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PROPOSED PROGRAM OF STUDIES TO DEVELOP METHODS OF DESIGN OF STABLE CHANNELS IN ERODIBLE MATERIAL

by

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SUMMARY

The Bureau of Reclamation has in prospect an immense program of design for earth canals. The total estimated cost of unlined canals now under construction or in authorized projects is very close to one-quarter of a billion dollars. The total length of these canals is about 2,000 miles, with discharges up to a maximum of about 12,000 second-feet. This does not include many projects now under study. In Region 7 alone, the cost of canals on projects under study but not yet authorized amounts to about $217,000,000. Some of these projects will, no doubt, later be approved, and especially if this country should be faced with a major depression probably a considerable part of them would be constructed. It does not seem unlikely that in future years, between one-quarter and one-half billion dollars worth of unlined canals will be constructed.

If these canals are to be designed with the high standard of skill which has characterized the work of this Bureau in the past, it is imperative that a comprehensive study be inaugurated immediately to develop the best possible methods of design for unlined canals flowing in earthern channels. Although considerable study of this subject has been made in the past, largely in India, no adequate solution of the problem has been developed. The science of design of earth canals is much less developed than that for earth or masonry dams. Great savings in first cost of the canals and in their cost of maintenance could, no doubt, be made if an adequate method of design was developed. The science of hydraulics has advanced to the point where such a development is possible. This Bureau will not be meeting its responsibilities if it does not give to this immense program of work the best designs that it is possible to develop. The methods which have been used when hydraulic science was in a less developed state will not be adequate for the future.

It is true that the Bureau has built many miles of canal, and usually the results have been satisfactory. In general, in the past, canals have been designed for water carrying comparatively little sediment in regions of coarser soils. In the future the greater part of them will be built in the Great Plains region where material through which they pass will be fine and sediment loads are high. Much more difficulty can be expected under these conditions. Also, it is not known to what extent less expensive canals could have been used in the past and still provide as good service as these which were built. In the future, only the least expensive canals which will give satisfactory service should be built.

Considerable progress was made in connection with the design of the All-American Canal in the development of the broad outline of the hydraulic principles governing the design of stable channels, but the acceleration of the construction of that project, because of the necessity of providing employment during the depression, prevented a thorough study. In recent months considerable thought has been given to the stable channel problem, and it is the writer's belief that these principles have now been worked out to the point where a solution can confidently be expected, if adequate studies are carried out. The principles developed are in qualitative form, and what is needed is to get quantitative data to make these principles applicable to actual design problems. What is proposed is a series of office studies, laboratory tests, and a study of experience with Bureau and other canals, which will give the optimum combination of theory and experience and thus produce the best results for actual design. The proposed program will also include the presentation of these results in the form best suited to design use in the various offices of this Bureau.

The program is divided into eight divisions, each of which is made up of several different studies in the office, laboratory, or field. In Appendix I is given in some detail the purpose and proposed procedure for each of these studies.

This program covers the same ground as that given for stable channels in the comprehensive report* for sediment studies previously submitted but, because of the necessary delay in undertaking the former program, the present program speeds up somewhat the rate of carrying it out. Largely because of lack of suitable personnel, comparatively little can be accomplished in FY 1950, except laying the ground work for active execution in FY 1951 and 1952.

The total cost of the proposed program will be about $300,000, but it is not the intent that the execution of this entire program be finally adopted at the present time. The first part of the program, which will be most productive in proportion to costs, can be carried out first, and the remainder approved later if the prospect for future construction work and the success of the initial steps justifies further expenditure. The cost of the proposed program for FY 1950 is $25,000. The expenditures recorded for FY 1951, 1952, and 1953 are $100,000, $100,000, and $75,000, respectively.

The writer is confident, however, that the entire program will prove well justified economically, especially if a big public works program is brought on by a depression. If these studies should reduce the first

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*Lane, E. W. and Maddock, Thomas, Jr., "Proposed Bureau of Reclamation Program for Securing Basic Information for Sediment Control in Streams, Canals, and Reservoirs," April 28, 1948.

cost and maintenance of the projects by only 1 percent of their construction cost, they would save several times the entire cost of the studies. The proposed studies would also give invaluable data for the solution of other sediment problems of the Bureau and other projects of this Government in the United States. It is important, however, that this program be undertaken promptly in order that the results be available for canal design at the earliest possible date.

In the following report are outlined the studies which are necessary to secure the quantitative data required to make the general principles, which have been developed, applicable to engineering design. The details of the methods to be employed, the cost of the work, the order of procedure, and the economic justification of the work is also included.

