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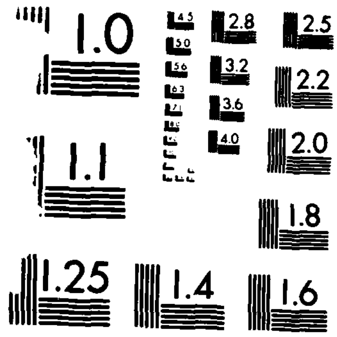

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NATIONAL BUREAU OF STANDARDS-1963-A

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TECHNICAL REPORT NO. 14

ARIZONA CANAL DIVERSION CHANNEL SELECTION OF ROUGHNESS COEFFICIENTS FOR DESIGNING THE CONCRETE-LINED CHANNEL

September 1985

Committee on Channel Stabilization

CORPS OF ENGINEERS, US ARMY

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

REPORTS OF COMMITTEE ON CHANNEL STABILIZATION

Technical Report	Title	Date
1	Symposium on Channel Stabilization Problems	
	Volume 1	Sep 1983
	Volume 2	May 1964
	Volume 3	Jun 1965
	Volume 4	Feb 1966
2	Review of Research on Channel Stabilization of the Mississippi River, 1931-1962	Sep 1963
3	Effect of Water Temperature on Discharge and Bed Configuration, Mississippi River at Red River Landing, La.	Aug 1966
4	Channel Stabilization Publications Available in Corps of Engineers Offices	Nov 1966
5	A Procedure for Computation of the Total River Sand Discharge and Detailed Distribution, Bed to Surface	Nov 1968
6	Water-Temperature Effects on Stage-Discharge Relations in Large Alluvial Rivers	Sep 1969
7	State of Knowledge of Channel Stabilization in Major Alluvial Rivers	Oct 1969
8	Channel Stabilization, Interoceanic Sea-Level Canal, Lower Atrato River Portion, Route 25, Colombia, South America	Oct 1969
9	Sedimentation Aspects, Project for Navigation and FLood Control, Lower Colorado River, Texas	May 1972
10	Chena River Lakes Project, Alaska, Problems Relating to Channel Development, Erosion, and Bank and Levee Protection	Mar 1973
11	Jackson Hole Flood Control Project	Mar 1974
12	Mississippi River and Tributaries Project, Problems Relating to Changes in Hydraulic Capacity of the Mississippi River	Aug 1974
13	Columbia-Cowlitz-Toutle Rivers, Washington, Restoration Subsequent to Mt. St. Helens Eruption	Sep 1985
14	Arizona Canal Diversion Channel, Selection of Roughness Coefficients for Designing the Concrete-Lined Channel	Sep 1985

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William A. Thomas		Waterways Experiment Station

Preface

Establishment of the Committee on Channel Stabilization in April 1962 was confirmed by Engineer Regulation 15-2-1, dated 1 November 1962, and re-authorized by ER 15-2-1, dated 25 June 1971 and 30 April 1980. As stated in ER 15-2-1, the objectives of the Committee, with respect to channel stabilization, are:

- a. To review and evaluate pertinent information and disseminate the results thereof.
- b. To determine the need for and recommend a program of research; and to accomplish advisory technical review of research when requested.
- c. To determine basic principles and design guidance.
- d. To provide, at the request of field offices, advice on design and operational problems.

This report, prepared by the Committee on Channel Stabilization, for the US Army Engineer District, Los Angeles, represents the requested opinions and recommendations of the Committee concerning appropriate roughness values for computing the capacity for the concrete-lined portions of the proposed Arizona Canal Diversion Channel, Phoenix, Arizona.

Copies of this and other reports of the Committee on Channel Stabilization can be obtained from the US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, Mississippi 39180-0631.

Contents

ARIZONA CANAL DIVERSION CHANNEL

SELECTION OF ROUGHNESS COEFFICIENTS FOR

DESIGNING THE CONCRETE-LINED CHANNEL

Introduction

1. During the week of 8-12 February 1982, the US Army Engineer Division, South Pacific, and the US Army Engineer District, Los Angeles, invited the Committee on Channel Stabilization to meet with them in an effort to determine the most appropriate roughness value to use in computing the capacity for the concrete-lined portions of the proposed Arizona Canal Diversion Channel in Phoenix, Arizona. Prior to the meeting, the Los Angeles District prepared a report titled "Manning's Roughness Coefficients Used for Designing Concrete-Lined Channels" and furnished copies to each Committee member ~~(Appendix A)~~. The report reviewed their experience in designing concrete-lined channels, listed and described field measurements, and discussed Manning's n values computed from field measurements. The report also discussed data and Manning's n values from Bureau of Reclamation irrigation projects. This report formed the basis for much of the meeting's discussions.

Field Trips

2. The early part of the week included a field trip in the Phoenix area to several project areas including the proposed alignment for the Arizona Canal Diversion Channel. A subsequent field trip was made in the Los Angeles area that included the recently completed Cucamonga Creek flood-control channel and several sites on other projects where field measurements were made for Manning's n value determinations.

