G. E. Burnett

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

CANAL CAPACITY STUDIES
WAVE FORMATION BY BRIDGE PIERS

Report No. Hyd-485

Hydraulics Branch
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

August 15, 1967

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

CONTENTS

ABSTRACT

Prototype and laboratory measurements were made of the heights and frequencies of waves generated by segmented bridge piers set in the flow prism of the Delta Mendota Canal, Central Valley Project. Large oblique angles of the bridges and the openings in the piers caused waves to be generated on the canal water surface. The waves reduced the freeboard of the canal lining and means were sought for reducing the wave height. The studies showed that full closure of the spaces between pier segments was necessary to reduce wave heights to a minimum. Partial closure did not produce satisfactory reductions in height. Conformance of the waves formed by the 1:24 scale model and the prototype was very good.

DESCRIPTORS-- hydraulics/ *waves/ *open channel flow/ flow resistance/ head losses/ Froude number/ canals/ *bridge piers/ instrumentation/ hydraulic models/ prototype tests/ laboratory tests/ model tests/ freeboard/ frequency
IDENTIFIERS-- Delta-Mendota Canal, Calif/ Central Valley Proj, Calif/ *wave height/ California/ similitude/ *canal capacity tests

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Office of Chief Engineer
Division of Research
Hydraulics Branch
Special Investigations Section
Denver, Colorado
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Laboratory Report No. Hyd-485
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Submitted by: H. M. Martin

CANAL CAPACITY STUDIES, WAVE FORMATION BY BRIDGE PIERS

INTRODUCTION

Evaluation for design purposes of the individual effect of the many factors influencing the hydraulic behavior of large water conveyance channels is a complex problem. The size, shape, and invert grade of the conveyance must be determined from the cumulative resistance-to-flow of the boundary surface in line canal structures, structures with piers in the flow prism, and other local obstructions to the flow of water. Although the exact quantitative effect of each factor has not been accurately known, the design procedures developed over a number of years and applied by engineers with a broad background of experience produced conveyances capable of carrying the desired quantity of water with proper freeboard.

Recent experience has indicated that these procedures, successfully used, in the design of small and medium sizes of canals, are not apparently, adequate for large concrete-lined canals on flat slopes. Tests on large Central Valley Project canals showed the capacity to be as much as 20 percent below the design discharge. Surface roughness of the lining, canal curves, and the large number of structures such as supports for pipe crossings and bridge piers, individually or as a group, apparently produced more resistance to flow than anticipated, resulting in a reduction in discharge.

Roadways across the canal require bridges that are sometimes placed at oblique angles to the canal alinement.

Piers supporting the bridge in the water prism are usually constructed parallel to the direction of flow in the canal. Because of the bridge angle, the piers are staggered with respect to the canal cross section, Figures 1, 2, and 3.

Segmented piers used for reasons of economy in highway bridge construction have produced undesirable water surface waves at the bridges, Figure 4A. Although the oscillatory waves had greatest amplitude near and under the bridge, they affected the flow in straight lengths of the canal for distances of approximately one-half mile upstream and downstream of the bridges, Figure 5. These waves encroached on the 1.5-foot (45.8 cm (centimeters)) canal freeboard. Overtopping of the lining by these waves could occur at maximum discharge. This report presents the results of a study of the wave formation and means of reducing or eliminating the waves.

SUMMARY AND CONCLUSIONS

The peak-to-trough amplitude of the waves was measured near two bridges, Miles 56.60 and 81.69, of the Delta-Mendota Canal. At Bridge 81.69, the waves on the canal side slopes had an amplitude of 2 feet (61 cm), for a canal discharge of 3,100 cfs (cubic feet per second), (88 cubic meters per second) Table 1 (page 4).

A 1:24 scale model canal having a cross section of 1.2-foot depth, 2-foot bottom width (36.6 cm deep, 61 cm wide), and 1-1/2:1 side slopes was used to study the waves caused by the piers, Figure 6. Flow in the model, scaled from observed velocities and depths in the prototype canal, produced good conformance of wave action, Figures 4, 8, and 9. The wave patterns in the prototype and model appeared to have the same origins. The waves were largest on the upstream side of the bridge near the farthest downstream abutment (Abutment 2, Plan, Figures 3 and 5A). On the opposite side of the canal on the downstream side of the bridge (Abutment 1, Figure 3) the waves had slightly less height. In the model and prototype, oscillatory waves were propagated both upstream and downstream from the bridge location, Figures 4 and 5C. Disturbance waves caused by the presence of the segmented piers were evident in both the model and prototype structures under and near the bridges.

Both the frequency and amplitude of the measured model waves were converted to prototype dimensions using Froude number relationships. This conversion was based on the judgment that gravity forces predominated in the model both in producing flow and surface waves. Viscous effects were larger in the model than in the prototype canal and caused a rapid decay of the wave amplitude along the model side slopes.

Wave amplitudes measured on the side slopes in the model were in approximate agreement with those measured in the prototype. For the bridge at Mile 56.60, Table 1 (measured wave amplitude 1 foot, 30.5 cm), a 1-foot wave was measured in the model. For the Bridge Mile 81.69 (amplitude 2 feet) a 1.2-foot (36.6 cm) wave was measured in the model, Tables 2 and 3. Wave heights were measured between the piers and the side slopes in the model, Figure 7. These model and prototype heights could not be compared satisfactorily because no measurements were available between the piers and side slopes in the Delta-Mendota Canal.

Two methods of reducing the wave action were explored in the model: (1) a reduction in the size of the spaces between segments of the pier, and (2) full closure. Both methods reduced the wave action but the best suppression was provided by full closure of the spaces, Figures 8 and 9.

Based on the results of the model studies, the spaces were closed between segments of all similar bridge piers of the Delta-Mendota Canal using sheet metal over wood forms. A continuous flow surface was thus provided for the full length of the pier. Operation of the canal after closure of the spaces between pier segments showed no oscillatory wave action.

INVESTIGATION

Prototype

Approximate wave amplitudes on the canal slopes, wave frequencies, and wave lengths, Table 1, were measured in August 1958, during a field inspection of the bridges selected for study. The wave amplitudes were observed on a staff gage anchored to the side slope of the canal lining. The wave frequencies were counted and timed with a stopwatch.

Table 1

	Bridge	
	MP 56.60 Station 2283+63 Figures 1 and 2	MP 81.69 Station 3641+41 Figure 3
Wave		
Amplitude (feet trough to peak)	1	2
Frequency (cycles per minute)*	23	23
Length (feet)	25-35	25-35
Discharge (cfs)	3,400	

*Waves reached maximum and decreased in cycles about four times per minute.

