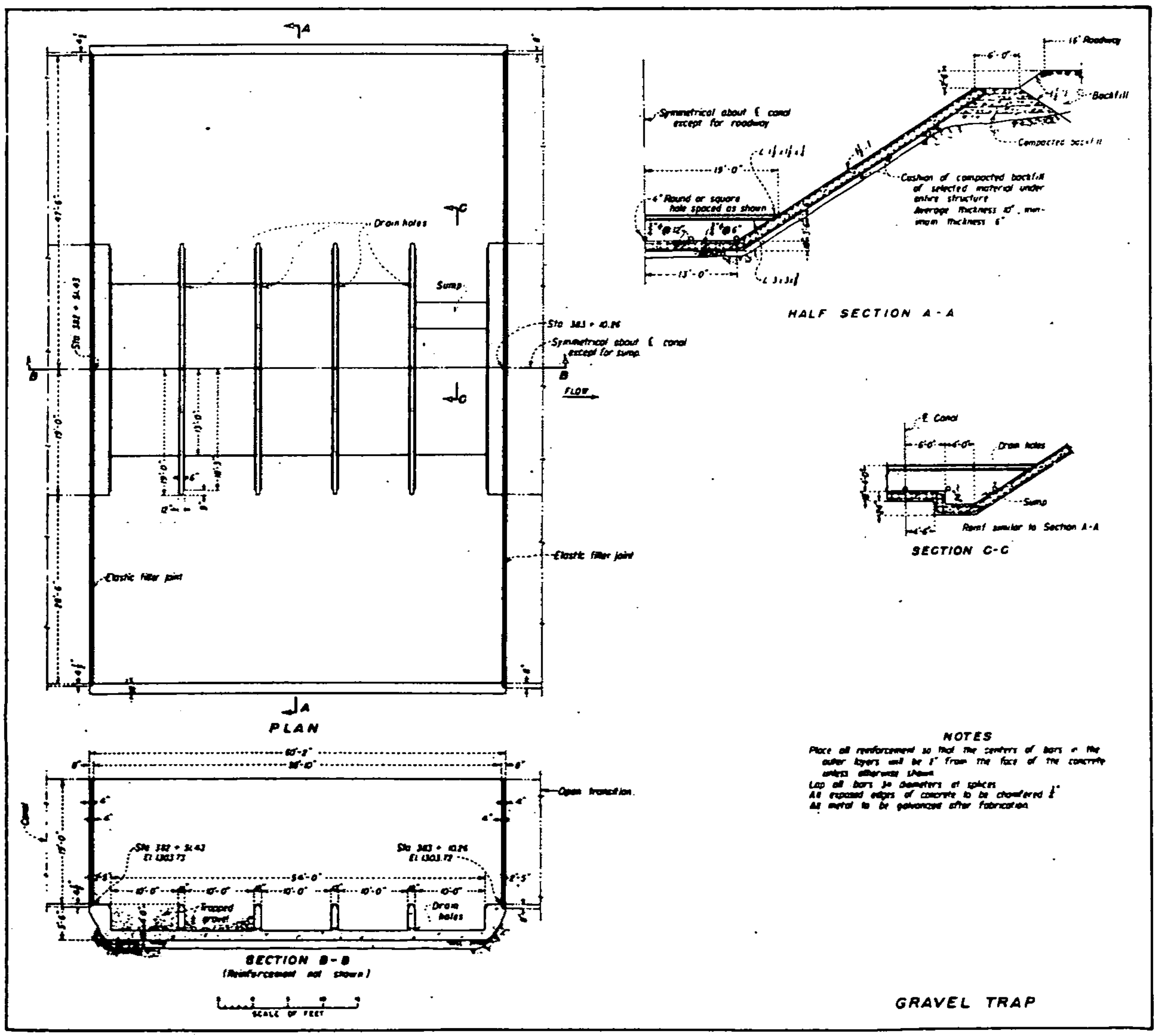


FIGURE 10 - The gravel trap is designed to prevent the entry of heavy debris into the siphon.

single diameter. This saving is exclusive of any saving that might accrue through the re-use of the forms from the Dry Coulee Siphon.

Figure 11 shows typical details of the monolithic concrete pipe. Contraction joints, with 1/4- by 10-inch wrought-iron water-stops, are provided at 25-foot intervals. Pipe bends, in either alinement or profile, are made to radii about 12 times the inside diameter to permit the bends to be made up of a series of straight pipe sections 25 feet long. By forming bends in this manner, the

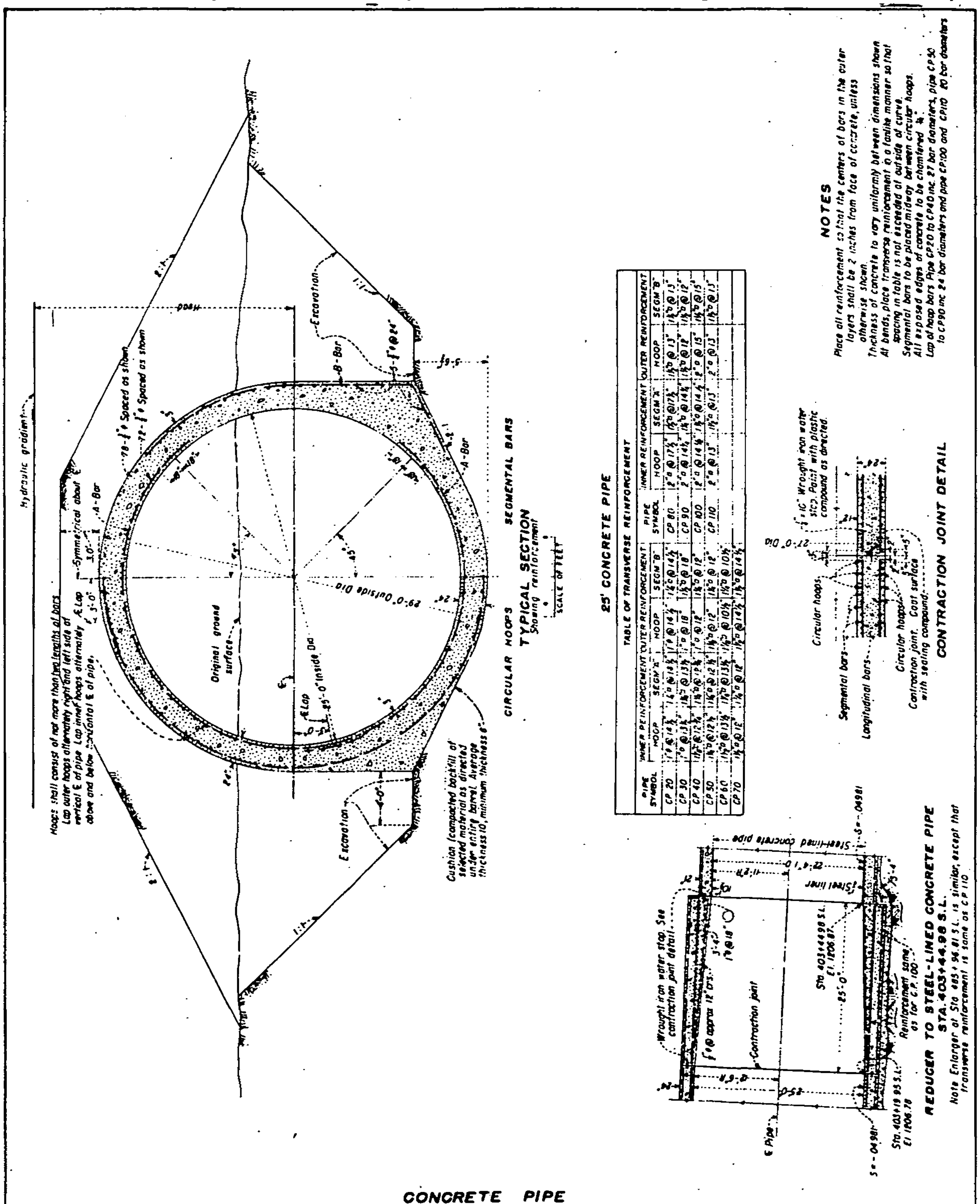


FIGURE 11 - The reinforced concrete pipe is cast in place. The inlet and outlet legs of the siphon are made of this pipe.