Description of the Project

3. The Arizona Canal Diversion Channel is one feature of the New River and Phoenix City streams flood-control project.

4. The New River and Phoenix City streams flood-control project, as described in House Document 216, 89th Congress, 1st Session, was authorized by the Flood Control Act of 1965. The proposed recommended plan for controlling

flood flows consists of four dams: Dreamy Draw (completed in 1973), Cave Buttes, Adobe, and New River Dams; 20 miles of channelization - Arizona Canal Diversion Channel and portions of Cave and Skunk Creeks; and 19 miles of flowage easements with some floodproofing, levees, and channelization - Skunk Creek and the New and Agua Fria Rivers.

5. This report will discuss only the proposed concrete-lined portion of Arizona Canal Diversion Channel. The proposed diversion channel will have both rectangular and trapezoidal shapes and vary in size from 36 to 100 ft bottom width. The channel, as proposed, will be designed for a 100-year flood with 2 ft of channel freeboard. The channel traverses a heavily populated area and receives runoff from a drainage area that has experienced significant urbanization over the past 30 years.

General Committee Meeting

Arizona Canal Diversion Channel Design

6. Los Angeles representatives briefed the Committee on the Arizona project with particular emphasis given to design of the diversion channel and the value of the Manning n. Preliminary design of the diversion channel for costing purposes has been completed. The Los Angeles District used a Manning's n value of 0.014 to size the concrete-lined portions of the channel, a design value that they believe is conservative and have used for a number of years in designing concrete-lined channels for other projects. As a result of OCE comments, the District evaluated the effect on channel size of increasing the n value to 0.016. Computations indicate that channel depths would increase from 1.3 to 2.9 ft, assuming the 2-ft freeboard requirement would be retained as part of the design criteria. This increase represents a significant increase in estimated first cost for the proposed project. Because of the adverse impact on estimated project costs caused by increasing the value of Manning's n, the District collected and analyzed available prototype data from concrete-lined channels in the Los Angeles area and initiated a review of available USBR data on concrete-lined channels to determine, to the extent possible, Manning's n values from prototype channels. The report referenced in the introduction contains pertinent data and the District's analysis. A copy of the report is attached as Incl 1. A summary of the District's position is taken from that report and is as follows:

> ... prototype data that were gathered to determine n values in concrete-lined flood control channels show that, if anything, an n value of 0.014 is conservative. The reason for these relatively low n values is the quality of concrete finishes in these channels and the mild climate. It is true that the Bureau of Reclamation has experienced n values higher than 0.014 in some of their irrigation canals; however, aquatic growth was the primary cause of this. Aquatic growth does not occur to nearly this extent in our concrete flood control channels. For these reasons, we feel that our practice of using an n of 0.014 for design of concrete-lined channels is appropriate.

Design Values from Other Offices

7. Following presentations from the Los Angeles representatives, members of the Committee were requested to comment on design practices in other Corps Districts and Divisions. Response from Committee members indicated that generally an n value of 0.014 to 0.015 has been used by other Corps offices.

Committee Conclusions

8. Following the general meeting, the Committee met separately to deliberate on the Los Angeles presentations and other discussions. Based on discussions, the Stabilization Committee has the following concerns regarding the design of the Arizona Canal Diversion Channel: (a) adequacy of Los Angeles and/or USBR data to fully support selection of 0.014 as a channel design value, (b) use of a single roughness coefficient to design the diversion channel, (c) flows greater than the 100-year flow should be analyzed, (d) consideration of program of data collection, and (e) sedimentation in the diversion channel.

Adequacy of Data Presented

9. Prototype data for the Los Angeles area represent low flows primarily. Similar data over a wide range of flows would lend much greater weight particularly in regard to use of the data to determine or aid in the selection of a design roughness coefficient. It is also noted that flows in the proposed Arizona Canal Diversion Channel will be subcritical rather than supercritical, creating the possibility of unexpected sediment and debris deposits that could affect flow efficiency. The USBR data more closely correlates with the proposed diversion channel, particularly in regard to hydraulic radius;

however, as pointed out by the District the USBR n values generally greater than 0.014 were believed to be affected by aquatic growth and vegetation in the canals tested. Since the USBR data represent conditions more closely related to the diversion channel, these data should be analyzed in greater detail and reliable data points identified and correlated with the Los Angeles data to define, to the extent possible, a curve of Manning's n versus hydraulic radius.

10. Most of the USBR data are for deep flow depths and low velocities, while the Corps data are for shallow flow depths and high velocities. The two sets of data seem more consistent when they are plotted. Figure 1 plots Darcy's f against Reynold's number as in the familiar Moody diagram. In Figure 1, both the Corps and the Bureau data scatter considerably; but they seem to form a consistent data set when the variations of hydraulic resistance with Reynold's number are taken into account.