Model

A 1:24 scale model canal having a cross section of 2-foot bottom width, 1-1/2:1 side slopes, and 1.2-foot depth was used to study flow characteristics of the segmented piers, Figure 6A. Flow entering the model was measured by calibrated Venturi meters and was distributed uniformly over the canal cross section by two baffles 28 inches apart, one 4 inches thick of gravel and one 3-1/2 inches thick of aluminum shavings (downstream). The double baffle with a 2-foot length of canvas attached to and floating downstream from the aluminum baffle was used to eliminate (within practicable limits) all waves caused by water inflow.

The test piers were installed in a 28-foot straight reach of the model, 20 feet downstream from the aluminum baffle. A 15° curve of 8-foot radius, and 15 feet of straight channel conveyed the water from the test reach to the model exit. A wave absorber of three vertical pieces of wire lath shaped to the canal section, two touching each other and one 3-5/8 inches downstream, and a floating piece of canvas were constructed at the downstream end of the channel. The absorber was 30 inches upstream from the discharge control (tailgate) located at the downstream end of the channel. This absorber prevented waves generated at the discharge control from traveling upstream to the test section.

Concrete Bridge Piers (Model)

Wave action.--Flow and wave action, similar to that observed in the prototype, Figure 4A, was reproduced satisfactorily in the model, Figure 4B. In both prototype and model, wave patterns were complex, caused by the angle of the bridge and the pier alinement. Time and instrumentation necessary to analyze the complex wave system and the causes were not available nor was a complete explanation warranted by the purpose of the study. The investigation was concerned primarily with measuring the model wave heights for correlation with the prototype, and with finding a means of eliminating or appreciably reducing the wave amplitudes.

Wave measurement.--Wave amplitudes and frequencies were measured on lines parallel to the bridge centerline and tangent to the upstream and downstream ends of the piers, Figure 6B.

Capacitance-type wave probes were used in the model to measure the wave amplitude and frequency. Two probes of 0.015-inch-diameter enameled wire mounted on "U" shaped frames were suspended on 3-inch channels by point gage staffs, Figure 6C. Locations of the probe between the pier and canal side slope were established with reference to the pier centerlines. The voltage signals from the wave probes were recorded on a direct-writing oscillograph.

Wave measurement results.--Waves generated by the model piers were apparently composed of capillary ripples superimposed upon small gravity waves.1/ In the model and in the prototype, the speed of the gravity waves caused by the piers exceeded the approach velocity to the piers. The waves traveled upstream as well as downstream, Figures 5 and 8. Wave amplitudes diminished rapidly both upstream and downstream, but the waves were discernible for a model distance of approximately 18 feet upstream from the piers. With a longer approach channel and less surface disturbance from the inlet baffles, waves would have persisted for a greater distance. The general similarities between the model and prototype in wave formation were very good.

1/Rouse, H., "Elementary Mechanics of Fluids," John Wiley and Sons, Inc., 1946, p. 324.

Records of wave action were interpreted to determine frequency and amplitude. Waves from the model piers, Figures 8A, 1 and 2, that produced an encroachment on the canal freeboard had a frequency ranging from approximately 93 to 107 cycles per minute, depending on the depth and quantity of flow. Examination of the recordings showed that the wave amplitude reached a maximum and decreased at a frequency ranging from approximately 9 to 18 cycles per minute. The average frequency from 14 records was 13.3 cycles per minute. Traces from each of the probe locations were measured to obtain the indicated maximum amplitude of the waves. Wave amplitudes in this study were measured as the maximum vertical distance on the recording between an adjacent trough and peak of the pen trace. Surface tension effects on the wave-height probe were evident in some of the traces in the form of flattened wave peaks. The reduction in recorded height for the waves affected by the surface tension on the probe wire was estimated to be about 10 percent.

Both frequency and amplitude of the waves were converted to prototype dimensions using Froude number relationships. This conversion was based on the judgment that gravity forces predominated in the model both in producing flow and surface waves. Viscous effects were evident along the model side slopes, however, causing a rapid decay of the wave height. The flow, with a Reynolds number of 88,400 for the minimum average velocity and depth, was turbulent.

Relationships used for converting the model data were as follows:

<u>Wave height</u>

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

L_r = length ratio
L_m = model length
L_p = prototype length

Wave frequency

$$f = \frac{V}{\lambda}$$

$$\frac{f_m}{f_p} = \frac{V_m/V_p}{\lambda m/\lambda p} = \frac{V_r}{L_r}$$

$$\frac{f_m}{f_p} = \frac{\sqrt{L_r}}{L_r} = \frac{1}{\sqrt{L_r}}$$

$$f_p = f_m\sqrt{L_r}$$

f = wave frequency
V = velocity of propagation
λ = wave length

$V_r = \sqrt{g_r L_r}$, with the gravity ratio g_r for all practical purposes unity
$V_r = \sqrt{L_r}$

The first series of wave measurements was made for piers having a 32-inch space between segments to represent the bridge at Mile 56.60, Figures 1 and 8A. The angle between the canal and bridge centerlines was 49°32'. Results of the wave measurements are recorded in Table 2 and Figure 7. The maximum wave height of approximately 0.33-foot prototype was measured for a discharge of 3,100 cfs. The maximum height was measured at a distance of 18 feet from the pier centerlines toward the canal slopes on both the upstream and downstream sides of the bridge. Maximum wave height for a 4,000-cfs discharge was 0.29 foot. Wave runup on the side slopes was a maximum of 1 foot for the 3,100-cfs discharge, agreeing well with the prototype measurements.

A second series of wave measurements was made for piers having a 21-inch space between segments, Figures 3 and 9A. The overall pier length for both bridges was nearly the same, 33 feet 6 inches for the bridge at Mile 81.69 and 35 feet 8 inches for Mile 56.60.

Higher waves were measured for the piers having 21-inch spaces between segments, Table 3 and Figure 7. The position of the maximum measured waves in the canal for the second set of piers occurred again at a distance of about 18 feet from the pier centerlines on both the upstream and downstream sides of the bridge. The maximum measured wave for the bridge at Mile 81.69 was 0.59 foot for a depth of 15.6 feet at a discharge of 3,100 cfs. Wave runup on the side slope was 1.2 feet.

The frequency of the waves generated by the second set of piers was 19.3 per minute compared to the 19.1 waves per minute for the first piers at the 3,100-cfs discharge. Thus, for comparative purposes the waves were generated at about the same frequency by both sets of bridge piers.