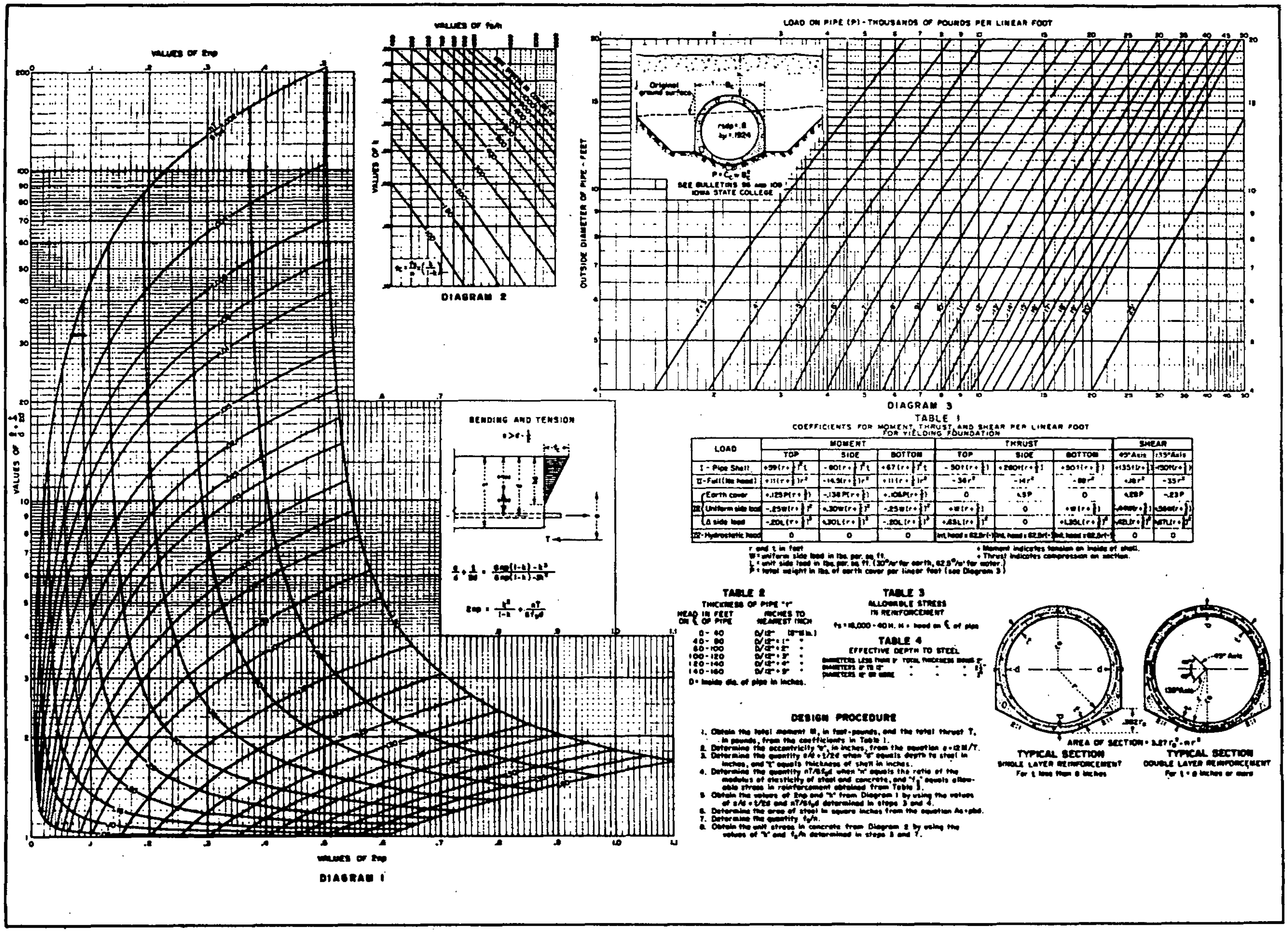


FIGURE 12 - Design of the reinforced concrete pipe is based on formulas from these curves.

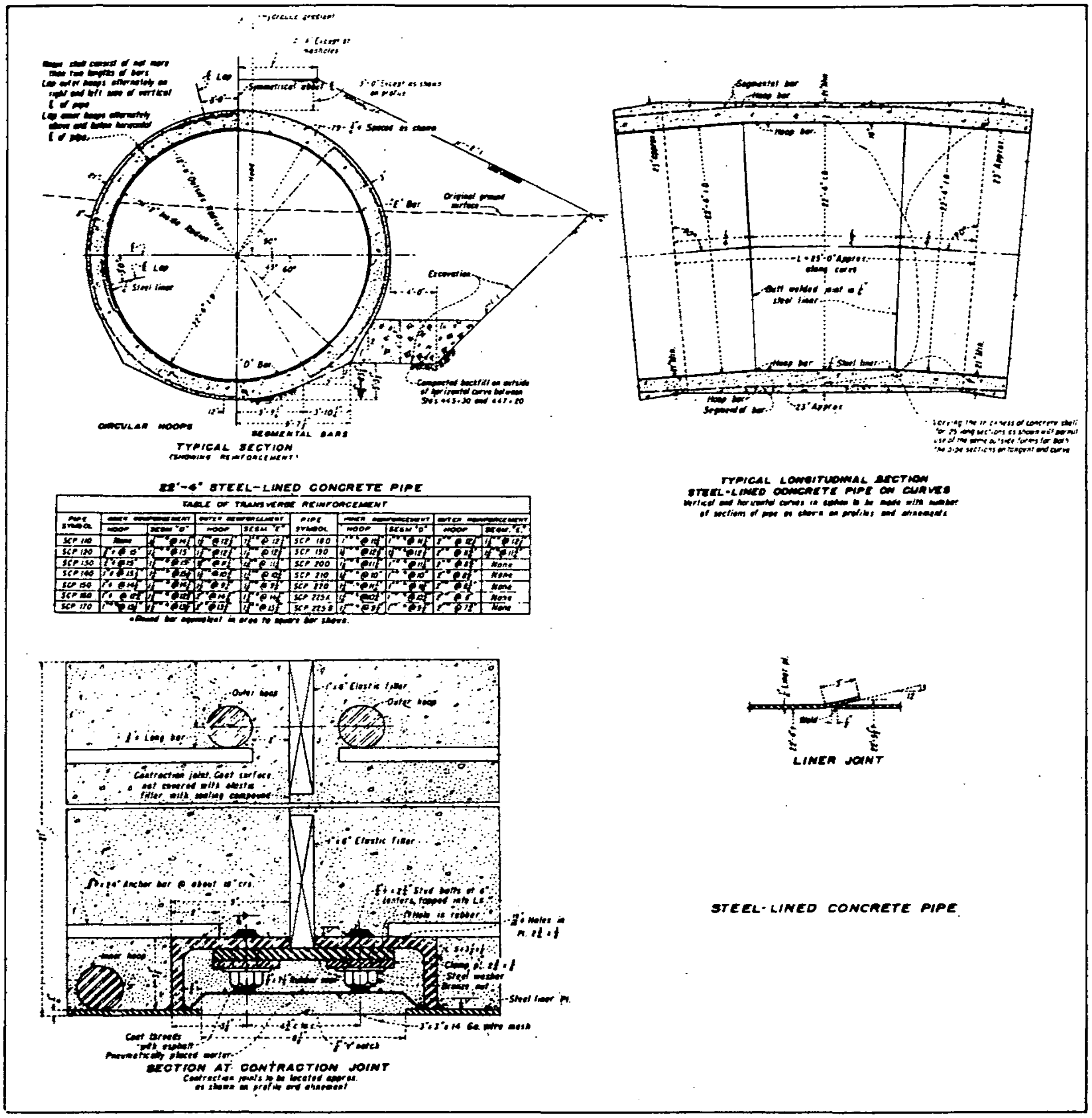


FIGURE 13 - Steel-lined reinforced concrete pipe forms the central portion of the siphon, where the hydraulic head exceeds 100 feet.

movable steel forms for straight pipe sections can be used for the sections on bends; only minor modifications to the form ends adjacent to the joints will be necessary.

The design of the pipe is in accordance with the formulas shown on Figure 12. The external earth cover was assumed to be 3 feet. Reinforcement was determined for each 10-foot increment of hydrostatic head. The allowable concrete stresses were assumed in accordance with the recommended working stresses for 3,000-pound concrete given in the Joint Committee Specifications, 1940 edition.[1] The allowable tensile stresses for the reinforcement steel were assumed in accordance with standard Bureau practice for siphon designs, as follows: $f_s = 16{,}000 - 40H$, where f_s = allowable tensile stress and H = hydrostatic head in feet, measured from the hydraulic gradient to the center line of the pipe.

1 "Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete," Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete: Proceedings, ASCE, Part 2, June 1940, sec. 878.