INTRODUCTION

The purpose of the following memorandum is to present the need for developing an adequate method for the design of earth canals, so that they will neither scour out nor fill with sediment. Because of the very large quantity of earth canals which the Bureau is expecting to construct in the near future, and the lack of an adequate method of design, it is imperative that steps be taken to develop such a method, in order that satisfactory designs of these structures may be prepared. In the following pages are pointed out the need for these studies, the principles controlling the design of earth canals which have so far been developed, the need for perfecting these principles, the methods proposed for securing the data necessary to perfect them and an estimate of the cost.

EARTH CANALS IN THE BUREAU'S PROGRAM

The magnitude of that part of the Bureau's program which involves the construction of earth canals is startling. The magnitude of the expenditures for earth canals which can be expected in the future is uncertain, but it is sure to be a very large sum. No attempt has been made, in connection with this study, to get a complete list of the earth canals which may be constructed by the Bureau of Reclamation but enough investigation was made to indicate the order of magnitude of the work in prospect.

A partial investigation showed that unlined canals on projects already authorized (a small part of which are under construction) amounted to over $248,000,000. On most of these canals even preliminary designs have not yet been started. It does not include several million dollars of canals in Region 1, on which a decision has not been made as to whether they would be lined or unlined. In Region 7 alone, the canals and laterals in prospect but not yet authorized, most of which will be unlined, total about $217,000,000. More details of these costs are given in Appendix II. In addition, there is the Central Utah Project with 314 miles of unlined canal; the Bitterroot Project in Montana with 172 miles of main canal, much of

which may be unlined; the Mountain Home Project in Idaho, which probably includes large mileage of unlined canals; and numerous other small projects containing earth canals.

It may be said therefore that there is a prospect that as much as a half billion dollars of earth canals will be constructed in the not far distant future, especially if a severe depression should develop. Even if half of these failed to materialize, it would still be a quarter of a billion dollars, a really tremendous sum of money for such work.

THERE IS NO ADEQUATE METHOD FOR THE DESIGN OF EARTH CANALS

There is no adequate method for the design of earth canals so that they will neither scour the banks and bed because of excess velocities nor fill up with sediment because of low velocities. It is true that rough methods of canal design are available to prevent scour from excess velocities in canals, which have enabled the Bureau in the past to design many miles of canal which are fairly successful. Since no rational method for such designs exist, however, it is probable that the reason for their success in many cases is that they are overdesigned. All that is known is that they work, but it is not known how much cheaper they could have been constructed and still work just as satisfactorily. Until the hydraulic principles controlling design have been worked out it will not be possible to know completely what savings may be possible by the use of better design methods.

Another reason why the designs used in the past have been fairly successful is that the water flowing in them has usually been comparatively free of sediment. Most of the water supplies have been from rivers carrying comparatively small sediment loads. Usually, too, the material through which the canals passed was comparatively coarse. In the canals now in prospect, however, the conditions will not be so favorable. Many of the large projects will be in the Great Plains region where the streams frequently carry large sediment loads and pass through material which is easily eroded. Under these conditions, much more trouble can be expected than has occurred on projects designed in the past.

In India, where conditions somewhat similar to those which are encountered in our Great Plains region exist, a great deal of trouble with scour and filling of the irrigation canals has been encountered. Because the extent of their projects greatly exceeds that of the irrigation work in this country, a great deal of experience has accumulated and much study has been given to developing methods of canal design. A great deal of progress has been made and for certain conditions considerable success has been obtained, but the results of these studies have not been found to be applicable to other parts of the country, where conditions differ. Unfortunately, the methods developed are largely empirical and it is therefore not safe to adopt them where conditions are different from those in the region where the methods were developed. Since at least one important factor, the quantity of sediment carried, has not been adequately considered in the Indian

development nor has adequate data on it been collected, it is not known with sufficient exactness what the conditions are, under which the methods developed are successful. It is, therefore, not safe to adopt the Indian methods for design in this country, where the conditions may be different.

THE NECESSITY OF STUDIES TO DEVELOP ADEQUATE DESIGN METHODS

To adequately design the great numbers of canals which this Bureau has in prospect it will be necessary to develop the basic theory of design of stable channels in erodible material and the quantitative relations between the various factors involved. While much use can be made of the work of previous studies in this field and the data collected on them, because the basic theory involved was not known, the data collected does not contain all of the information necessary for complete use, and additional data covering these points will have to be collected.