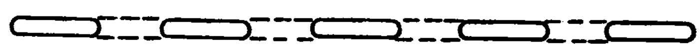
The increase and decrease in the maximum height of the waves ranged from 1.6 to 3 cycles per minute and averaged 2.3. The 2.3 cycles were 0.4 cycle less than the average for the first set of piers. The cycling for both sets of piers was less than 4 cycles per minute for the prototype structures, Table 1.

A graphical comparison of the change in wave height with respect to the position of measurement (within the acute angle formed by the canal and bridge centerlines) shows waves of slightly higher magnitude than those measured may occur at a location about 16 feet from the pier centerlines, Figure 7. Waves of minimum height occurred near 5- and 30-foot distances from the piers. The intersection of the water surface and canal slope was approximately 33 feet from the pier centerlines.

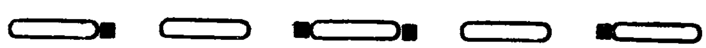
Wave Reduction

Two methods of reducing the wave action were explored in the model: (1) a reduction in the size of the spaces between pier sections and (2) full closure. Closure and restrictions included those made in the following manner:

1. Four spaces between the five piers were closed for the full height, width, and thickness of the space between pier sections, Figures 8B, 9B, and 9D.



2. Four spaces were restricted by adding the equivalent of four 12- by 12-inch timbers the full height of the space, Figure 8C.



3. Four spaces were restricted by adding the equivalent of four 15-inch cylindrical columns the full height of the space, Figure 8D.

Waves generated by model piers with open spaces were of sufficient magnitude to measure with reasonable reliability. Suppression of the waves by the filling of the spaces between segments of the piers reduced the wave amplitude below the height where accurate measurements could be made. This fact precluded an exact determination of the wave amplitude reduction caused by the closure and restriction of the pier spaces.

All of the suppression devices reduced the height of the waves. The best suppression was provided by the full closure of the space between pier segments, Figures 8B and 9B. Small waves and ripples from the nose and sides of the piers were noticeable in the model. The height of these ripples was not measureable in the model and were not believed to be of sufficient size to be of concern in the prototype structure.

Timbers and cylinders located at the trailing and leading ends of the first and fifth pier sections and the leading and trailing ends of the third pier section measurably reduced the wave size, Figures 8C and 8D. The size of the waves was less than those produced by piers with open spaces, but were larger than those occurring when the spaces between the pier segments were closed.

CONCLUSIONS

Excellent similarity was obtained between the waves generated in the model and those observed in the operating canal. As a result of the model studies, the spaces of the Delta-Mendota Canal bridge piers were closed with sheet metal on wood forms in 1961, under Specifications No. 200C-466. A continuous flow surface was thus provided along the full length of the pier. No oscillatory waves occurred at the bridges in the canal after closure of the piers. The freeboard of the canal lining at the bridges, without the waves after the pier closure was equal to that in the unobstructed canal.

Table 2

CONCRETE PIER WAVE ACTION
BRIDGE MILE 56.60
DELTA-MENDOTA CANAL
CANAL CAPACITY STUDIES
(Data from 1:24 scale model)

Probe Location*	Distance from pier center-line toward canal slope (feet)	Wave height: Discharge 3,100 cfs depth 15.6 feet (feet)	Wave height: Discharge 4,000 cfs depth 17.4 feet (feet)
Left	2	0.04	0.02
Right	2	0.04	0.04
Left	6	0.02	0.24
Right	6	0.0	0.26
Left	10	0.1	0.26
Right	10	0.11	0.08
Left	14	0.24	0.07
Right	14	0.25	0.07
Left	18	0.29	0.02
Right	18	0.30	0.05
Left	22	0.24	0.07
Right	22	0.29	0.12
Left	26	0.12	0.12
Right	26	0.19	0.17
Left	27.5	0.04	--
Right	30	0.01	0.07
Left	30	--	0.12
Right	32	0	--
Wave runup (trough to peak) on right canal slope, 19 feet upstream from bridge centerline		1	0.5
Frequency		19.1 waves per minute	21.8 waves per minute
Wave heights reached a maximum and decreased to smaller values at 1.8 to 3.7 cycles per minute, average 2.7			

*Upstream angle between bridge and lining on right side of canal and downstream angle between bridge and lining on left side of canal (Figures 1, 2 and 8).

HYDRAULIC PROPERTIES

CANAL SECTION	A	V	Q	r	n	s
Lined Section No.7	1129.05	3.719	4199	10.77	.014	.00005

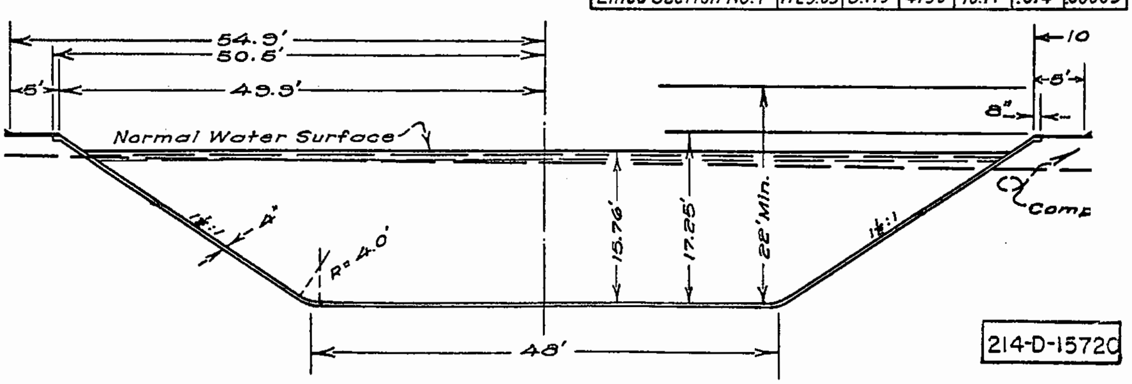


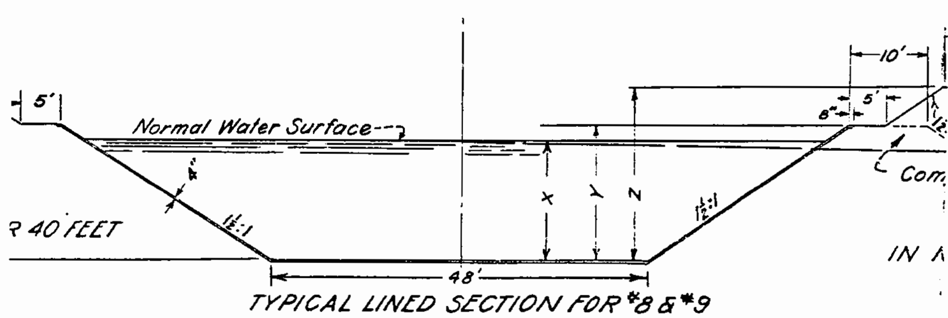
Table 3

CONCRETE PIER WAVE ACTION
BRIDGE MILE 81.69
DELTA-MENDOTA CANAL
CANAL CAPACITY STUDIES
(Data from 1:24 scale model)