Steel-lined Monolithic Concrete Pipe

1. Unit stresses.--In developing the new type of monolithically constructed concrete pipe in which the steel liner is an integral part of the pipe, design criteria were assumed as follows:

a. The allowable unit stresses in the concrete were derived from the Joint Committee on Specifications for 3,000-pound concrete with an n value = 10. They are: f_c = 1,350 psi, v = 90 psi, and u = 150 psi for deformed bars. The allowable bond stress, u, for the steel-liner plate, for which no value is given in the code, was assumed as 100 psi, or about 80 percent of the bond stress given for smooth bars.

b. Normal practice in the design of monolithic concrete pipe requires a reduction in the allowable tensile stresses in the steel in order to minimize cracking and insure watertightness, but in designing the reinforcement steel for the new type of pipe, the fact that the steel-liner plate provides a watertight membrane permitted the elimination of this requirement. Therefore an allowable unit stress for the reinforcement steel of 20,000 psi was considered to be appropriate.

c. The allowable unit stresses for a steel liner are dependent on the type of steel used. In general, plate-steel pipe is of material conforming to class B, ASTM Designation A 285-46. This steel has a yield point of 27,500 psi and an ultimate strength of 55,000 psi. As these strengths are materially below those of the reinforcing steel, use of steel plate of a higher grade was given consideration. Since the steel-liner plate must be welded, steel of good welding quality was considered essential. Consequently, the ASTM Designation A 285-46 was adhered to, but class D steel was specified rather than class B. Class D is described as having an ultimate strength of 60,000 psi and a yield point of 33,000 psi, permitting an allowable design stress of 20,000 psi which is in accordance with usual practice. Efficiency of the welds in the liner plate is assumed conservatively at 80 percent, so that at the welds the allowable stress becomes 16,000 psi.

2. Design.--The cross section and details of the steel-lined concrete pipe are shown in Figure 13. The lower portion of the outside of the pipe is sloped inward so as to approach more nearly a circular shape, since such a shape is more efficient for pipe under high heads where the hoop or tensile stresses become dominant in comparison with the stresses caused by earth loads and the dead load of the pipe.

a. Load assumptions.--The pipe is assumed to be subject to loads due to earth pressure around the pipe, to the dead load of the pipe itself, and to the internal hydrostatic pressure. The internal pressure produces uniform tension, T, in the pipe according to the formula $T = 62.4\ Hr_o$, where T = tension in pounds, H = hydrostatic head in feet from hydraulic gradient to the top of the inside of the pipe, and r_o = inside radius of pipe in feet.

The remaining portion of the hydrostatic head, i.e., that portion represented by the pressure from the top to the bottom of the pipe, produces bending, direct, and shear stresses. It is designated as water load and is considered in combination with the earth load and the dead load.

Figure 14 illustrates the assumed distributions of earth loads around a rigid pipe. The reaction of external loads is assumed to be distributed over the bottom of the pipe, limited by a certain central angle and varying as some function of the angle θ. The limits of the central angle are dependent on the bedding of the pipe. Moment, thrust, and shear are given for central angles of 45° and 90° and for various values of θ in Figure 15.

Distributions of earth loads and of soil reactions are assumed to be bulb-like in shape as indicated in Figure 14.

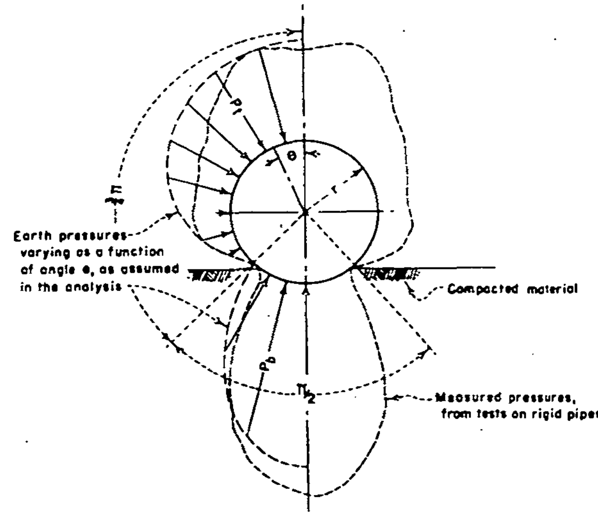
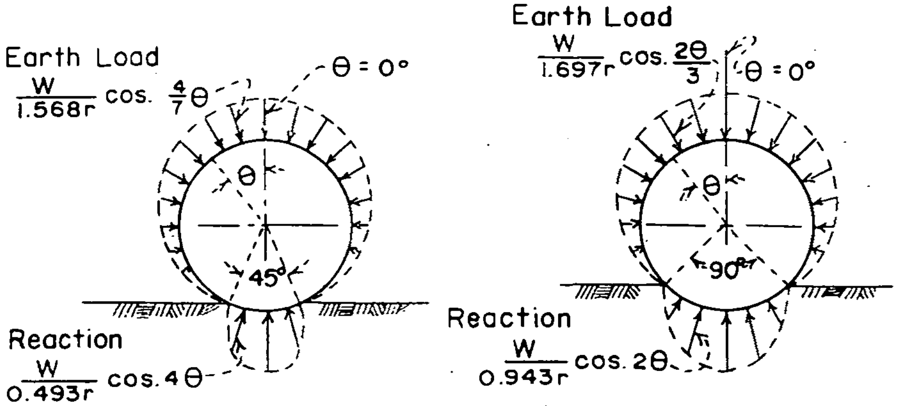


FIGURE 14 - Earth pressures on the buried pipe and the reactions thereto resulting from the bedding of the pipe are assumed on the basis of bulb-shaped force diagrams, an assumption borne out by tests.

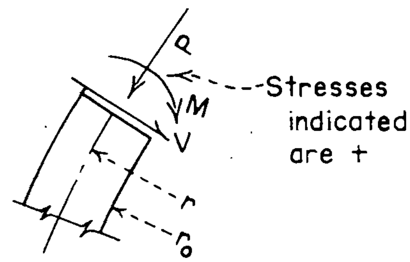


Note: Reactions for Water Load and Dead Load are assumed to have the same distribution as for Earth Load.

M = coef. x W x r

P = coef. x W

V = coef. x W



For Earth Load W = total weight of earth on pipe.
" Water " " = $62.4 \pi r_o^2$
" Dead " " = $W_p 2\pi r t$

For 45° reaction

θ	EARTH LOAD			WATER LOAD			DEAD LOAD		
	M	P	V	M	P	V	M	P	V
0°	-.064	+.453	0	-.078	-.234	0	-.078	-.075	0
90°	+.073	+.590	+.071	+.088	-.068	+.075	+.088	+.250	+.075
105°	+.084	+.601	+.008	+.097	-.059	-.003	+.097	+.301	-.003
150°			-.292			-.323			-.323
180°	-.158	+.359	0	-.174	-.330	0	-.174	+.147	0

For 90° reaction

θ	EARTH LOAD			WATER LOAD			DEAD LOAD		
	M	P	V	M	P	V	M	P	V
0°	-.067	+.383	0	-.070	-.220	0	-.070	-.061	0
90°	+.081	+.530	+.066	+.081	-.069	+.061	+.081	+.250	+.061
105°	+.089	+.539	-.010	+.088	-.062	-.017	+.088	+.299	-.017
150°			-.273			-.261			-.261
180°	-.126	+.324	0	-.122	-.272	0	-.122	+.207	0

PIPE ANALYSIS

FIGURE 15 - Moment, thrust, and shear calculated for various values of the angle θ, and for both 45° and 90° bedding angles.