Fortunately, considerable progress has already been made in this development. In connection with the design of the All-American Canal, considerable progress was made in developing the basic theory involved, but before the quantitative relations between the various factors could be worked out the necessity of providing employment during the depression caused the construction to be advanced several years and adequate time to develop these relations was not available. The program proposed herein, therefore, is merely the completion of that started for the design of the All-American Canal. It is greatly hoped that this time it can be carried out before another depression makes construction necessary before the program can be completed and the results incorporated in the designs.

THE PROPOSED PROGRAM

The program proposed to secure the data needed to develop adequate design methods for earth canals and to present the results of studies in the best possible form for use by the design organizations, can be divided into eight major divisions, each of which can be further subdivided into several parts, as shown in Table 1. In Appendix I is given a brief discussion of each of these subdivisions and the methods of carrying it out.

Table 1

OUTLINE OF PROPOSED PROGRAM OF STUDIES

1. Critical Velocities and Tractive Forces

    a. Analysis of available literature on tractive force
    b. Angle of repose in granular material
    c. Field study of San Luis Valley and other canals
    d. Field study of critical tractive forces in cohesive material
    e. Velocity conditions causing initial particle motion on a canal bed

Table 1--Continued

OUTLINE OF PROPOSED PROGRAM OF STUDIES

2. Effect of Bends on Velocity and Shear Distribution

   a. Hydraulic Laboratory study of flow distribution in bends
   b. Field (prototype) studies of flow distribution in bends
   c. Experience with scour at bends in Bureau and other canals

3. Velocity and Shear Distribution Studies

   a. Laboratory study of velocity and shear distribution in straight channels
   b. Mathematical study of velocity and shear distribution in straight channels
   c. Investigation of possibilities of developing an analogy for velocity distribution in straight channels
   d. Field (prototype) tests of velocity distribution in straight channels
   e. Refinement of mathematical analysis of stable channel shapes
   f. Field studies in San Luis and other canals of velocity and tractive force distribution

4. Laws of Sediment Transportation

   a. Turbulence jar studies of pick up and temperature effects
   b. Mathematical studies of laws of sediment transportation
   c. Field measurements to secure data for development of laws of sediment transportation
   d. Laboratory measurements to secure data for development of laws of sediment transportation
   e. Relation of turbulence to sediment transportation

5. Experience in Bureau and Other Canals

   a. Comparison of observed conditions in Bureau and other canals with indications of field and laboratory tests

6. Comparison of Design Procedures Developed with Data in Literature

   a. Comparison with Kennedy, Lacey, and others' results from India
   b. Comparison with canal sections in use in Egypt

7. Preparation of Formulae, Diagrams, and Tables

   a. Preparation of formulae, diagrams, and tables covering various combinations of canal cross-section shape, sediment type, and surrounding material type combined with the hydraulic factors of discharge and slope

Table 1--Continued

OUTLINE OF PROPOSED PROGRAM OF STUDIES

8. Construction of Outdoor Hydraulic Laboratory

a. Construction of an outdoor Hydraulic Laboratory at the Denver Federal Center for determining the scour and velocity distribution at bends, and other studies in the stable channel field

RELATION TO OVER-ALL SEDIMENT PROGRAM

The program outlined herein covers one section of the over-all sediment program submitted in 1948 by Thomas Maddock, Jr., Head of the Sedimentation Section of the Branch of Project Planning, and the writer under the title "Proposed Bureau of Reclamation Program for Securing Basic Information for Sediment Control in Streams, Canals, and Reservoirs," April 28, 1948. In the program submitted in that report the whole field of sediment studies was divided up into five parts, of which the first dealt with the problem of stable channels. The program discussed herein covers the same ground as that in the first item of the comprehensive program; namely, the part headed "Stable Channels," but has divided the subject somewhat differently than in the previous report. The estimate of total work required, however, has not been changed. Only in minor particulars has the scope of the program been changed, as further study of the problem has indicated that improvements in the previous proposals were desirable, but no major changes are contemplated.

As originally submitted, the program covered 7 years, but most of the work was included in the first 5 years. Since considerable time has elapsed since that program was proposed, during which, because of lack of funds, little progress was made, it will be necessary to accelerate the work considerably if the results are to be available in time to be used in the design of the Bureau projects. It is therefore proposed to cover this work in a period of about 3 years instead of the 5 proposed in the comprehensive program.

ORDER AND RATE OF CARRYING OUT

The order in which it now seems best to carry out the work is shown in Table 2. This shows the programs proposed for FY 1950 to 1953, inclusive. If these studies are to reach their maximum usefulness, the results of them must be available at the earliest possible moment, in order to be employed in the design of as many canals as possible. The program has therefore been compressed into as brief a time as it now seems practicable to carry it out. The program for FY 1950 can be carried out on the funds already authorized for sediment and general hydraulic studies. This is as much as personnel limitations are likely to allow. The programs proposed for 1951 and 1952 are considerably larger and will necessitate additional personnel or the cooperation of outside laboratories.