Probe Location*	Distance from pier centerline toward canal slope (feet)	Wave height Discharge 3,100 cfs depth 15.6 feet (feet)
Left	2	0.15
Right	2	0.20
Left	6	0
Right	6	0
Left	10	0.07
Right	10	0.27
Left	14	0.37
Right	14	0.53
Left	18	0.42
Right	18	0.59
Left	22	0.32
Right	22	0.47
Left	26	0.15
Right	26	0.24
Left	30	0
Wave runup (trough to peak) on left canal slope, 39.5 feet upstream from bridge centerline		1.2
Frequency		19.3 waves per minute

Wave heights, reached a maximum and decreased to smaller values at 1.6 to 3 cycles per second, average 2.3

*Upstream angle between bridge and lining on left side of canal and downstream angle between bridge and lining on right side of canal (Figures 3 and 9).



X = 14.26 feet
Y = 15.75 feet
S = 0.00005

214-D-15905

FIGURE I
REPORT HYD-485

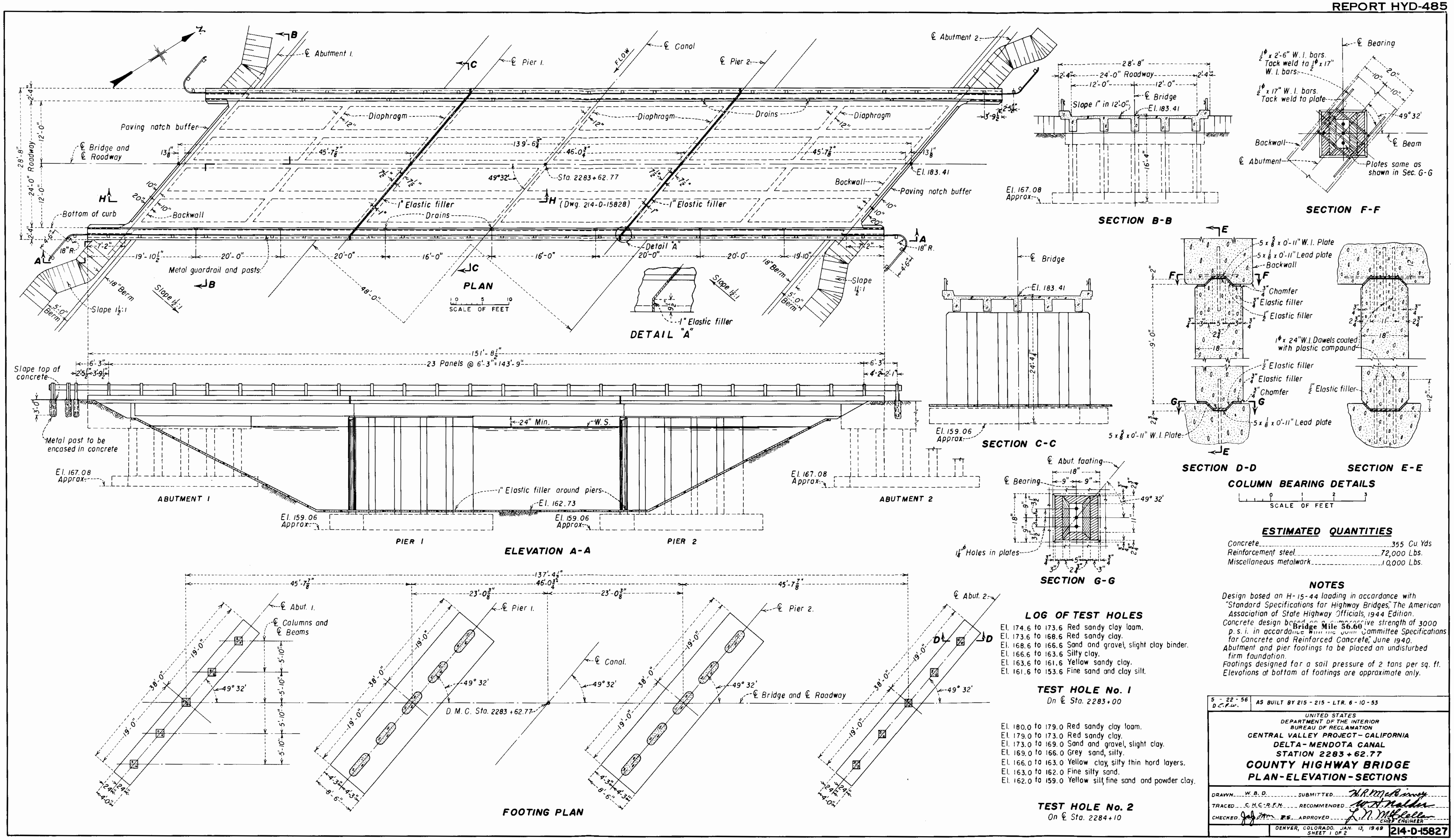
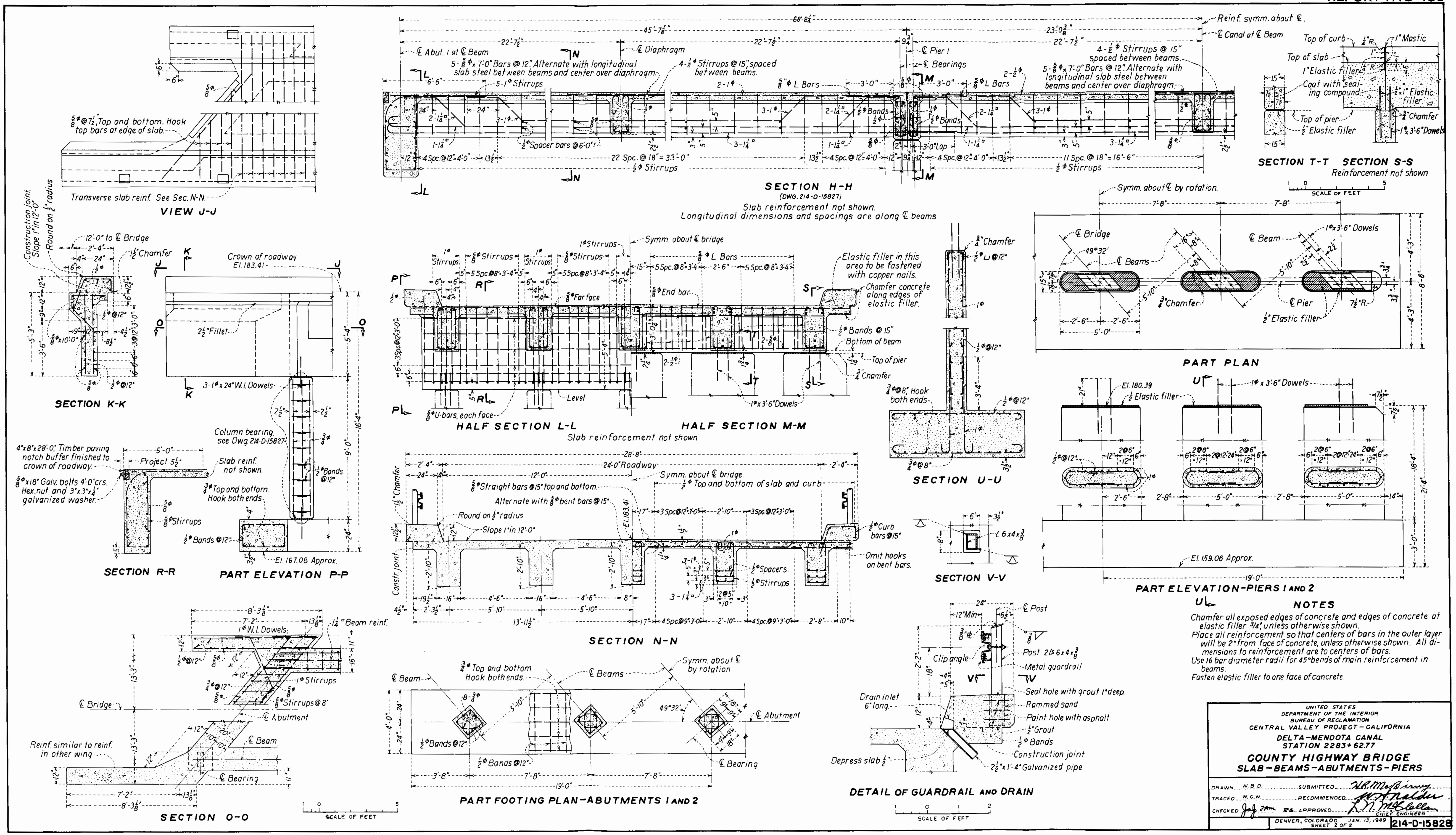
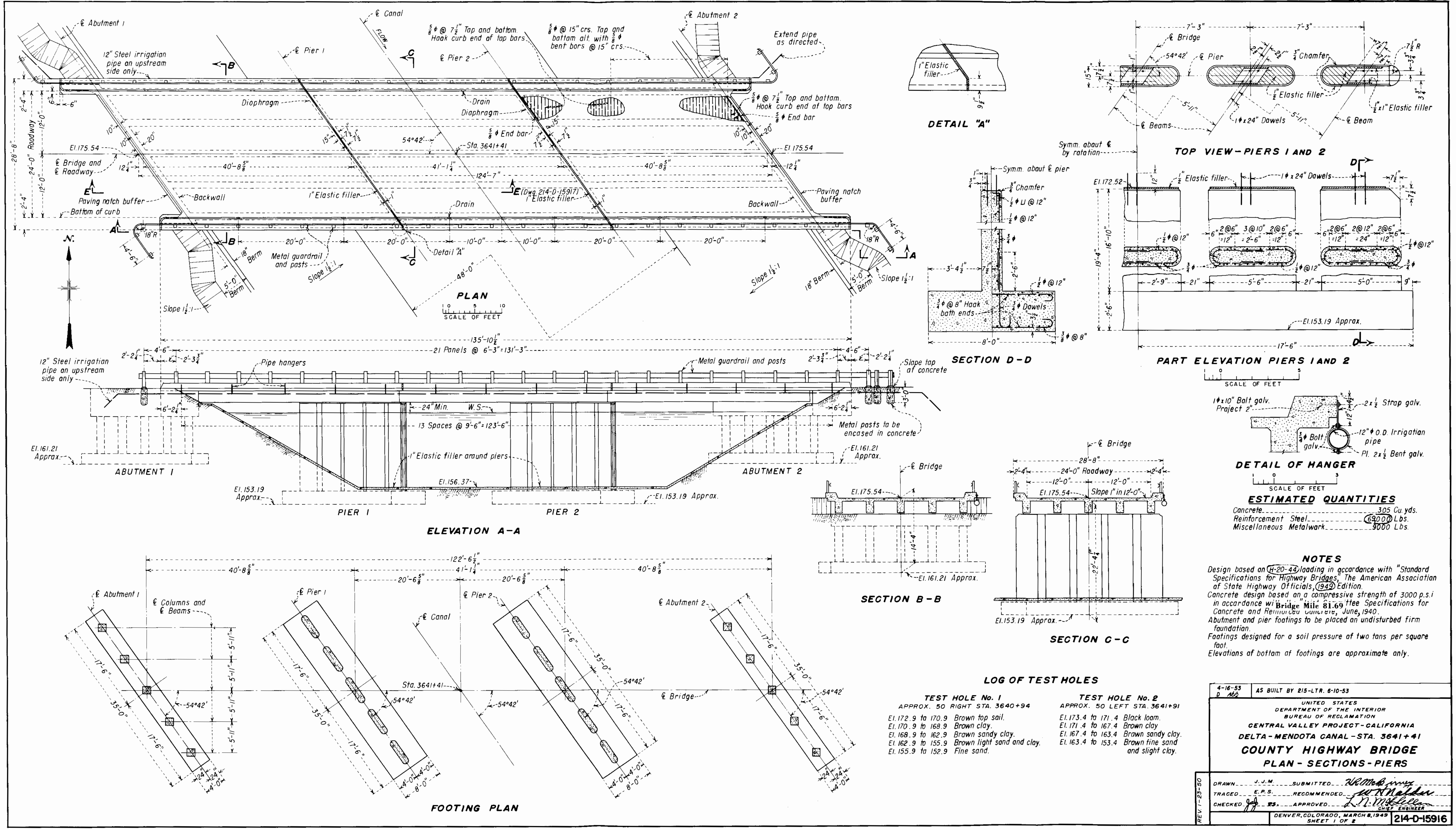


FIGURE 2
REPORT HYD-485





ESTIMATED QUANTITIES

Concrete	305 Cu. yds.
Reinforcement Steel	69000 Lbs.
Miscellaneous Metalwork	9000 Lbs.