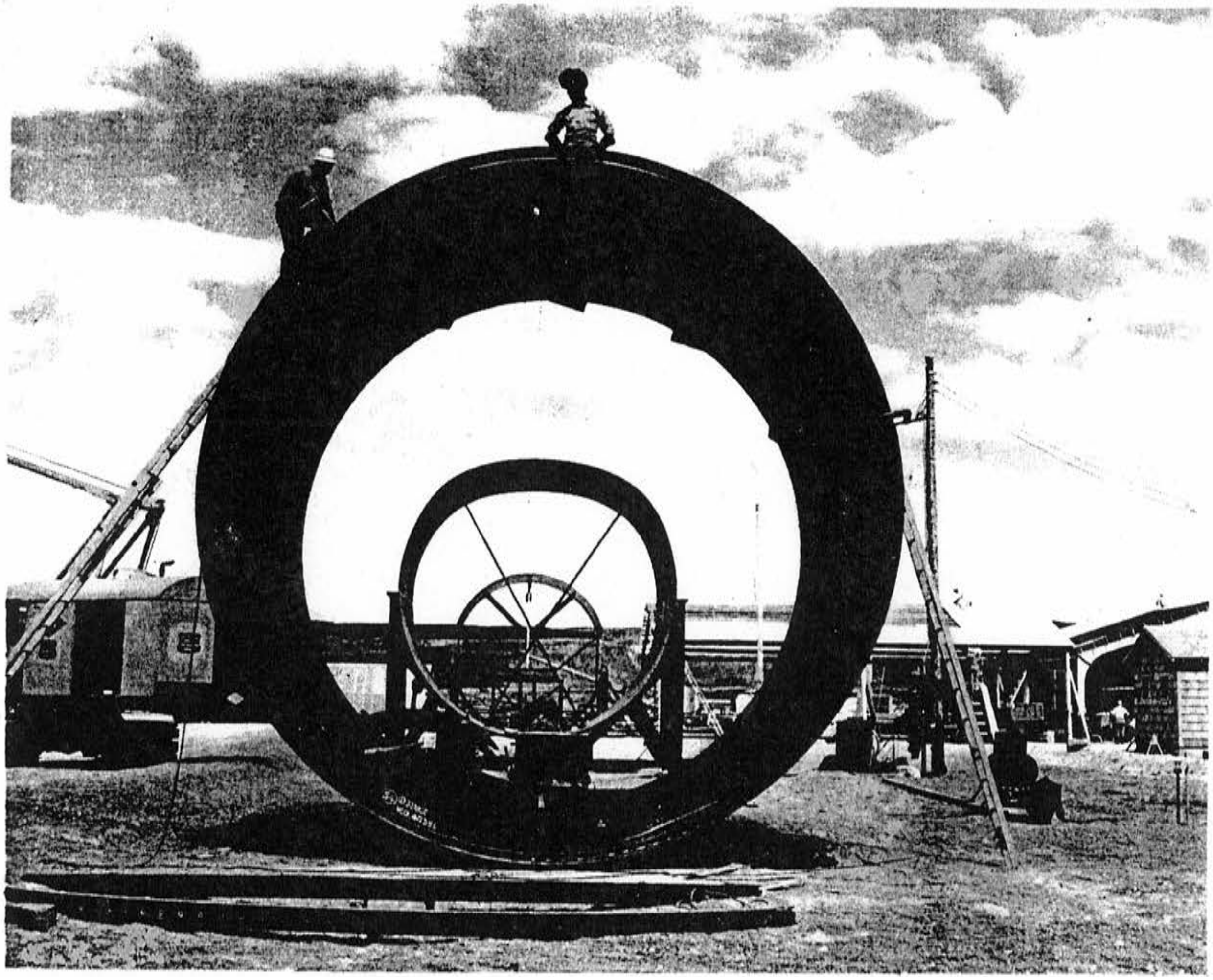


FIGURE 16 - Fabrication of the 1/4" steel-liner plate requires the use of internal structural-steel forms to support the plates during welding.

Note: Inspection during construction has disclosed that when the liner is tapped, a hollow sound is given off at many places. This phenomenon has also been observed in the construction of penstocks encased in mass concrete, yet when the hollow-sounding places were explored by drilling no voids could be found, nor could any grout be forced into such places. Nevertheless, some concern was felt over the adequacy of the bond between the liner and the concrete. While the maximum calculated bond stress is only 65 psi, a re-analysis of the pipe was made, assuming no bond at all. The result of this analysis shows that for heads greater than 180 feet the reinforcing steel bars will be stressed up to 25,000 psi. Under lower heads, the stress will be considerably above this figure because the liner is not fully effective, and it is designed as a considerable percentage of the reinforcement.

To ascertain the actual bond between liner and concrete, strain gages are being installed on the siphon. It is hoped that the measurements will clarify the interaction of concrete and liner. Meanwhile, and in order to avoid delays in actual construction, the reinforcement of the inner layer has been increased so that, neglecting bond, a design stress of 25,000 psi will not be exceeded. The additional steel required amounts to about 1 percent of the total cost.

b. Weld locations. In order that the steel-liner plate may be built with the greatest economy, the stress distribution around the circumference of the pipe must be considered. The internal water pressure, as has been stated, produces tensile or so-called hoop stresses, which are the same at any point in the shell. However, the stresses due to earth loads, weight of pipe, and weight of water vary from point to point, and the greatest tensile stresses on the inside surface of the pipe occur at the vertical diameter. On the outside surface the greatest tensile stresses occur at the horizontal diameter. As these stresses are additive to the hoop stresses, the maximum tensile stresses occur at the vertical and horizontal diameters. Near the diameters inclined on a 45-degree angle from the horizontal, the moments due to earth load, water, and weight of pipe are zero, so that the tensile stresses in the pipe at these points are those produced by internal pressure alone. In view of this, and assuming that the large diameter of the pipe requires that each steel-liner course be built up of four plates joined by four longitudinal welds, and that at these welds the allowable stress is only 16,000 psi, the greatest strength and economy of construction will be achieved if the longitudinal welds are located on those diameters which are inclined at an angle of 45° from the horizontal. Thus, full advantage of the 20,000 psi allowable stress in the base material of the liner can be taken at the vertical diameter, where the tensile stresses are at the maximum.

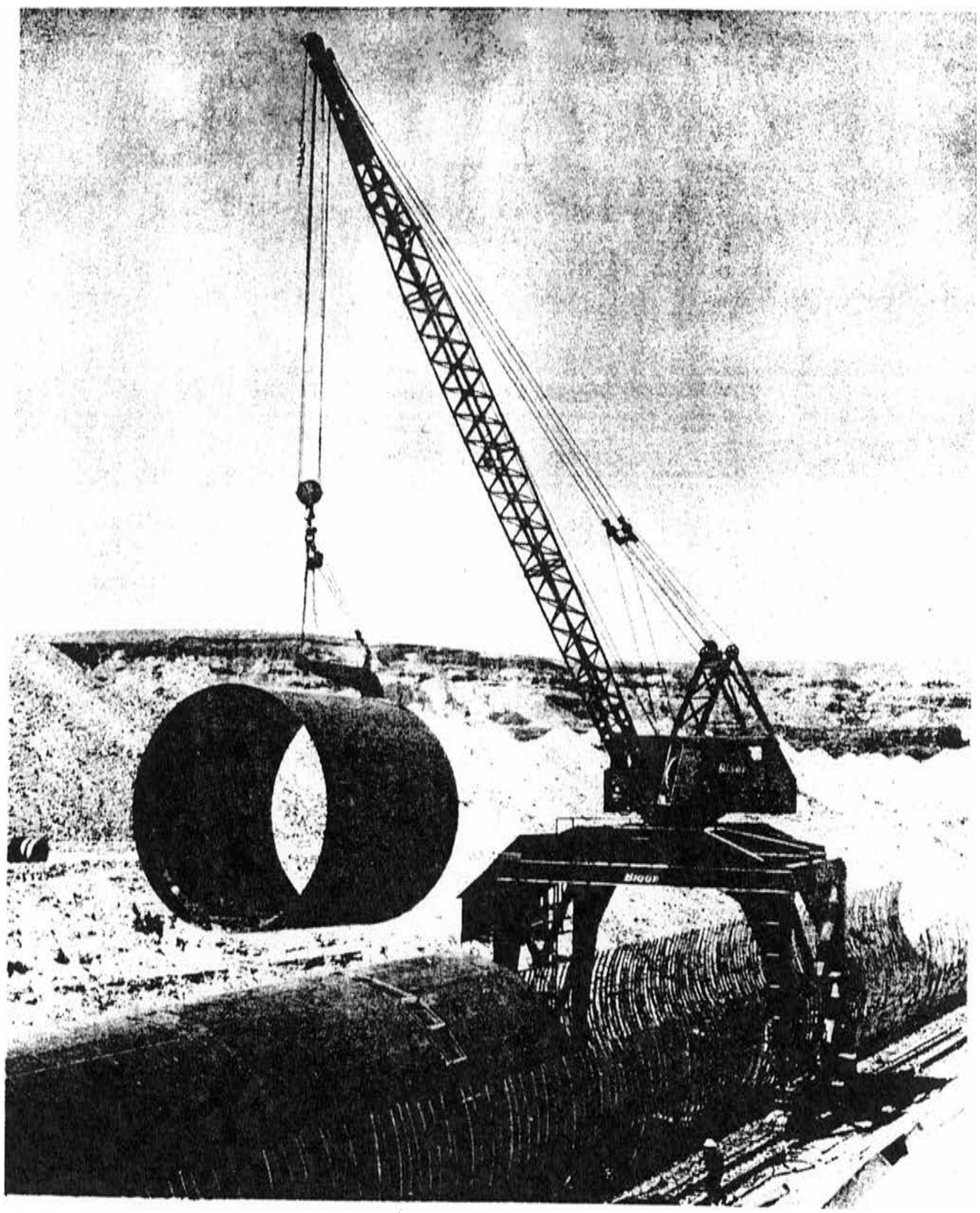


FIGURE 17 - Steel-liner plate is placed in position by a traveling crane after the reinforcement for the lower portion of the pipe is in place.