Table 2

PROPOSED PROGRAM OF CARRYING OUT STUDIES AND ESTIMATED COST

Remainder of Fiscal Year 1950	Estimated cost	Items of Table 1
Determinations of angle of repose	$ 1,500	1b
Field study of San Luis Valley Canals	9,750	1c&3f
Analysis of critical tractive force literature	2,250	1a
Mathematical studies of velocity and tractive force distribution	2,250	3b
Mathematical studies of laws of sediment transportation	1,500	4b
Refinement of mathematical analysis of stable shapes	1,500	3e
Turbulence jar studies	3,750	4a
Reconnaissance for field measurements of tractive force and sediment transportation	1,500	4c
Bureau experience on scour on bends	1,000	2c
Total Cost Fiscal Year 1950	25,000	
Fiscal Year 1951		
Construction of outdoor laboratory	22,500	8a
Laboratory mathematical and field studies of tractive force and velocity distribution	19,500	3a,b,d&f
Mathematical, field, and laboratory studies of laws of sediment transportation	22,500	4b,c,d&e
Working up of results of San Luis Valley Canal observations	5,250	1c&3f
Hydraulic laboratory studies of effect of bends	3,750	2a
Completion of turbulence jar studies	3,750	4a
Study of Bureau and other experience in earth canals	9,000	2c,5a
Comparison of our results with data in literature	10,000	6a&b
Working out preliminary design formulae, tables, and diagrams	3,750	7a
Total Cost Fiscal Year 1951	100,000	
Fiscal Year 1952		
Laboratory mathematical and field studies of tractive force and velocity distribution	8,500	3a,b,d&f
Mathematical, field, and laboratory studies of laws of sediment transportation	33,000	4b,c,d&e
Laboratory and field studies of effect of bends	26,250	2a&b

Table 2—Continued

PROPOSED PROGRAM OF CARRYING OUT STUDIES AND ESTIMATED COST

	Estimated cost	Items of Table 1
Fiscal Year 1952 (Continued)		
Critical tractive forces in cohesive materials	$ 3,750	1d
Study of Bureau and other experience in earth canals	7,500	2c&5a
Comparison of our results with data in literature	7,500	6a&b
Working out design formulae, tables, and diagrams	7,500	7a
Possibility of developing analogy for velocity distribution in straight channels	2,250	3c
Velocity conditions causing initial motion	3,750	1e
Total Cost Fiscal Year 1952	100,000	
Fiscal Year 1953		
Mathematical, field, and laboratory studies of laws of sediment transportation	45,000	4b,c,d&e
Comparison of our results with data in literature	11,250	6a&b
Working out design formulae, tables, and diagrams	11,250	7a
Critical tractive forces in cohesive materials	7,500	1d
Total Cost Fiscal Year 1953	75,000	
Total Cost Entire Program	300,000	

COST OF THE PROPOSED PROGRAM

The details of the cost of the program proposed are also shown on Table 2. This totals $25,000 for FY 1950, $100,000 for FY 1951, $100,000 for FY 1952, and $75,000 for FY 1953. The total cost of the program proposed is $300,000.

ECONOMIC JUSTIFICATION

The $300,000 estimated as the total cost of this project seems like a very large sum of money, and it undoubtedly is. However, when compared with the cost of the work over which its benefits would be spread, it is a relatively small item. On page 3 it has been pointed out that the estimated cost of unlined canals on authorized projects of this Bureau is over $248,000,000, that in Region 7 alone the estimated cost of canals and laterals on projects under study but not yet authorized is about $217,000,000, and that very large projects no doubt including many unlined canals are

under study in other regions. It can be said therefore that there is a prospect of the construction, in the not far distant future of half a billion dollars worth of unlined canals, especially if a severe depression should develop. Even if only half of this work was carried out, it would cost a quarter of a billion dollars, a truly tremendous sum of money.

The proposed program is therefore of the order of magnitude of one-tenth of 1 percent of the prospective expenditure. It is the writer's belief that savings in first cost and maintenance of the order of at least 1 to 2 percent of the construction cost are not at all unreasonable to expect as a result of the carrying out of this program, and the benefit will therefore be at least 10 to 20 times the cost of the study. If the writer's judgment is 900 percent in error, the project will still have a cost-benefit ratio of 1.0 or more.