11. Figure 2 plots Manning's n against hydraulic radius for both the USBR and the Corps data. Again, the two data sets seem fairly consistent with the Corps data representing the lower end of the range of R (hydraulic radius). With respect to n values, data seem to scatter around the lower envelope of the USBR data. The vertical arrow at about 15 ft hydraulic radius denotes the approximate value for the Arizona Canal Diversion Channel. Figure 2 confirms that for the concrete surface at the site of the field measurements Manning's n tends to increase with hydraulic radius. This is in consonance with theory and laboratory measurements in which the Moody diagram is based. It means that where Manning's n is determined by measurement in a channel at a low flow depth, we should expect the n value to be greater at a deeper flow depth. Study of Figure 2 reveals that for the hydraulic radius R of around 15 ft a design n value of 0.014 might be acceptable; but it would be conservatively low.

12. In summary, the data supporting a design value of 0.014 are weak from several aspects; however, the data are equally weak in supporting another alternate value. It is the opinion of the Committee that an n value of 0.014 is adequate to design the Arizona Canal Diversion Channel for costing purposes. However, a varying value of n should be determined and used for detailed design of individual reaches of the channel.

Use of Single Coefficient
to Design Total Channel

13. Open-channel flow involves a number of factors that usually are combined into a single roughness coefficient or factor (Manning n , Chezy C , Darcy k , etc.) Application of Manning's n is widely used, and the Los Angeles District prefers this application for design of the diversion channel. However, it is the opinion of the Stabilization Committee that the method of roughness application should be through the use of the Moody type approach. The logarithmic relation (Moody approach) that relates resistance factors to the Reynolds number and relative smoothness (R/k_s) is the best available approach for determining friction losses in concrete-lined channels. All the technical literature and scientific experiments since Prandtl and Von Karman support this. The mechanics are available to use the logarithmic relations to obtain proper n values for a particular application, and this should be done as backup and support data for the final design. Support for a variable n value rather than a constant value is demonstrated by the n versus R (Figure 2) relation exhibited at the meeting which was developed from field data and showed that n varied with depth of flow or hydraulic radius. For small roughness such as a concrete surface, the logarithmic relation also shows that n values increase with depth or hydraulic radius.

14. The sensitivity of the design profile to alternate determinations (use of constant n and varying n) should be made and recorded. It appears that the accuracy of depth of flow for channel wall height can be within a foot. The need for the Moody approach determination is to best determine locations of initial overtopping as design information for the control of these locations.

Freeboard Considerations

15. The Moody type approach should be used to determine the n value to be used for the final depth of flow and a higher n value (0.016, for example) to determine the possible upper bound for the depth of flow with the same design flow. The difference would be freeboard. The freeboard would, therefore, be a variable height throughout the project depending on channel conditions and the n value used for a specific reach. Low points in the height of protection should be provided as necessary to have controlled overflow sections to reduce the potential damages for flows greater than the design flow.

Flows Greater than 100 Years

16. The consequences of flows exceeding the design flows for the Arizona Canal Diversion Channel is particularly important due to its length and the transfer of discharge from one drainage area to another. The project should allow for a reasonable increase in discharge to be confined. Areas where overtopping would result in more serious damage than preproject conditions should have increased freeboard. Flooding resulting from the standard project flood postproject should be determined and the results presented to the community for their consideration. Resulting residual damages should be included in the project economics.

17. The project should be analyzed to determine those locations where flooding would result in the least damage and the project designed to the extent feasible to limit possible overtopping to those locations.

Data Collection

18. The questions that have arisen in regard to the design of the diversion channel spotlight the need for prototype data from similar projects. Problems associated with data collection (funding, manpower, cost, etc.) are noted; however, the Los Angeles District is in a position to benefit the state-of-knowledge in roughness coefficients for high-velocity concrete-lined channels. This District, as well as others, should make an effort to obtain as much data as possible. Projects could have built-in, self-recording devices procured with project funds and maintained by locals as part of the local cooperation.

Sedimentation in Diversion Channel

19. Members of the Committee are concerned that a potential for excess sediments entering the diversion channel will exist at particular locations. These sediments could have significant impact on the design flowline if sufficent energy is not available to transport these sediments through the channel. The General Design Memorandum should address this concern.