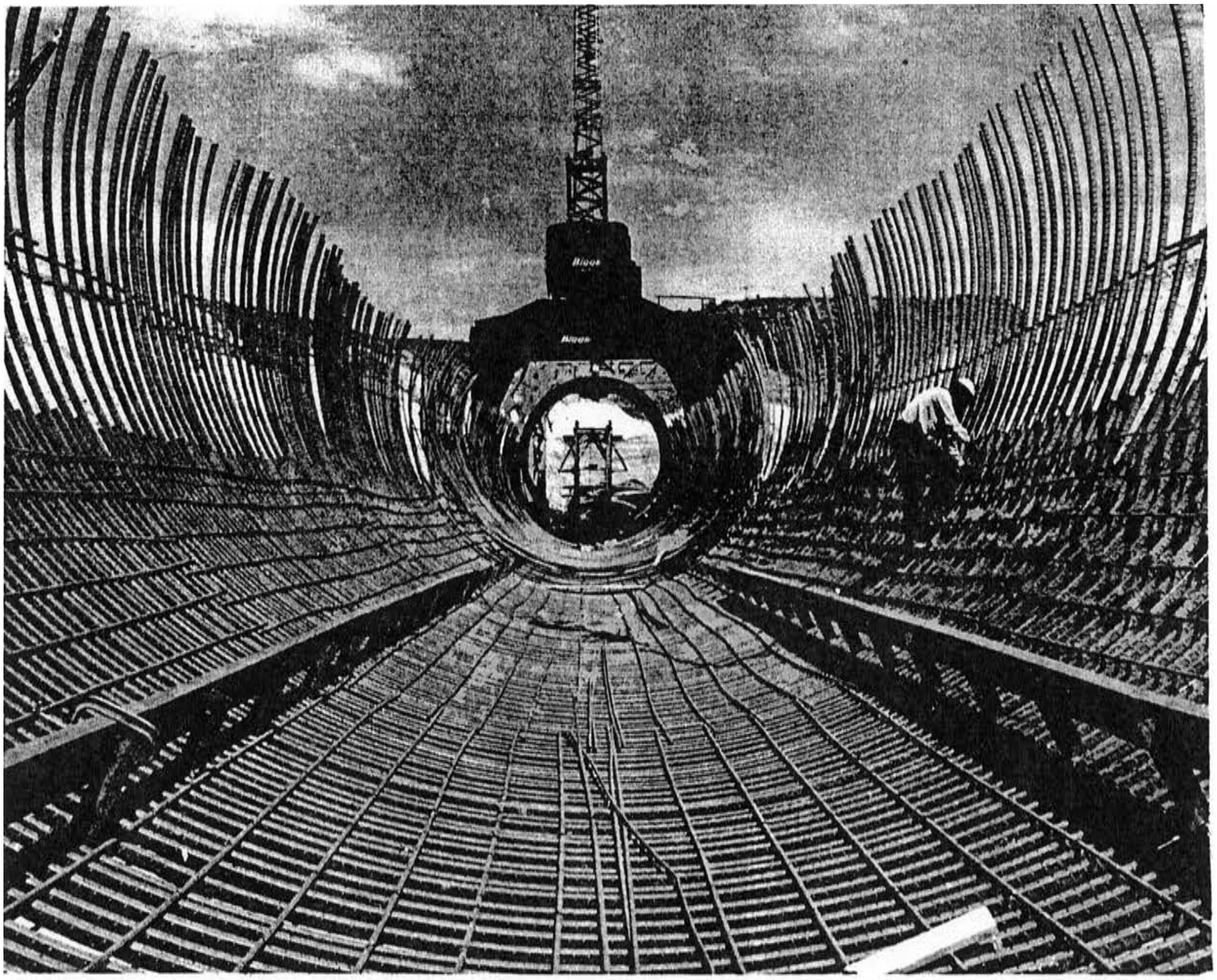


FIGURE 18 - Steel reinforcement being placed on a portion of the Soap Lake Siphon. The crane in the center is placing a section of the steel-plate liner in position.

c. Working rule for steel stresses. With the inner layer of reinforcement placed directly against the liner plate, the allowable stress in the reinforcement is controlled by the allowable stress in the steel liner. If four longitudinal welds are used in a liner course and these welds are located at diameters inclined 45°, where the total stress equals the hoop stress, a working rule may be stated as follows: "For the allowable unit stress in steel, whether reinforcement or liner, use 16,000 psi for hoop stresses alone, and 20,000 psi for a combination of hoop stresses and bending stresses." For smaller pipe, where the steel liner may be made from not more than two plates, the most economical construction will dictate the location of the longitudinal welds near the horizontal diameter. At these points the hoop stress on the inside surface of the liner is reduced by the bending stress, and depending on the magnitude of this bending stress it may be possible to use the 20,000 psi allowable stress for design purposes, not only for a combination of hoop and bending stresses but also for the hoop stress alone.

d. Bends. Bends in alinement and profile of the steel-lined concrete pipe are made to large radii, as with the concrete pipe, so that the bends become a series of straight pipe sections 25 feet in length. This permits the use of the same outside forms on curves as on tangent sections. Forces at the bends created by the water pressure are directly proportional to the hydrostatic head. They assume major proportions on high-head pipe but are unimportant where heads are low. The water pressure in the pipe produces a uniformly distributed radial force over the entire length of the bend, see

Figure 20, which can be approximated as follows:

$$P = \frac{50D^2H}{R}$$

P = radial force in pounds per linear foot of pipe,

D = inside diameter of pipe in feet,

H = hydrostatic head in feet, measured from hydraulic gradient to the center line of the pipe,

R = radius of bend in feet, measured to the center line of the pipe.

Forces to be taken into account in such bends in profile are indicated in Figures 21 and 22. Bends of the type shown in Figure 21, where the radial forces are resisted by soil pressures, are generally of no great concern. But in bends of the type shown in Figure 22, the radial forces tend to push the pipe out of the ground. Resisting these forces are the weight of the full pipe and the earth cover. Prudence requires that the effectiveness of the earth cover be discounted, as such cover might be removed or be washed away. In the case of the Soap Lake Siphon, where bends are made to a radius of about 400 feet, the weight of the full pipe is approximately four times as great as the radial force.

Bends in alinement present a somewhat different problem, since the radial forces act horizontally as shown in Figure 23. These radial forces combined with the vertical loads of the full pipe and earth cover will produce a resultant force, inclined at an angle α to the vertical. In designing the Soap Lake Siphon, the radius of the bends (approximately 400 feet) was selected so