OTHER BENEFITS OF THE PROPOSED PROGRAM

The economic justification previously stated does not consider a wide range of benefits which the knowledge gained would bring to this Bureau, to other organizations designing hydraulic work in the United States and in foreign countries. For example, in the design of canals to be protected from seepage by the buried membrane method, as developed in connection with the low-cost lining program, it is necessary to choose the slopes and cross sections so that the material covering the buried membrane is not washed away, thus exposing the membrane to damage from stock and from other sources. The procedures developed by this program should be very valuable in designing these canals. The results obtained by these studies will be equally applicable in the design of drainage canals. The necessity of designing drainage canals that will not scour is strikingly emphasized by the great damage caused by the Gering Drain on the North Platte Project. The limits of safe slopes for drainage canals under the various conditions of soil material will be adequately worked out by these studies.

The knowledge of the laws of sediment transportation which this program proposes to investigate will also be of great value in other studies under way by this Bureau. It is very much needed to enable better estimates to be made of the rate of degradation which will occur below dams, or the aggradation which will take place above them. It will be very useful also on the studies for the control of the channel of the Middle Rio Grande.

The information gained in these studies will be widely used by the Corps of Engineers in the design of stable channels on their flood control projects and by the Department of Agriculture on their drainage channels. It would eventually be useful throughout the world where irrigation, drainage, or flood control is practiced.

NEED FOR RAPID PROGRESS IN THIS INVESTIGATION

There is urgent need for rapid progress in this investigation. If the results of these studies are to be used on the design of canals, they must be carried out before the canals are designed. A large program of canal work is already under design in this Bureau on which these results would be valuable. An extensive field design organization is being built up and is beginning to work out canals on a large number of projects. The sooner the results of the studies are available, the more will be the number of the canals on which the savings can be realized.

The extent of the program of canal work which the Bureau will be called upon to design is indefinite, but it is sure to be very large. In case of a major depression, an extremely large program for rapid construction by this Bureau would be expected. To be prepared for such an emergency, these studies should be made with the greatest practicable speed. As the work progresses, the picture of the future program of this Bureau will become increasingly clear. It is not proposed that the entire program proposed herein be finally adopted at this time. If this study is started now on a considerable scale, as the work progresses, if the Bureau's construction projects or the success of the program do not justify carrying it on as proposed, a change of plan can be made, and thus major mistakes can be avoided. On the other hand, if the program is not started promptly and the large program of works already under way continues, large unnecessary expenditures will result. It is urgent therefore that the program be started promptly.

APPENDIX I

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TECHNICAL DETAILS OF PROPOSED PROGRAM

In the following paragraphs, each of the lines of study proposed under the eight sections in Table 1 on pages 9 and 10 are discussed in detail, to indicate more clearly what is planned, the results to be expected, and how the study will be carried out. The projects will be subdivided as shown in that table.

1. Critical Velocities and Tractive Forces

a. Analysis of available literature on tractive force. An analysis of the available literature on tractive force would be made to obtain the relation between particle size and critical tractive force as determined by previous experiments. A preliminary study indicates that the results of various experimenters are very conflicting, but as much information as possible should be obtained in this way, since it can be done with comparatively little expense.

b. Angle of repose in granular material. If a search of the literature does not provide the data, a series of experiments would be made to determine the angle of repose of granular material under various conditions. The angles of repose of coarse, granular material of three or four sizes composed of particles of (a) very rounded, (b) average, and (c) very angular shape would be measured. Sufficient experiments would be made to determine whether or not the slope under water differed from that in air, and if so, the slopes in all cases would be measured for both conditions. The effect of other shapes, such as disks, etc., on the angle of repose would also be observed.

c. Field studies in San Luis and other canals of critical velocity and tractive force. To determine the critical velocities and tractive forces which will just move bed material of various particle sizes, in prototype-size channels, it is proposed to determine the conditions in canals such as those in the San Luis Valley canals and other canals where the situation is similar. The reconnaissance and determination of procedures for the San Luis Valley canals has already been completed. An attempt will be made to secure data on other canals with bed material of somewhat smaller material size.