Committee Recommendations

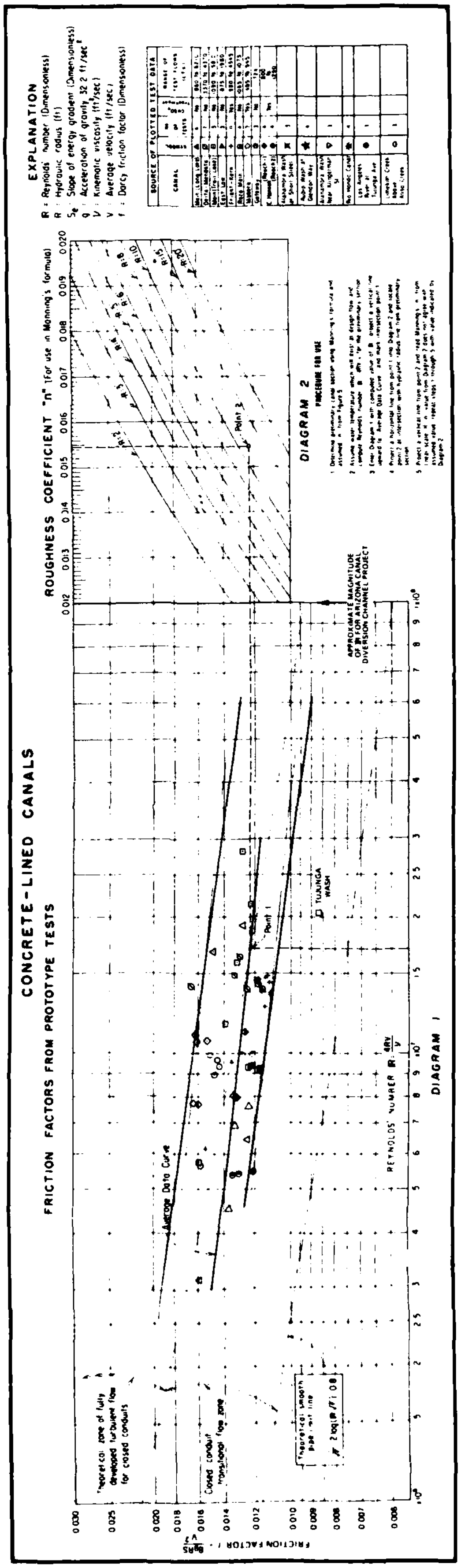
20. As a result of the Committee meeting following the general presentations, the following actions for Los Angeles District are recommended:

_a_. The Los Angeles District should retain the constant n value of 0.014 and a freeboard of 2-ft design of the diversion channel for costing purposes primarily.

_b_. The District should employ a method of roughness application through the use of the Moody type approach to design a water-surface profile and to test the sensitivity of the freeboard design with the results of the sensitivity analysis included in the Design Memorandum as backup and support data.

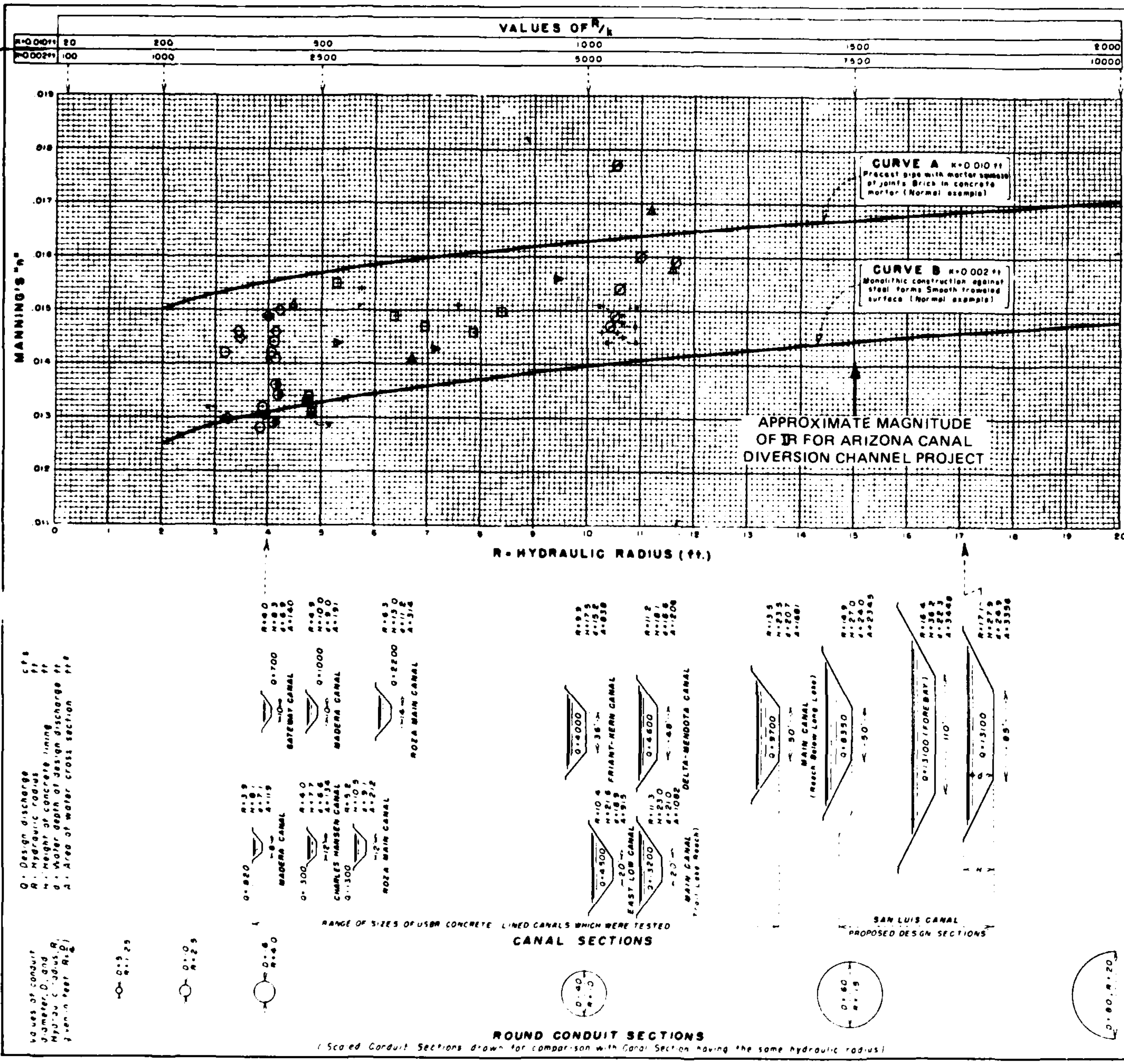
_c_. Using the recommended Moody approach, the District should analyze the diversion channel to identify locations of initial overtopping for flows exceeding design flows and use this information as design data to establish least-damaging initial overtopping locations.