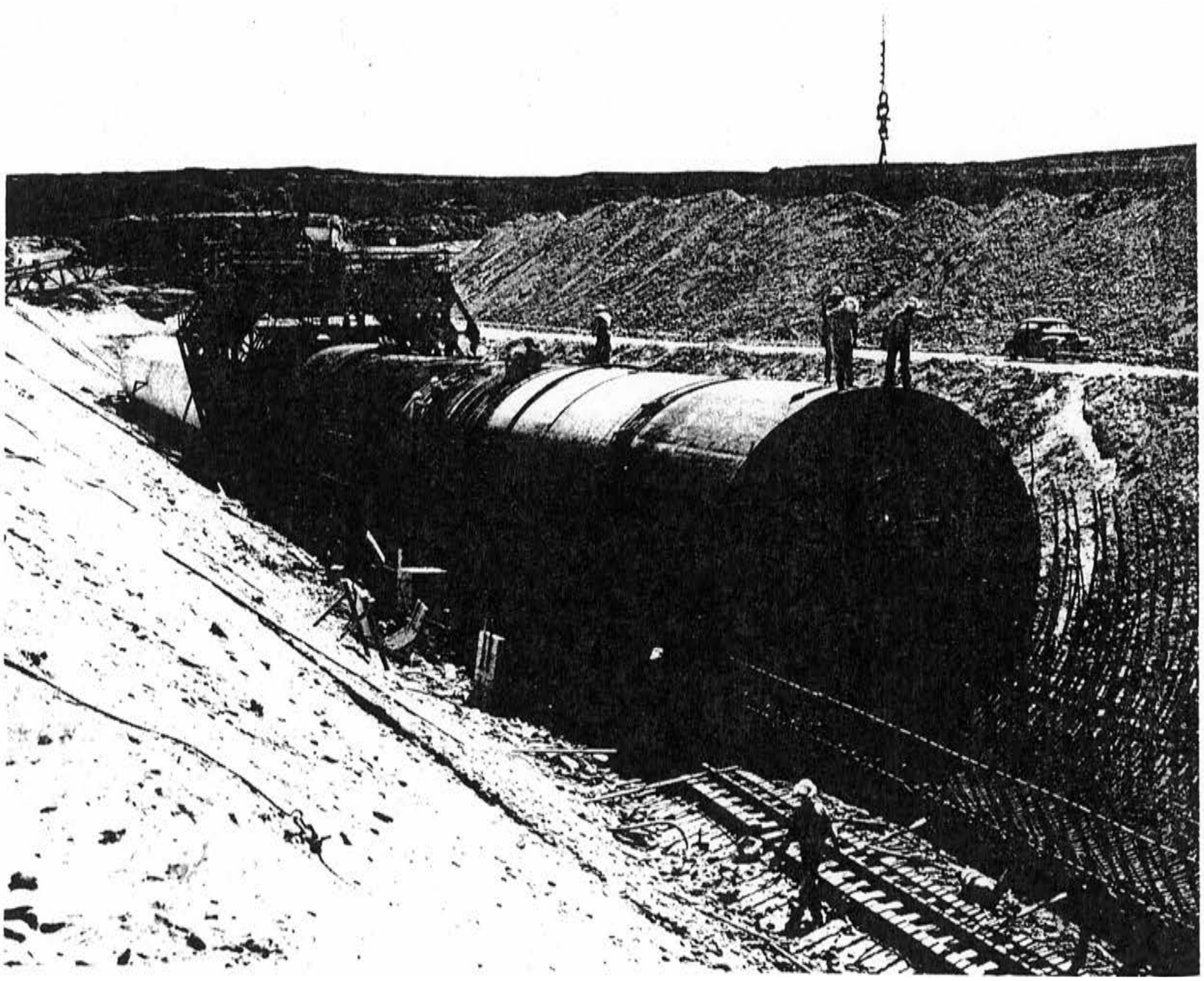


FIGURE 19 - The sequence of construction is shown, with the concrete-placing jumbo and a length of completed pipe in the background.

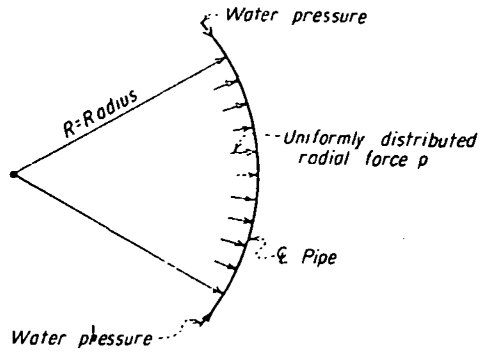


FIGURE 20 - Water pressure in the pipe exerts a uniform radial pressure at all bends in the alinement.

that the radial force is of such magnitude that the resultant force falls within the middle third of the base, which limits the angle α to 15°. At bends where the inclination of the resultant approaches this 15-degree angle, compacted backfill 4 feet thick is placed at the outside of the curves as shown in Figure 13. At the bends, assumptions for the stress computations differ from those for straight pipe only with respect to the pressure bulb for the reaction. The pressure bulb for tangent sections of pipe is assumed to be limited to a 90-degree

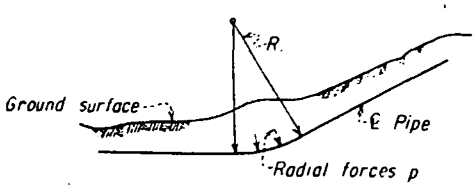


FIGURE 21 - No concern is felt for the stability of the pipe where radial forces at vertical bends tend to force the pipe into the ground.

central angle and centered about the vertical diameter, while on bends it is reduced to a 60-degree central angle, centered about the resultant and inclined at the angle α, where α has a maximum value of 15°. The 60-degree central angle is assumed so that the pressure bulb will fall completely within the limits of the undisturbed foundation, the compacted backfill not being depended upon to carry pressures. Coefficients for moments, shears, and thrust for the 60-degree pressure bulb were obtained by interpolation from the values given in Figure 15 for 90-degree and 45-degree pressure bulbs. When design of the pipe on the Soap Lake Siphon is compared for tangent and bend sections, it is found that approximately 12 percent more steel is required at the bends than on the tangents.

3. Steel-liner plate. As the unit price of steel-liner plate is about three times that of reinforcement steel, a desire for economy in costs made it essential to use as thin a liner as was compatible with good construction practice. Since the Bureau had had no previous experience with construction of steel-lined concrete pipe, experiences gained

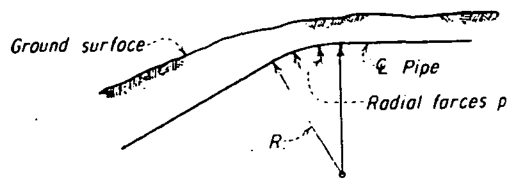


FIGURE 22 - At vertical bends where radial forces tend to lift the pipe out of the ground, care in design will keep the forces within safe limits.

with the movable steel forms on the construction of 25-foot diameter concrete pipe at Dry Creek Siphon were especially valuable. As the movable steel forms were provided with 1/4-inch thick skin plate, and since conditions prevailing in the steel industry at the time designs were prepared made delivery of steel sheets of thicknesses up to 3/16 inch extremely uncertain, a 1/4-inch thick plate was adopted for the final

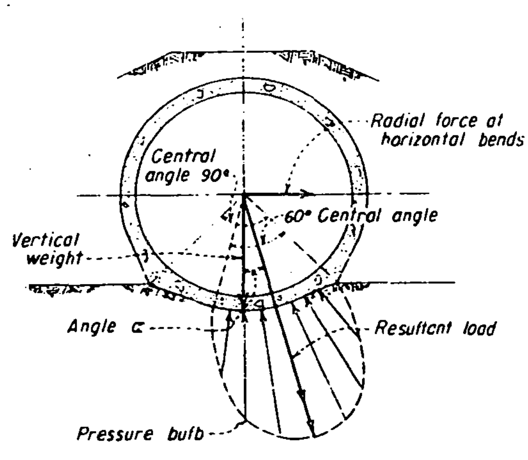


FIGURE 23 - Bulb-like reactions to radial loads at bends in alinement are assumed to be symmetrical about the resultant load.

designs. In order to keep the liner to a true circle during construction, the use of bracing was specified and it was required that the bracing remain in place until the concrete had reached a strength of 1,500 psi, which is about 4-1/2 times the strength required for the calculated stress caused by the weight of the pipe. It was assumed that the steel liner would be assembled in courses 25 feet long. A small bell was provided at one end of each course to facilitate assembling and welding of those adjoining.

4. Reinforcement. Square and round reinforcement bars are placed in the outer layer, but for the inner layer, which is placed against the liner plate, only round bars are used to insure adequate contact of the concrete with the liner adjacent to the bars. The hoop reinforcement is supplemented with segmental bars at places of maximum stress as shown on Figure 13. The minimum spacing center to center of bars is 2-1/2 diameters for round bars and three times the side dimension for square bars. The longitudinal reinforcement, provided at the outside face only, consists of 3/4-inch round bars spaced about 12 inches center to center. Longitudinal reinforcement serves as temperature reinforcement only and its amount is rather arbitrary.

5. Contraction joints. As the steel-lined pipe is buried, the temperature variation in the pipe and the movements caused thereby will be small. Further, the welded steel-liner plate furnishes a continuous watertight membrane, and therefore the necessity for providing contraction joints may be questioned. On the other hand, to omit all joints for the entire length of over 8,000 feet also seemed questionable. In the final design, the contraction joints are spaced about 500 feet apart. It is intended to observe these joints carefully over the years and thus obtain information from which to determine the proper spacing of those joints actually required, if any. The details of the contraction joints are shown on Figure 13. The joints are designed so that they may be replaced from the inside of the pipe. One-half-inch thick rubber seal clamped to steel angles which are welded to the steel liner provides watertightness and permits movements between adjoining pipe runs. On the inside of the pipe the rubber seal is protected with pneumatically placed mortar (gunite), reinforced with wire mesh.

Manholes and Blowoff Structures

1. Manholes. The inside surface of the steel-lined concrete pipe is to be protected with a coal-tar enamel coating. To provide access and ventilation during painting operations, manholes, 24 inches in diameter, are spaced at intervals of 500 feet. For the unlined concrete pipe, where no coating is required, the manholes are omitted.