NOTES

Design based on H-20-44 loading in accordance with "Standard Specifications for Highway Bridges," The American Association of State Highway Officials, 1949 Edition.

Concrete design based on a compressive strength of 3000 p.s.i in accordance wi Bridge Mile 81.69 ttee Specifications for Concrete and Reinforced Concrete, June, 1940.

Abutment and pier footings to be placed on undisturbed firm foundation.

Footings designed for a soil pressure of two tons per square foot.

Elevations of bottom of footings are approximate only.

LOG OF TEST HOLES

TEST HOLE No. 1
APPROX. 50 RIGHT STA. 3640+94

El. 172.9 to 170.9	Brown top soil.
El. 170.9 to 168.9	Brown clay.
El. 168.9 to 162.9	Brown sandy clay.
El. 162.9 to 155.9	Brown light sand and clay.
El. 155.9 to 152.9	Fine sand.

TEST HOLE No. 2
APPROX. 50 LEFT STA. 3641+91

El. 173.4 to 171.4	Black loam.
El. 171.4 to 167.4	Brown clay
El. 167.4 to 163.4	Brown sandy clay.
El. 163.4 to 153.4	Brown fine sand and slight clay.

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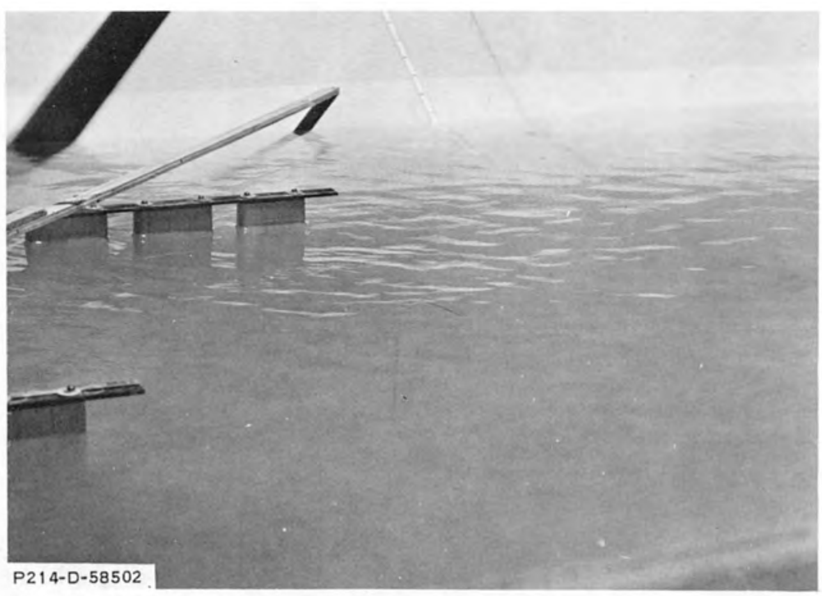
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
DELTA-MENDOTA CANAL-STA. 3641+41

COUNTY HIGHWAY BRIDGE
PLAN-SECTIONS-PIERS

REV. 1-23-50
DRAWN J.J.M. SUBMITTED
TRACED E.P.S. RECOMMENDED
CHECKED APPROVED CHIEF ENGINEER

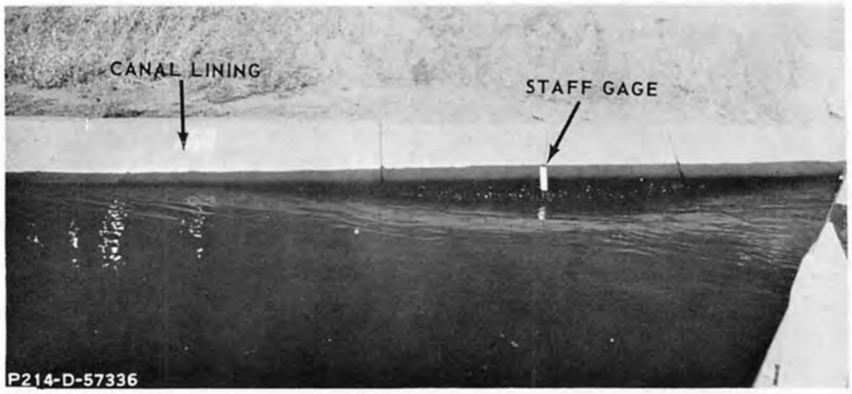
DENVER, COLORADO, MARCH 8, 1949 SHEET 1 OF 2 214-D-15916

A. Waves caused by segmented piers under concrete highway bridge at Mile 81.69--Delta-Mendota Canal, Central Valley Project--Discharge of about 3,100 cfs flowing left to right, wave height trough to peak in canal flow estimated at 6 to 12 inches.



B. Waves caused by model bridge piers Mile 81.69--Discharge equivalent to 3,100 cfs prototype at a 15.6-foot depth (Figure 3). Wave height about 7 inches (prototype).