_d_. The District should seriously investigate ways and means of obtaining, within given constraints, a greater data base from operation of numerous high-velocity concrete-lined channels in the Los Angeles area and in the future from low-velocity channels in the Phoenix area.



CONCRETE-LINED CANALS
FRICTION FACTORS FROM PROTOTYPE TESTS
ROUGHNESS COEFFICIENT "n" (For use in Manning's formula)
EXPLANATION
DIAGRAM 1
DIAGRAM 2
REYNOLDS' NUMBER
Average Data Curve
TUJUNGA WASH
APPROXIMATE MAGNITUDE OF R FOR ARIZONA CANAL DIVERSION CHANNEL PROJECT

Figure 1



NOTES

Curves A and B on this chart are based on the following development

The average velocity of flow (V) in an open channel may be expressed by two formulas

1 $V = \left[\frac{1.486R^{\frac{1}{6}}}{n}\right]\left[RS_e\right]^{\frac{1}{2}}$ (Manning's formula), or by

2 $V = \left[(32g)^{\frac{1}{2}} \log 14.8\left(\frac{R}{k}\right)\right]\left[RS_e\right]^{\frac{1}{2}}$

Formula 2 is an approximation of the Colebrook-White equation for flow near the turbulent region as developed by Peter Ackers in Hydraulics Research Papers No 1 and 2, "Resistance of Fluids Flowing in Channels and Pipes," published by the Department of Scientific and Industrial Research of England in 1958 5/

Equating formula 1 to formula 2 and solving for "n"

$$n = \frac{1.486R^{\frac{1}{6}}}{(32g)^{\frac{1}{2}} \log 14.8\left(\frac{R}{k}\right)} = \frac{0.0463R^{\frac{1}{6}}}{\log 14.8\left(\frac{R}{k}\right)}$$

Where n = Manning roughness coefficient
R = Hydraulic radius (ft.)
S_e = Slope of energy gradient
k = Equivalent sand grain roughness of the rigid boundary surface (ft) (Typical k values and descriptions of surfaces taken from the research papers mentioned above)
g = 32.16 ft / sec.^{2}

Assuming that k is constant for a given type of canal surface, "n" increases with hydraulic radius in the range shown.

The plotted data were taken from straight test reaches or from reaches which contained only 1 or 2 short horizontal curves.

Reaches of Delta-Mendota and Friant-Kern Canals contained structures with piers which extended into the flow prism. Estimated head losses caused by these piers were deducted for computations of "n" values shown.

Plots of computed "n" values from nine concrete lined canals are shown on the diagram at the left and are described below.

SOURCE OF PLOTTED TEST DATA				
CANAL	SYMBOL	No. OF TESTS	$CuSO_4$ Treatment	RANGE OF TEST FLOWS (cfs)
Main (Long Lake)	△	4	No	860 to 6210
Delta-Mendota	Ø	7	No	3370 to 4370
Main (Trail Lake)	⊡	5	No	1090 to 5810
East Low	▶	3	No	875 to 1980
Friant-Kern	+	11	Yes	980 to 4545
Roza Main	⊟	4	No	1065 to 1075
Madera	⊙	7	Yes	485 to 945
Gateway	◉	3	No	724
C. Hansen (Reach 1)	◇	4	Yes	800 to 1290
C. Hansen (Reach 2)	◆	4		
Alahambra Wash at Short Street	✖	5		
Rubio Wash at Glendon Way	★	4		
Alahambra Wash Near Klingerman St	▽	3		
Rio Hondo Canal	✱	4		
Los Angeles River at Tujunga Ave	●	3		
Limekiln Creek Above Aliso Creek	○	3		

FIGURE 2

Appendix A: Manning's Roughness Coefficients Used for Designing Concrete-Lined Channels

1. General. In a recent conference with representatives of the Hydrology and Hydraulics Branch from the South Pacific Division, the Los Angeles District was informed that the Division Office has recently received comments from OCE for a project in another District in the Division regarding Manning's n values used for the design of concrete-lined channels. These comments suggested use of n values in the range of 0.016 to 0.017. The basis for the use of n values of this magnitude appears to be from a Bureau of Reclamation Technical Memorandum 661 titled "Analysis and Description of Capacity Test in Large Concrete-Lined Channels."