2. Blowoff structures. To drain siphons, blowoffs are generally provided, but only at the low points. At Soap Lake Siphon, local interests voiced concern regarding mixing the ameliorative water of Soap Lake with any great amount of fresh water, which would

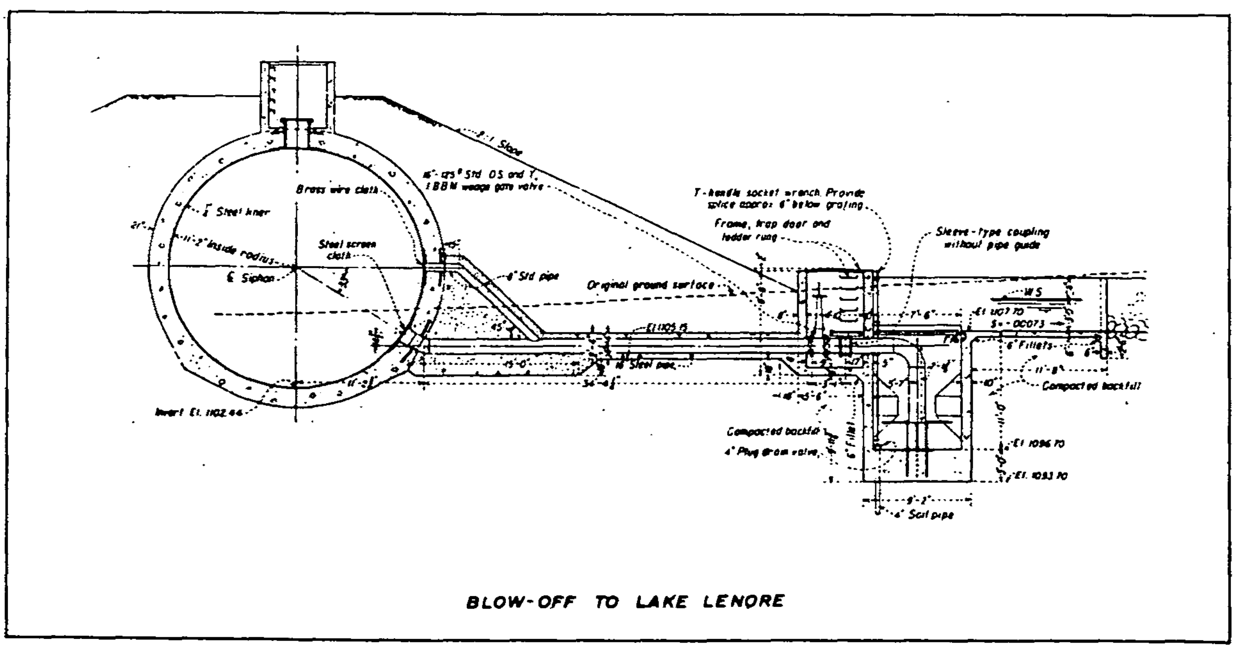


FIGURE 24 - To avoid excessive dilution of Soap Lake, a blow-off structure with drainage to Lake Lenore is provided.

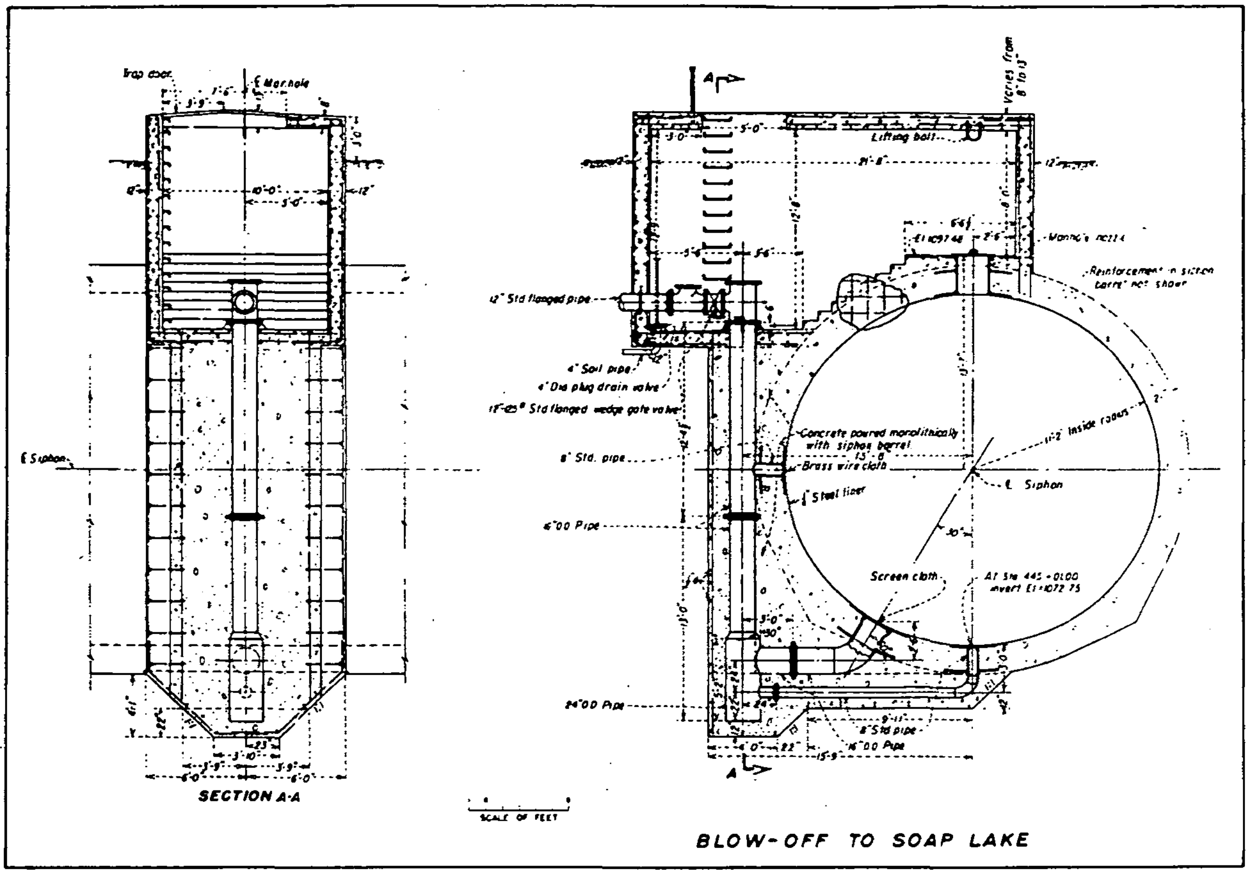


FIGURE 25 - The blowoff structure at the lowest point of the siphon drains into Soap Lake.

be the case when draining the siphon. In view of the above, two blowoff structures are provided, one at the low point and another at an elevation 32 feet higher. The blowoff structure at the higher elevation is so located that the greater portion of the siphon can be drained through a small artificial channel 5,000 feet long into Lake Lenore to the north.[2] By using this means of disposing of most of the water, the blowoff at the low point will drain only a small amount of fresh water into Soap Lake, which will not dilute the lake water to any great extent, thus satisfying the objections. The blowoff structures are shown in Figures 24 and 25. To unwater the siphon completely, pumping is required, and will be done by means of a portable pump placed in the vertical shaft provided for that purpose in the blowoff structure at the low point.

[2] Bureau of Reclamation, Laboratory Report No. Hyd-277, Hydraulic Model Studies of the Stilling Well for the Blow-off Structure, Soap Lake Siphon, Columbia Basin Project, 1950.

QUANTITIES AND COST DATA

The cost data tabulated below are based on the estimated quantities as prepared for the specifications. The unit prices are the contractor's bid prices. The unit prices for concrete were arrived at by adding to the contractor's bid prices the cost of aggregates and cement which is furnished by the Government. Therefore, the costs given in the table represent total construction costs but do not include contingencies or engineering. In order to facilitate future estimates on similar work the costs are given separately for the various features.

Figure 26 has been prepared to give quantities and cost per linear foot of pipe for various hydrostatic heads for both types of pipe, i.e., concrete pipe and steel-lined concrete pipe. For each type, certain items such as concrete, joints, and steel liner remain constant regardless of head. However, the reinforcing steel increases with the hydrostatic head. The cost curves for the pipe do not include the cost of the earthwork.