CANAL CAPACITY STUDIES
Wave Similarity--Prototype and Model

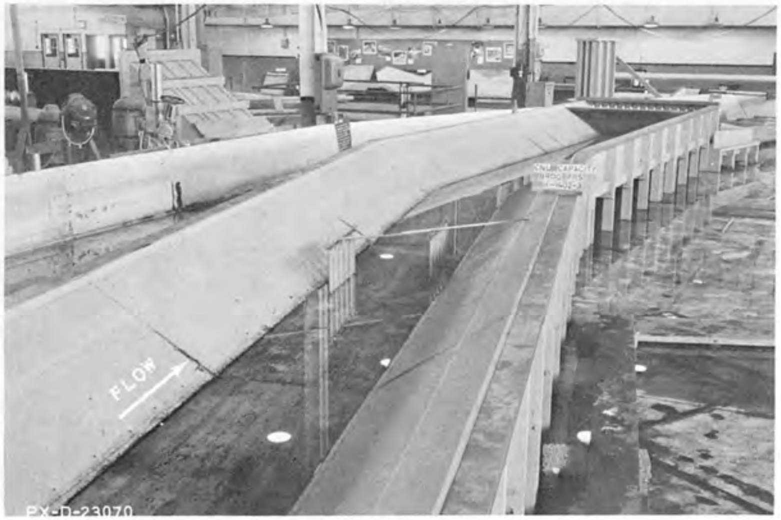


A. Bridge Mile 81.69--Wave formed at upstream left side of canal, Abutment 2, Figure 3.

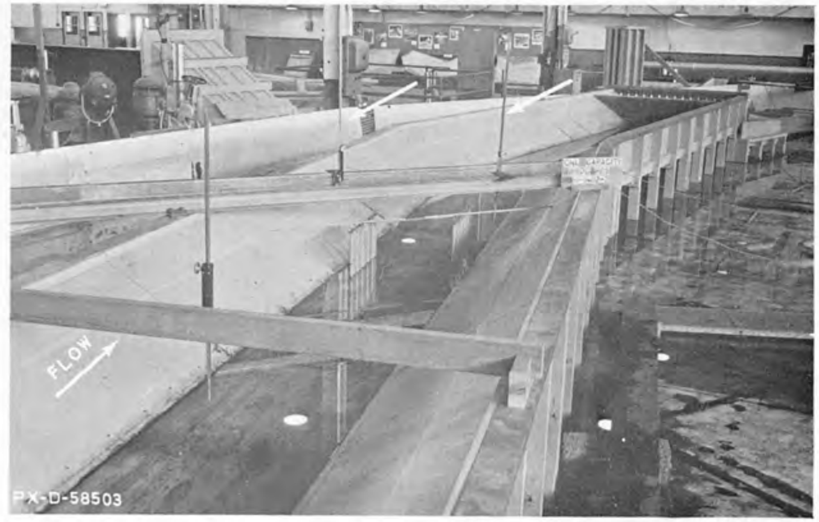
B. Bridge Mile 56.60--Wave formed at upstream right side of canal, Abutment 1, Figure 1.

C. Bridge Mile 56.60--Waves reflected upstream for approximately one-half mile.

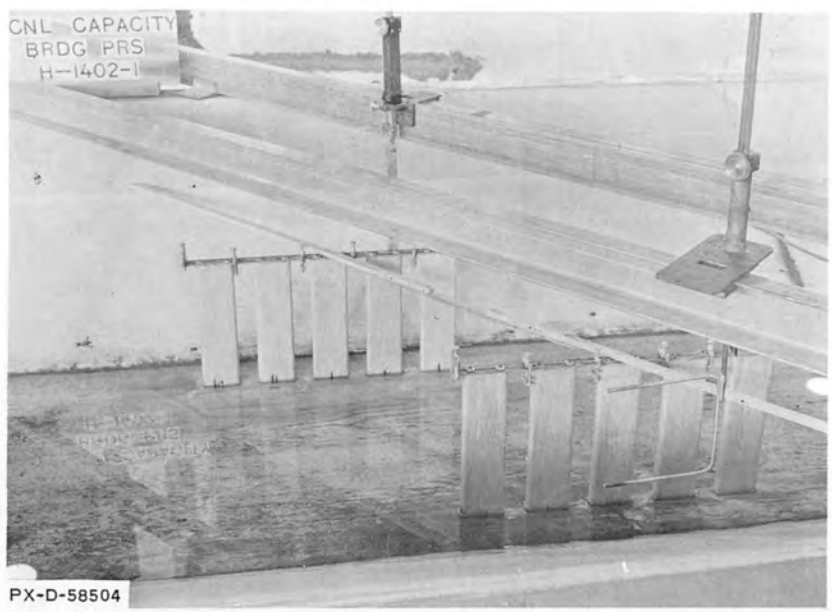
CANAL CAPACITY STUDIES
Wave Action at Bridges in the Delta-Mendota Canal
August 1958



A. Bridge piers in 2-foot bottom width trapezoidal channel, 1.2-foot depth.



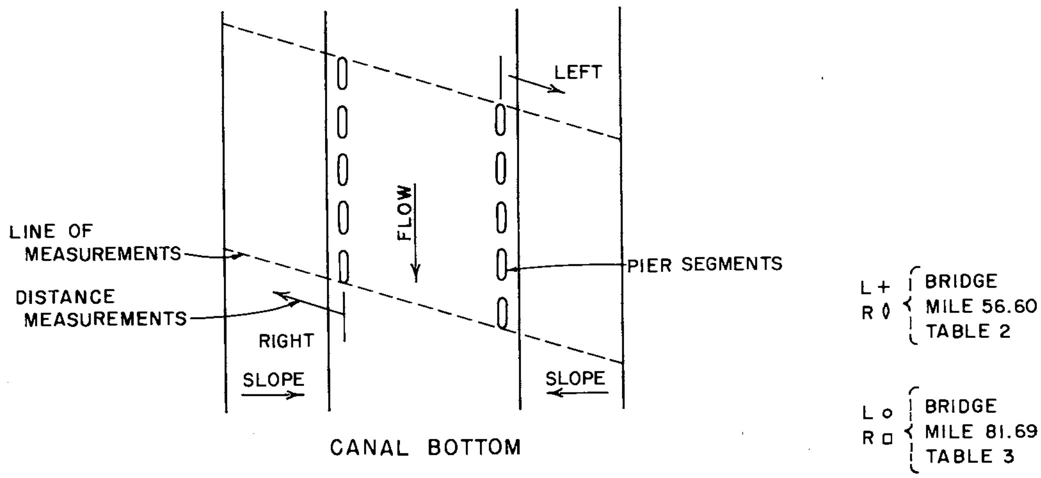
B. Two capacitance probes used for wave height measurements near bridge piers--Point gage for flow depth measurement upstream from piers.