As a byproduct of these studies, a great deal of data on the effect of particle size on hydraulic roughness will be obtained. This will enable more accurate values of roughness to be used in design, which should result in considerable savings. The data collected in these measurements on roughness and particle size should therefore be combined with that available from other sources and a relation developed which can be used in future designs.

d. Field study of critical tractive forces in cohesive material. This study would be composed of two parts: (1) a study of velocities or tractive forces which caused scour of cohesive material in its natural condition in canal banks and (2) the velocities and tractive forces acting on the berms of canals which formed from fine material carried in suspension in the water. The limiting values which caused scour for both types of material would be determined by actual measurement.

e. Velocity conditions causing initial particle motion on a canal bed. This study is primarily for the purpose of investigating the possibility of developing the approach to the stable channel problem from the standpoint of velocity rather than from tractive force. It would investigate the conditions causing the initial movement of a particle on a stream bed as influenced by the vertical velocity curve near the bottom, the effect of the velocity fluctuations due to turbulence, the stabilizing effect of the inertia of the particle under the variable force due to turbulence, and the effect of the shape of the particle. An attempt would be made to combine the knowledge obtained from these studies into an analysis of channel stability from the approach of velocity rather than tractive force.

2. Effect of Bends on Velocity and Shear Distribution

a. Hydraulic Laboratory study of flow distribution in bends. To determine the effect of bends and work out the safe values of curvature for various materials, it is proposed to study the flow conditions in a wide range of bend conditions. This would involve the measurement of the distribution of velocities at a considerable number of sections of bends having various ratios of bottom width to depth and radius of curvature to bottom width. The maximum increase in velocity and shear adjacent to the sides would be worked out from these observations.

The possibility would be studies of reducing scour at bends by using spiraled curves, and of depressing the bottom on the inside of the curve. The use of larger sections on curves, to reduce velocity, with gradual transitions upstream and downstream would also be tried.

b. Field (prototype) studies of flow distribution in bends. These studies would be made to determine how closely flow distributions in actual canals followed the measurements made in models. A limited number of sites on actual canals will be selected and measurements of flow distribution at various cross sections made. If the cases of model observations under 2a above do not provide model comparisons of these cases, special models of these prototypes will be made and tested.

c. Experience with scour in bends in Bureau and other canals. To provide a check on the conclusions on the effect of bends on canal stability developed from the model and prototype tests and, if necessary,

empirical relations for safe curve radii for various conditions, extensive observations will be made on the radii of bends in Bureau and other canals where scour is troublesome. The velocities, canal shapes, bed and bank material will be observed and the results will be tied in to the results of model and prototype tests.

3. Velocity and Shear Distribution Studies

a. Laboratory study of velocity and shear distribution in straight channels. This study is proposed to be in two parts: (1) the measurement of velocity distribution and the determination of shear distribution indirectly and (2) the measurement of shear distribution directly. For the first part it is proposed to set up a straight, sloping trapezoidal channel with sides hinged so that various side slopes could be obtained. This would be as large as the circumstances would permit, and long enough to insure that an equilibrium velocity distribution was established in it for a reasonable length of channel upstream from any effect of dropdown or other action at the discharge end. By running various discharges through the channel, using different side slopes, a wide range of ratios of depth of flow to bottom width could be secured for the various commonly used side slopes. Careful measurements of the velocity would be made in this channel at a cross section where the flow was steady and uniform and the velocity distribution in equilibrium, and the results plotted and isovels or velocity "contours" plotted. By drawing orthogonal lines (at right angles to the contours) it is possible to develop the shear distribution on the sides and bottom of the canal. In addition to trapezoidal sections, other cross sections could be investigated.

The shear at various points on the sides and bottom of this channel could be measured by making small sections of the bottom or sides movable and measuring the longitudinal thrust of the water on these sides. This would require somewhat delicate work, but work of a very similar nature has been done in air, and it is believed this could be successfully carried out.

b. Mathematical study of velocity and shear distribution in straight channels. This study would also be two parts: (1) a study of velocity distribution in straight channels along the line of that carried on by Keulegan in "Laws of Turbulent Flow in Open Channels," National Bureau of Standards, Research Paper RP1151, Journal of Research of the National Bureau of Standards Vol. 21, December 1938, pp. 707-741; and (2) a mathematical study to determine the velocity distribution in a very wide channel, in particular the tendency of the water at the surface to flow at somewhat lower velocity than at a small distance below the surface. This phenomenon enters into the development of the shear distribution on the sides and bottom of a channel from the velocity distribution.

c. Investigation of the possibility of developing an analogy for velocity distribution in straight channels. It is believed that an analogy might be developed which would give, with a precision sufficient for practical purposes, the velocity distribution in a straight channel of any usual shape. A membrane analogy perhaps could be used, with the membrane or soap film stretched over an opening the sides of which were in the shape of two cross sections of the channel under investigation, placed in the same plane with their water-surface lines coinciding. The effect of the velocity distribution, mentioned in the second part of Section 3b above, could perhaps be induced by a thread stretched under the proper tension along these water-surface lines.