2. This information, if true, is causing much concern in the Los Angeles District. The Los Angeles District has successfully used n values of 0.014 for the past 45 years in designing concrete-lined channels. Use of higher n values would be a change in our criteria. This would affect several studies that are currently under way in the District. Because of the potential impact on the current design studies of increasing the n values, it is important that we clarify as soon as possible the Corps latest philosophy regarding n values to be used in the design of concrete-lined channels. If there is a change in criteria being anticipated, the Los Angeles District requests that the information being presented in this paper be considered before the finalization of any criteria change.

3. Existing Criteria. In EM 1110-2-1601, Hydraulic Design of Flood Control Channels, paragraph 8b(1) states that three equations, (1) Chezy, (2) Manning, and (3) Darcy are in general use for determination of losses due to friction. The EM does not recommend one equation over the others, although it does give considerable emphasis to the Chezy equation. All three equations are empirical, with some degree of model and prototype verification. The use of any one of the three equations by a District requires that the District develop an expertise on selection of roughness values for the particular equation. In the Los Angeles Distict, we have developed experience designing channels using the Manning formula.

4. On pages 8 and 9 of EM 1110-2-1601, there is a discussion of friction coefficients. In this discussion, it is recommended that in solving for the Chezy C, a k value of 0.007 foot be used as the equivalent roughness factor for concrete-lined channels in determining discharge capacity and a k value of 0.002 foot be used to determine the maximum velocity. As we will discuss in coming paragraphs, we feel that an equivalent roughness of 0.007 foot may be too high for our concrete-lined channels.

5. As already stated, the Los Angeles District has considerable experience in designing high-velocity and low-velocity channels using the Manning formula. For concrete-lined channels we use an n value of 0.014 for determining discharge capacity and 0.012 for maximum velocity. We feel that an n of 0.014 represents a conservative value consistent with the quality of concrete finishes in our channels and allows for the effects of weathering and concrete erosion. Most of our concrete-lined channels have been constructed with either metal trowel or wood float finish. Rectangular channel wall forms are normally plywood, which also provides a relatively smooth surface. Weathering

does not pose a problem for our channels. Unlike many parts of the country, the southwest, especially the southern California coastal area and the Phoenix area, has a mild climate and is not subject to freezing-and-thawing action.

6. Prototype Data. The best way to check the adequacy of the n values used in the design of concrete-lined channels is to gather data from these channels during flood events. Since there are many miles of concrete-lined channels constructed by the Corps of Engineers and local flood control districts in southern California, one would expect a large volume of prototype data available for examination. However, due to the short-duration flood events that are characteristic of the southern California coastal streams, not as much data as was first expected are available. The data that are available come from four sources: (1) data collected from the March 1938 flood, (2) data collected from a test made on Tujunga Wash in 1966; (3) data obtained from the Los Angeles County Flood Control District; and (4) observations made during the floods of January and February 1969. From these data, n values and equivalent roughness coefficients, k , are computed. The following paragraphs will discuss these data.

a. Flood of March 1938. During the March 1938 flood, data were collected at five locations on four concrete-lined channels in southern California for the purpose of determining the Manning roughness coefficient. Following is a summary of these data.

(1) Alhambra Wash at Short Street. The channel in this location is rectangular in cross section with a width of 40 feet. The invert grade is 0.005611. Five current meter measurements were made by the Los Angeles County Flood Control District. At the time of each measurement, a considerable amount of silt was observed on the channel invert. The silt was present because the channel upstream of this was not completed at the time of the 1938 flood. The discharges ranged from 17 to 715 cfs with depths ranging from 0.19 to 1.5 feet and n values ranging from 0.0127 to 0.0187. The following table summarizes the data:

Measurement		1	2	3	4	5
Discharge	Q	142	138	715	104	17
Area	A	23.3	28.9	63.4	21.8	7.4
Mean Velocity	V	6.1	4.8	11.3	4.8	2.3
Hydraulic Radius	R	0.6	0.7	1.5	0.5	0.2
Slope	S	0.005611	0.005611	0.005611	0.005611	0.005611
Roughness Coefficient	n	0.0127	0.0187	0.0129	0.0150	0.0157
Equivalent Roughness	k	0.0037	0.043	0.0030	0.012	0.015

(2) Rubio Wash at Glendon Way. The channel cross section at this location is rectangular with a width of 48 feet. No silt was observed on the invert and the quality of concrete was noted as exceptionally good. Four current meter measurements were made by the Los Angeles County Flood Control District. The discharge ranged from 189 to 895 cfs with depths ranging from 0.4 to 1.2 feet and n values from 0.009 to 0.0109. The following table summarizes the data:

Measurement		1	2	3	4
Discharge	Q	895	720	315	189
Area	A	58.4	51.6	27.0	19.9
Mean Velocity	V	15.3	14.0	11.7	9.5
Hydraulic Radius	R	1.1	1.2	0.6	0.4
Slope	S	0.0097	0.0097	0.0097	0.0097
Roughness Coefficient	n	0.0107	0.0109	0.009	0.0091
Equivalent Roughness	k	0.0006	0.0008	0.00016	0.00025

(3) Verdugo Wash near Oakmont Country Club. The channel cross section in this reach of Verdugo Wash was trapezoidal with 1.50-horizontal to 1.0-vertical side slopes and a bottom width of 43 feet. The concrete was noted to be of poor quality with a rough finish. The invert grade was 0.02608. Two methods were used to determine the roughness coefficient. The first was to measure the discharge using a pitot tube. Using the area and mean velocity from this measurement, an n of 0.0116 was computed. The second method consisted of measuring the depth of flow at the crest of a debris basin spillway located a short distance upstream of the study reach at the same time depth readings were made from staff gages located at three sections on the channel. The spillway was operating as an ogee during the test. Discharges over the spillway were computed using the weir equation $Q = CLH^{15}$ where a c of 3.58 was assumed. Three tests were made with discharges of 1,580 cfs, 1,930 cfs, and 2,432 cfs with corresponding n values of 0.0126, 0.0148, and 0.0151, respectively.