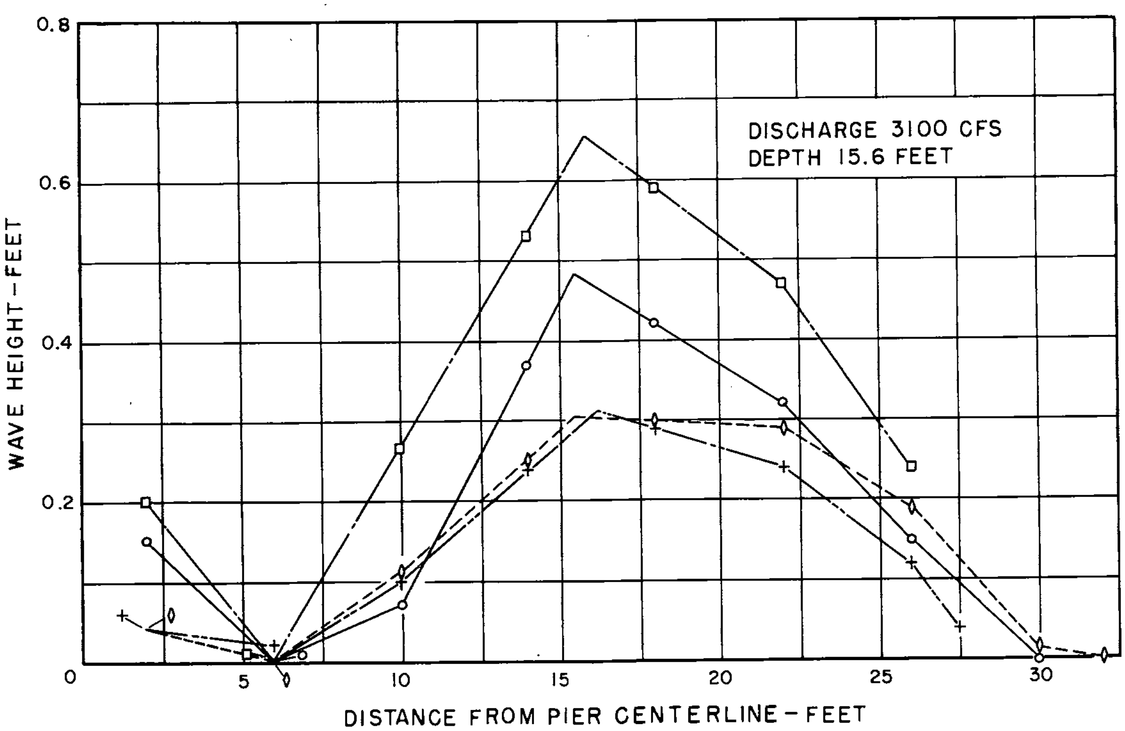


C. Capacitance probes and point gage staff mounts.

CANAL CAPACITY STUDIES
Bridge Pier Test Equipment

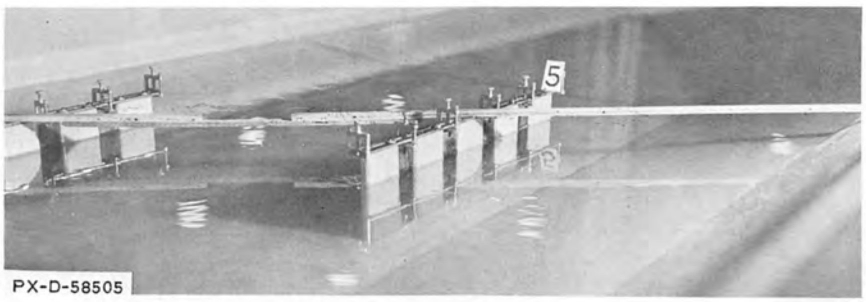
Figure 7
Report Hyd-485





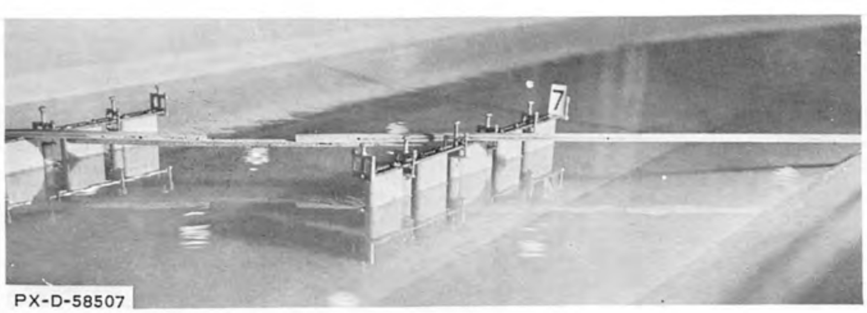
CENTRAL VALLEY PROJECT
DELTA-MENDOTA CANAL
CANAL CAPACITY STUDIES
WAVE HEIGHTS
1:24 SCALE MODEL-SEGMENTED BRIDGE PIERS

A. Wave action for segmented piers having 32-inch spaces.



B. Wave action minimized by closing spaces between segments.

C. Wave action reduced by four, 12- by 12-inch timbers in spaces.



D. Wave action reduced by 15-inch cylinders in spaces.

CANAL CAPACITY STUDIES
Methods of Reducing Wave Formation
Bridge Mile 56.60

A. Segmented piers having 21-inch spaces.

B. Pier spaces closed.

Discharge 3,100 cfs - Depth 15.6 Feet

C. Segmented piers having 21-inch spaces.

D. Pier spaces closed.

Discharge 3,500 cfs - Depth 15.6 Feet

CANAL CAPACITY STUDIES
Wave Reduction by Pier Closure - Bridge Mile 81.69

7-1750
(2-67)
Bureau of Reclamation

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
	MASS	
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
	FORCE/AREA	
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
	MASS/VOLUME (DENSITY)	
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
	MASS/CAPACITY	
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
	BENDING MOMENT OR TORQUE	
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
	VELOCITY	
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
	ACCELERATION*	
Feet per second^2	0.3048*	Meters per second^2
	FLOW	
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
	FORCE*	
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
	WORK AND ENERGY*	
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
	POWER	
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
	HEAT TRANSFER	
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
	WATER VAPOR TRANSMISSION	
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

GPO 835-159

ABSTRACT

Prototype and laboratory measurements were made of the heights and frequencies of waves generated by segmented bridge piers set in the flow prism of the Delta Mendota Canal, Central Valley Project. Large oblique angles of the bridges and the openings in the piers caused waves to be generated on the canal water surface. The waves reduced the freeboard of the canal lining and means were sought for reducing the wave height. The studies showed that full closure of the spaces between pier segments was necessary to reduce wave heights to a minimum. Partial closure did not produce satisfactory reductions in height. Conformance of the waves formed by the 1:24 scale model and the prototype was very good.

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Hyd-485
Schuster, J C
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USBR Lab Rept Hyd-485, Hyd Br, Aug 1967. Bureau of Reclamation, Denver, 11 p, 9 fig, 6 tab, 1 ref

DESCRIPTORS-- hydraulics/ *waves/ *open channel flow/ flow resistance/ head losses/ Froude number/ canals/ *bridge piers/ instrumentation/ hydraulic models/ prototype tests/ laboratory tests/ model tests/ freeboard/ frequency
IDENTIFIERS-- Delta-Mendota Canal, Calif/ Central Valley Proj, Calif/ *wave height/ California/ similitude/ *canal capacity tests

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