The equipment for obtaining the contour lines for such an apparatus is available in the Dams Division of this Bureau. If a sufficiently accurate analogy could be developed, it would provide a rapid and inexpensive method of determining the shear distribution for channels of a wide variety of shapes.

d. Field (prototype) tests of velocity distribution in straight channels. The purpose of this test is to determine whether the velocity distribution in a large channel would be the same as in a model channel of similar shape. There is good reason to believe that, for models of the size proposed for these studies, this would be the case, except for a negligible departure. Tests of this kind would be very convincing to anyone who might question the reliability of results based on model channels or, in case they showed a dissimilarity of model and prototype results, would prevent the mistake being made of relying on the results of model tests.

e. Refinement of mathematical analysis of stable channel shapes. In the Fan-Swain-Glover analysis for stable channel shape, the tractive force was assumed to be proportional to the depth. In an actual channel, the deeper portions of the flow tend to drag along the shallower portions. An approximation which would be nearer the true case is being investigated.

f. Field studies in San Luis and other canals of velocity and tractive force distribution. In connection with the measurements of critical tractive forces under Section 1c, observations should be made at favorable locations of canals in the San Luis Valley and other canals to obtain the velocity distribution in actual canals. These canals will usually be of nontrapezoidal shape and should give data under conditions somewhat different from that obtained in Section 3a.

4. Laws of Sediment Transportation

a. Turbulence jar studies of pick up and temperature effects. The laws of sediment transportation in suspension for sediment transported above a channel bottom have been investigated with sufficient thoroughness

for most practical purposes, but the relations of the pick up of the material on the bed (which replaces that which settles down on the bed), to the conditions of flow, has been covered inadequately. Section 4c of this program is planned to provide this information, but it will take considerable time to develop these results. To provide the best material possible until data from the field can be secured, the effect on pick up of artificial turbulence in a jar should be studied. This will use a jar of the type developed by Rouse,** in which turbulence is induced by a motor-driven reciprocating grid. Different sizes of unigranular material would be introduced in sufficient quantities to cover the bottom of the jar, and the pick up introduced by different degrees of turbulence would be observed. The effect of various ranges of sizes of material would also be studied. The effect of temperature, which appears to be considerable, would likewise be determined.

b. Mathematical studies of laws of sediment transportation. In these studies the laws of sediment transportation would be studied from the most fundamental aspects, by mathematical analysis of fluid mechanics principles. The existing literature along these lines would be studied and used as a starting point for further advances in this field. The probable nature of these advances will not become apparent until the studies of the present knowledge are made by qualified personnel.

c. Field measurements to secure data for development of laws of sediment transportation. To secure data to establish conclusively the laws of sediment transportation in large channels it will be necessary to observe the sediment transportation in many actual channels and relate the results to sediment transportation theory. It is therefore proposed to measure the sediment transported in as many canals as possible where conditions for these measurements are suitable. This would include the whole range of particle sizes, but particularly those in the sand range. The results would then be compared with sediment transport relations, as developed by various authorities in the past, or relations which may be proposed in the future by others or may be developed by this Bureau.

d. Laboratory measurements to secure data for development of laws of sediment transportation. In the development of the laws of sediment transportation, measurements made in laboratory channels will be very valuable. Studies such as the effect of temperature and the effect of particle shape can be made very effectively in such channels. Also studies comparing the transporting of sediment covering a considerable range of sizes as compared with material of a narrow-size range. The

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**"Experiments on the Mechanics of Sediment Suspension," H. Rouse, Proceedings of the Fifth International Congress of Applied Mechanics, 1938, pp. 550-554.

advantages of laboratory over field work is that in the laboratory the effect of one variable can be investigated by holding all other conditions constant and changing only one condition at a time. In field tests this can be done very rarely.

e. Relation of turbulence to sediment transportation. This study would involve the development of an instrument for measuring turbulence, and the technique for using it in determining the relation between turbulence and the transportation of sediment.

5. Experience in Bureau and Other Canals

a. Comparison of observations in Bureau and other canals with indications of field and laboratory tests. Data will be collected on canals of this Bureau and other agencies in this country, with which to test the sufficiency of relations for the design of earth canals which it is expected to develop from the laboratory and field tests planned under this program. In this way the reliability of these relations will be adequately established. A search would also be made for data to determine the safe minimum depth which could be used in canals designed to flow at maximum slope.