(4) Ballona Creek near Thurman Avenue. The Ballona Creek Channel at this location has a rectangular cross section with a 60-foot width and an invert slope of 0.00124. No comments as to the condition of the concrete at the time of the test were given. Staff gages were located at seven sections on each side of the channel. Five complete sets of readings of the staff gages were made. The discharge remained practically constant during this period, and the mean of all the readings was computed to give the depth at each cross section which was then plotted to form a water-surface profile. Discharge measurements were made from a pitot tube. From this information, an n value of 0.013 was estimated for a discharge of 5,400 cfs.

(5) Ballona Creek below Hauser Boulevard. The Ballona Creek Channel below Hauser Boulevard has a rectangular cross section with a width of 38.7 feet and an invert slope of 0.00357. No comments as to the condition of the concrete at the time of the test are given. Six staff gages were placed at six channel sections. The uniformity of the staff gage readings indicated that a true normal depth had been reached. The discharge was determined by correlating the staff gage readings with the discharge measurements at Thurman Avenue. For a discharge of 5,620 cfs and a depth of 7.36 feet, an n value of 0.0137 was computed.

b. Tujunga Wash Test. In December 1966, water was released from Hansen Dam into the Tujunga Wash Channel for the specific purposes of determining the Manning's roughness coefficient n . The reach of Tujunga Wash used for this test is rectangular in cross section with widths varying from 60 to 70 feet and wall heights varying from 10 to 15 feet. The invert slope is 0.0094 and the design discharge is 22,000 cfs. The walls were formed by using 3.25-inch tongue-and-groove lumber and the invert was finished with wooden floats. At the time of the test, the condition of the concrete was very good. A constant release of 5,000 cfs was made from Hansen Dam. This discharge was verified downstream of the dam by a USGS streamgaging party using a Price current meter and an optical flowmeter. Observers were positioned to establish a water-surface profile from staff gages painted on the channel wall. Depths ranged from 2.9 to 3.3 feet and velocity from 22.2 to 25.4 feet per second. Results of this test indicated an n value of 0.011 on tangents and 0.012 on curves.

c. Data from the Los Angeles County Flood Control District. Rating curves were obtained for 10 sites on 10 different streams from the Los Angeles County Flood Control District. These rating curves were developed from actual flow measurements. At each site, a condition of uniform flow was assumed. At each site, several discharges were used to compute n values. At a number of sites, the computed n values were suspect because of being either extremely high or low or having a large variation in magnitude. As a result of these findings, a closer examination was made of the assumption of uniform flow. Six of the sites did not have uniform flow conditions because of such factors as a nearby change in invert slope, a bridge construction, a change in cross section, or a nearby confluence. Following are the results at the four sites that were determined to closely approximate the uniform condition assumption.

(1) Alhambra Wash near Klingerman Street. This portion of Alhambra Wash was constructed in 1938 by the Corps of Engineers. The channel cross section at the streamgage (station 73+65) is rectangular in shape with a 40-foot bottom width. The invert slope is 0.005611. The design discharge is 12,440 cfs. The following table presents data from this site.

Discharge	Q	94	356	742
Depth	d	0.7	1.3	1.9
Mean Velocity	V	5.8	8.6	11.5
Hydraulic Radius	R	0.7	1.0	1.53
Roughness Coefficient	n	0.0116	0.0127	0.0129
Equivalent Roughness	k	0.0017	0.0035	0.0037

(2) Rio Hondo Channel Below Lower Azusa Road. The Rio Honda Channel was constructed by the Corps of Engineers in 1959. The channel cross section at the streamgage (Section 788 + 00) is trapezoidal in shape with side slopes of 2.25 horizontal to 1 vertical. The bottom width is 80 feet and the invert slope is 0.00375. The design discharge is 26,000 cfs. The following table summarizes the data for this site:

Discharge	Q	175	210	2,430	6,860
Depth	d	0.7	0.8	2.5	4.5
Mean Velocity	V	4.5	5.1	12.7	18.0
Hydraulic Radius	R	0.7	0.8	2.1	3.8
Roughness Coefficient	n	0.012	0.0111	0.0118	0.0123
Equivalent Roughness	k	0.0023	0.0011	0.0014	0.0011