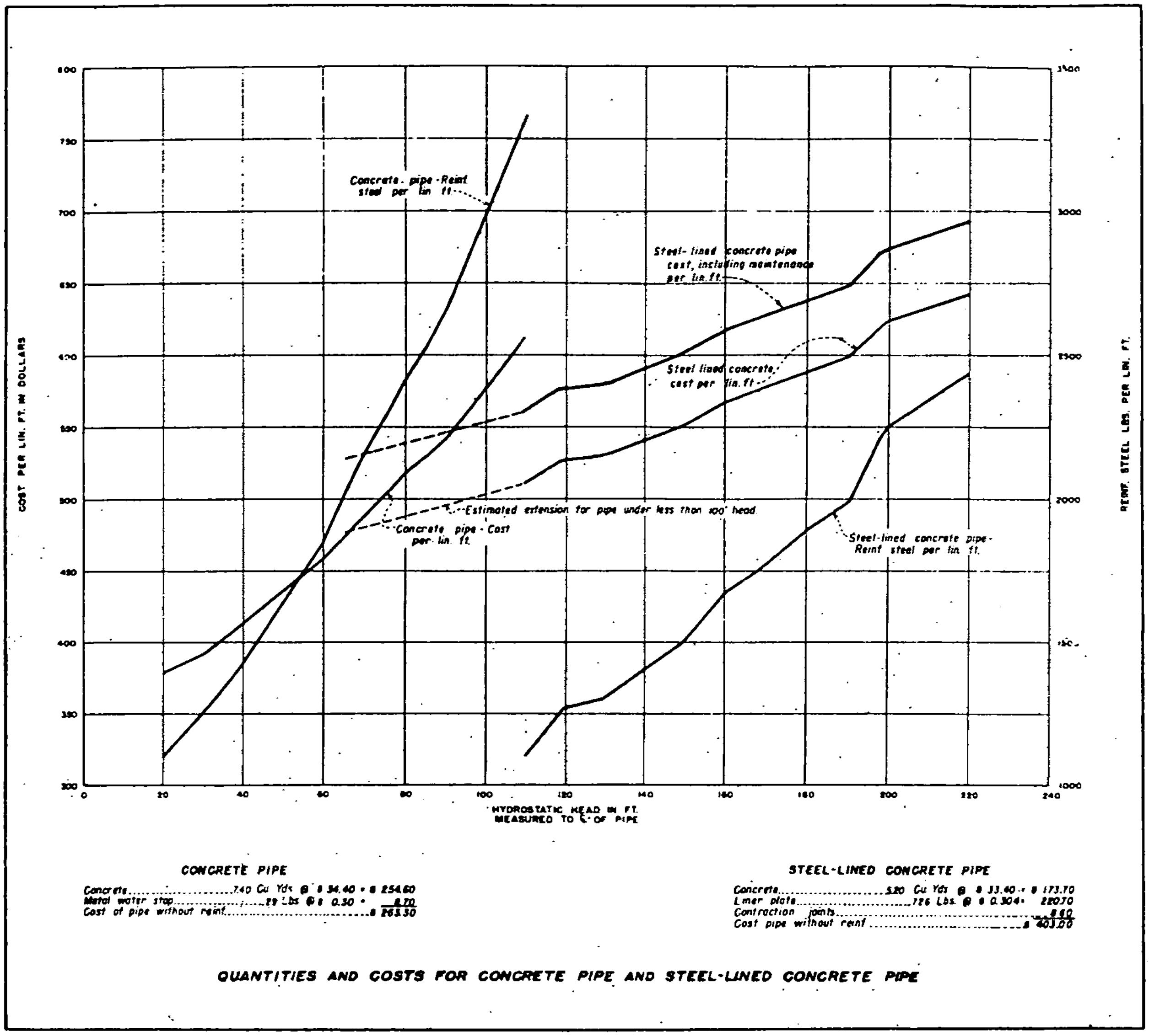


FIGURE 26 - Comparative costs of concrete pipe and steel-lined concrete pipe.

Previously it was mentioned that, in order to assure watertightness, steel-lined pipe is used for hydrostatic heads above 100 feet. In this connection, the cost curves for the two types of pipe shown in Figure 26 are of interest. As the cost curves intersect at a hydrostatic head of 67 feet, the limit of 100 feet set for satisfactory watertightness for concrete pipe is above the economic limit. However, as the cost curves include construction costs only, and as the inside protective coating for the steel-lined pipe will require maintenance not needed on the concrete pipe, allowance for such maintenance should be made when comparing the two types of pipe. Assuming that the protective coating will have to be completely replaced twice in the 40-year life of the structure, and estimating the cost of such work as 35 cents per square foot for each replacement, approximately $50 per foot will have to be added to the first or construction cost of the steel-lined pipe. Considering the above, the cost curves will intersect at a hydrostatic head of about 92 feet. Therefore, in the case of Soap Lake Siphon, where different diameters were used for concrete pipe and steel-lined concrete pipe, it can be stated that the steel-lined concrete pipe is more economical than concrete pipe for hydrostatic heads above 92 feet.

QUANTITIES AND COST DATA

Monolithic Concrete Pipe, Length 4,315 feet					
Item	Quantity	Unit	Unit Price	Amounts	Amounts
Excavation, common	900	cy	1.80	1,260	
Excavation, rock	149,200	cy	1.80	268,560	
Backfill	85,900	cy	0.40	34,280	
Hauling selected backfill	12,000	Mcy	0.35	4,200	
Compacting backfill	5,100	cy	3.50	17,850	
TOTAL earthwork					$ 326,150
Concrete pipe	32,000	cy	34.40	1,100,800	
Reinforcement	9,926,000	lb	0.105	1,042,230	
Metal waterstop	126,000	lb	0.30	37,800	
Miscellaneous metal	700	lb	0.50	350	
TOTAL concrete pipe					$2,181,180
TOTAL earthwork plus pipe					$2,507,330
Average cost per linear foot:				Earthwork	76
				Concrete pipe	505
				TOTAL	$ 581

Gravel Trap, Length 60 feet				
Item	Quantity	Unit	Unit Price	Amount
Excavation, common	600	cy	1.80	$ 1,080
Excavation, rock	3,700	cy	1.80	6,660
Backfill	1,000	cy	0.40	400
Compacting backfill	700	cy	3.50	2,450
Concrete	410	cy	62.20	25,500
Reinforcing steel	71,000	lb	0.105	7,460
Elastic filler	160	sf	3.00	480
Miscellaneous metalwork	4,300	lb	0.50	2,150
TOTAL				$46,180
Cost per linear foot				$ 767

Inlet Transition, Length 130 feet				
Item	Quantity	Unit	Unit Price	Amount
Excavation, common	800	cy	1.80	$ 1,440
Excavation, rock	5,400	cy	1.80	9,720
Backfill	3,700	cy	0.40	1,480
Compacted backfill	2,300	cy	3.50	8,050
Concrete	800	cy	87.20	69,760
Reinforcing steel	143,000	lb	0.105	15,020
TOTAL				$105,470
Cost per linear foot				$ 811

Steel-lined Monolithic Concrete Pipe Length 8,252 feet Cost Data					
Item	Quantity	Unit	Unit Price	Amounts	Amounts
Excavation, common	110,000	cy	1.03	113,300	
Excavation, rock	160,000	cy	1.68	268,400	
Hauling selected material	14,000	Mcy	0.327	4,580	
Backfill	190,000	cy	0.374	71,060	
Compacting backfill	9,000	cy	3.27	29,430	
TOTAL earthwork					$ 486,770
Concrete in pipe	43,000	cy	33.40	1,436,200	
Reinforcement	15,280,000	lb	0.0982	1,501,000	
Steel liner plate	6,000,000	lb	0.304	1,824,000	
Contraction joints	18	jt	3,930.00	70,740	
Blowoff pipe and valves	15,000	lb	0.61	9,150	
Miscellaneous metal	42,000	lb	0.47	19,740	
TOTAL pipe					$4,860,830
TOTAL earthwork and pipe					$5,347,600
Average cost per linear foot:			Earthwork		$ 59
			Steel-lined pipe		$ 588
			TOTAL		$ 647

Outlet Transition, Length 136 feet				
Item	Quantity	Unit	Unit Price	Amount
Excavation, common	900	cy	1.80	$ 1,620
Excavation, rock	6,700	cy	1.80	12,060
Backfill	4,600	cy	0.40	1,840
Compacted backfill	2,900	cy	3.50	10,150
Concrete	800	cy	87.20	69,760
Reinforcing steel	160,000	lb	0.105	16,800
Elastic filler	100	sf	3.00	300
TOTAL				$112,530
Cost per linear foot				$ 827

Cost Summary			
Feature	Length	Total Cost	Cost per lin. ft.
Gravel trap	60	$ 46,180	$767
Inlet transition	130	105,470	811
Outlet transition	136	112,530	827
Concrete pipe	4,315	2,507,330	581
Steel-lined concrete pipe	8,252	5,347,600	647
Testing siphon		17,550	
Box culvert and drain		35,200	
TOTAL	12,893	$8,171,860	$633

Interior - Reclamation - Denver, Colo.