6. Comparison of Design Procedures Developed with Data in Literature

a. Comparison with Kennedy, Lacey, and other results from India. In order to insure the reliability of the design procedures developed as the result of the investigations planned herein, insofar as the available data are sufficiently complete, comparisons will be made between these procedures and the observed data and relations developed in India by Kennedy, Lacey, and others. Extensive literature in this field is available in Indian and British publications, and every advantage should be taken of the wide experience and numerous measurements of the engineers who have built the world's largest canal systems.

b. Comparison with canal sections used in Egypt. The canal sections which have been found to be satisfactory in Egypt are so much narrower and deeper than those commonly used in India that they offer a good check on the design relations which it is expected to develop, in addition to those available from India. If the design relations developed are general in their application, they should reconcile the results of the experience in both countries and indicate the shapes developed in each country for the conditions which exist in the respective regions.

7. Preparation of Design Formulae, Tables, and Diagrams

a. There are a large number of factors controlling the shape of stable earth channels, in addition to the hydraulic factors of discharge, slope, and roughness. There are three principal factors: (1) cross-sectional shape, (2) sediment type and quantity, and (3) type of material

through which the canal is excavated. Cross-sectional shapes would be of two or more kinds, the most common ones being (a) trapezoidal and (b) most efficient sections. The sediment types would be four in number: (a) no sediment or clear water, (b) fine sediment only, (c) coarse sediment only, and (d) both fine and coarse sediment. Of course, under each of these except (a) there would be a range of sediment concentrations. For material through which the channel was excavated there would be two major classifications (a) cohesive and (b) noncohesive.

The diagrams which would be easiest to develop would probably be for trapezoidal channels carrying clear water in noncohesive material. This diagram would include the discharge, slope, bottom width, flow depth, side slopes, and grain size of the material through which the canal passed. The hydraulic roughness would be a function of this grain size. For example, a set of three diagrams could easily be constructed for each common channel side slope showing the entire range of discharge and material size the corresponding (1) slope, (2) bottom width, and (3) flow depth that would just produce impending motion on both the sides and bottom. Another diagram which could be constructed would be the most efficient channel for clear water flowing in noncohesive material. The analysis of this type could perhaps be best shown in the form of formulae rather than diagrams. Diagrams or formulae for the other 14 conditions could be developed as the analysis of them evolved.

In connection with the use of these diagrams it would be necessary to develop a method of determining, from the mechanical analysis of the material through which the canal was constructed, the limiting particle size which could be used. This would be the largest size that would not require an excessive movement of finer material to expose the particles of that size (or larger) and thus protect the bed and banks against further movement.

8. Construction of Outdoor Hydraulic Laboratory

a. It is proposed to construct an outdoor Hydraulic Laboratory at the Denver Federal Center to study those parts of this program which cannot be carried out with existing facilities. One of the first studies to be undertaken in this laboratory would be the study of the flow distribution in bends (Item 2a). Other studies which might be carried out in the outdoor laboratory would be the determination of the velocity and shear distribution in straight channels (Item 3a), velocity conditions causing initial particle motion on a canal bed (Item 1e), and measurements to secure data for the development of the laws of sediment transportation (Item 4d).

APPENDIX II

EARTH CANALS AUTHORIZED OR IN PROSPECT

Data on Unlined Canals on Authorized Projects

Region	Project	Canals	Length in miles	Maximum capacity cfs	Estimated cost dollars
4	Total		51.8	165	$ 1,598,000
6	Crosby-Mohall	Souris-Crosby-Des Lacs	1,465	10,500	43,233,000
	Lower Marias	Marias	77.1	2,200	18,211,000
	Missouri Diversion	Diversion Canal	86	7,500	31,486,000
	Oahe		370	11,800	80,580,000
	Shoshone Extension		85.5	1,400	16,736,000
	Other canals		807.2	1,800	33,183,000
7	Frenchman-Cambridge		195	230	12,026,000
	Bostwick Division		226.3	-	11,711,000
	Total		2,045.4		248,764,000
1	Several million dollars worth, division between lined and unlined canals not decided				

Canals in Prospect in Region 7

7	Colorado-Big Thompson		12,400,000
7	Blue-South Platte		39,430,000
7	Gunnison-Arkansas		11,610,000
7	Kendrick Project--First Unit		4,009,000
7	Mirage Flats Project (WCU)		1,099,000
7	Missouri River Basin	Cedar Bluffs Unit	2,763,000
		Kirwin Unit	2,285,000
		North Loup Division	8,987,000
		Middle Loup Division	25,551,000
		Columbus Division	40,490,000
		Grand Island Division	68,035,000
	Total		216,659,000

Note: These data may not be complete.