(3) Los Angeles River at Tujunga Avenue. This portion of the Los Angeles River was constructed by the Corps of Engineers in 1948. The channel cross section at the streamgage is rectangular with a bottom width of 120 feet. A low flow channel 12 feet wide and 3.17 feet deep is located at the center of the invert. The channel invert slope is 0.00368 and the design discharge is 52,000 cfs. The following table summarizes data for this site:

Discharge	Q	2,170	6,890	13,900
Depth	d	4.60	6.55	8.50
Mean Velocity	V	10.8	19.7	28.0
Hydraulic Radius	R	4.2	5.9	7.45
Roughness Coefficient	n	0.012	0.0129	0.0127
Equivalent Roughness	k	0.0008	0.0013	0.0009

(4) Limekiln Creek Above Aliso Creek. The Limekiln Creek Channel was constructed in 1962 by the Los Angeles County Flood Control District. The channel cross section at the streamgage (Section 16 + 00) is rectangular in shape with a bottom width of 24 feet. The invert slope is 0.00454 and the design discharge is 4,640 cfs. The following table presents data from this site:

Discharge	Q	258	480	878
Depth	d	1.25	1.8	2.55
Mean Velocity	V	9.7	12.1	15.2
Hydraulic Radius	R	1.13	1.57	2.10
Roughness Coefficient	n	0.0101	0.0104	0.0103
Equivalent Roughness	k	0.0003	0.0004	0.00025

d. Observations made during the floods of January and February 1969. Unfortunately no data were gathered during these floods from which roughness coefficients can be computed. However, design discharges were experienced in the San Antonio-Chino and Rio Hondo Channels during the 1969 flood and functioned as expected.

7. Summary of Prototype Data. Of the 10 sites where prototype data have been gathered, only two sites had some calculated n values greater than 0.014. These sites were Alhambra Wash at Short Street and Verdugo Wash near the Oakmont Country Club. At the Alhambra Wash site, because of an uncompleted portion of channel upstream of the site where the data were collected, silt was noted to have deposited on the bottom of the channel for certain discharges. This resulted in higher n values for the lower discharges. At the Verdugo Wash site, the n values measured varied greatly, with two of the four measurements exceeding 0.014. However, the concrete channel was noted to be in poor condition with a rough finish. Almost all of the remainder of the measurements were 0.013 or less. The equivalent roughness values computed were also generally much less than the recommended design value of 0.007 recommended in EM 1110-2-1601.

8. Bureau of Reclamation Data. As mentioned earlier, the Bureau of Reclamation's publication titled "Anlaysis and Description of Capacity Test in Large Concrete-Lined Channels" contains prototype data on roughness coefficients. In this report, the Bureau presents data collected from test to determine flow capacities and resistance coefficients in nine large concrete-lined irrigation canals located in the western United States. Some of the major conclusions of this study are as follows:

a. Flow resistance in the five largest canals tested (hydraulic radius 9 to 14) was greater than anticipated with computed n values ranging between 0.015 and 0.019.

b. Flow resistance in the four smallest canals (hydraulic radius 3 to 7) was close to that anticipated and ranged between 0.013 and 0.016.

c. The effect of size on values of n for straight clean reaches of concrete was slight.

d. Aquatic growths or coatings of various types were found on the surfaces of the concrete lining in all nine test canals. The amount and type of growth depended mainly on climate conditions and the canal water source. The extent of surface coverage varied seasonally and annually in a given channel.

9. At first glance, it would appear that the Bureau's findings conflict with the prototype data from the concrete-lined flood control channels in southern California. The n values computed from the data from the irrigation canals ranged from 0.013 to 0.019 while those computed from data from the flood control channels, with the exception of a few values already discussed, ranged from 0.010 to 0.014. Upon closer examination, it appears that the main differences in the findings from the two sets of data is aquatic growth. From description of canal conditions and pictures of the canals presented in the Bureau's publication, it is apparent that large amounts of aquatic growth were present in all nine of the canals. Also described in the report was the large impact this growth had on the roughness coefficients. In the flood control channels in southern California, only minor flows, if any at all, are present the majority of the time. This type of condition is not conducive to aquatic growth, so the flood control channels are clean, which results in less flow resistance.

10. Another possible reason for the differences in n values from the two sets of data is the concrete finish. From pictures in the Bureau's report, it appears that the general surface finish is relatively smooth; however, the contraction grooves appear to be rougher than those on flood control channels.

11. We feel that these two factors, primarily the aquatic growth and probably the surface roughness, are the main reasons for the differences between the two sets of prototype data. If the aquatic growth were totally removed from the irrigation canals, the roughness coefficients would be comparable to those experienced in flood control channels.

12. Summary. As discussed earlier in this paper, prototype data that was gathered to determine n values in concrete-lined flood control channels show that, if anything, an n value of 0.014 is conservative. The reason for these relatively low n values is the quality of concrete finishes in these channels and the mild climate which reduces the effects of weathering. It is true that the Bureau of Reclamation has experienced n values higher than 0.014 in some of their irrigation canals; however, aquatic growth was the primary cause of this. Aquatic growth does not occur to nearly this extent in our concrete flood control channels. For these reasons, we feel that our practice of using an n of 0.014 for design of concrete-lined channels is appropriate.

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