# MECHANICS OF LOCAL SCOUR
## PART II

## BIBLIOGRAPHY

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S. S. Karaki

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R. M. Haynie

Prepared for

U.S. Department of Commerce
Bureau of Public Roads
Division of Hydraulic Research
under Contract 11-8022

Civil Engineering Section
Colorado State University
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## FOREWORD

The mechanics of local scour is a three-year study undertaken by Colorado State University with the sponsorship of the U.S. Department of Commerce, Bureau of Public Roads, Division of Hydraulic Research, for the purpose of developing further detailed knowledge on the complex phenomenon known as local scour.

This report constitutes part of the first year-end report and presents a list of assorted references pertaining directly and some indirectly to local scour, along with short abstracts for each reference. Any list of references for this complex subject could include a generous coverage of related subjects and disciplines. The writers have included some of these references where it was considered that the information contained within related directly to a better understanding of the scour mechanism.

Each reference in this bibliography is identified by a number, author, year of publication, title, followed by an English translation of the title where appropriate, language identified if other than English, name of the periodical or book, volume, serial number where appropriate and page numbers.

The abstracts in most cases are short concise statements meant to be informative. In some instances the writers' opinions are expressed directly in the abstracts but the practice was limited to avoid confusion by the reader. There is no attempt made to unify symbols used by the various authors. Symbols of standard usage in alluvial channel literature are not always defined in the abstract, otherwise symbols are explained where they appear.

The references are arranged in chronological order by year and month according to the date of publication. Where no month is given the references are arranged alphabetically by author's last name within the year published. Where joint authorship is listed, the references are numbered according to the first author.

Indexes to the chronological bibliography have been prepared by authors and by subjects separately. In the author index each name is followed by the reference number and year of publication in parenthesis. The subject index is given by reference number only.


## ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the following individuals for their contribution and direct assistance in the conduct of this study in this first year; to Drs. Yevdjevich, Simons and Cermak for their advice and guidance, and to Mr. Markovic, Dr. Binder and Mr. Yano for their assistance in translation of foreign literature. Appreciation is expressed also to the Library Staff at Colorado State University, the staff of the U.S. Geological Survey at Colorado State University, the U.S. Bureau of Reclamation Technical Library in Denver, the Denver Public Library, the Libraries at the Universities of Colorado, California at Berkeley and Stanford, and the Bureau of Public Roads offices in Washington and Denver, for assistance in acquisition of many references.

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CONTENTS

## CHRONOLOGICAL BIBLIOGRAPHY

## WITH ABSTRACTS

1. Login, Thomas, 1868. On the benefits of irrigation in India and on the proper construction of irrigation canals. Minutes of Proceedings, Inst. Civil Engrs., Vol. XXVII, p. 471.

The political and economic benefits of canals are discussed. With regard to sediment transport and scour, it is stated that the power of water to hold sediment in suspension varies directly with velocity, and inversely with depth. Water in motion rolls rather than slides, and because of this rotating motion, water has the power to hold matter in suspension. At given velocities and depths, only a certain quantity of matter can be held in suspension, whatever may be the character of the bed and banks of the channel. If the velocity can be increased as the depth held constant, scour will take place. Conversely if velocity is decreased as depth held constant deposition would occur. Use of weirs to control canal slopes is also discussed.

2. Login, Thomas, 1869. The abrading and transporting power of water. Indian Roads and Railways, Engrg., Vol. 8, pp. 133-34, Illus., Aug. 27, 1869.

A silt bearing stream is retarded by having to exert a force sufficient to transport certain portions of the total sediment load, hence the energy slope must be greater than that for clear water. Sediment transport increases with velocity but decreases with depth because of the rotating motion of flow.

The author reasons that clear water can move faster than sediment laden water, hence greater scour occurs at relief bridges than at main bridges; and a deeper water way at all bridge sites would reduce scour. He also believes siphon crossings would be more economical than bridges because water velocity could be increased through a siphon and no scour would occur. There is no indication that siphons were even constructed for this reason however.

There is, in this paper, description of the effects of abrading and transporting power of water on roads and railway bridges in North India. In brief, the article states that all silt bearing streams, when in "train," only carry a given portion of sediment depending upon velocity and nature of the tranported material. Increase in velocity requires increase in slope and causes increased scour.

3. Hershel, Clemens, 1878. On the erosion and abrading power of water upon the sides and the bottom of rivers and canals. Franklin Institute Journal, Vol. 105, No. 5, pp. 330-358, Vol. 105, No. 6, pp. 393-403, Vol. 106, No. 1, pp. 26-28. May-July 1878.

General review of literature is presented on knowledge up to that time on the erosion of the bottom and sides of canals and rivers. A history of the engineering problems of the Cape Cod (Mass.) ship canal is presented. Sediment transport theory of Dubuat (1780-84), also that of J. Dupuit, Menard's observations on suspended sediment, Login's theory of wheeling, or rotating motion of water as affecting scour and M. Fargue's ideas on scouring power are reviewed.

4. duBoys, P., 1879. Le Rhone et les riviers a lit affonillable (French) (The Rhone and streams with movable beds.) Annals des Pontes et Chaussees, Ser. 5 Tome (Vol.) XVIII, 1879, pp. 141-195.

The publication introduces the concept of tractive force, or shear force at the bed of a stream. It is assumed that sediment moves in layers and the equation for transport is

$$G = \psi \tau_o (\tau_o - \tau_c) ,$$

where $G$ is rate of sediment movement in pounds per sec. per unit of stream width, $\psi$ is a coefficient dependent on sediment size, $\tau_c$ is critical tractive force and average tractive force is $\bar{\tau}_o = \gamma RS$ .

5. Morison, G. S., 1893. The river piers of the Memphis Bridge. Proc. Inst. Civil Engineers, Vol. CXIV, pp. 289-302, May 1893.

Details and descriptions of the construction of piers II and III of the Memphis bridge are given. The process of pier construction is described in detail and willow mats tied together were used around each pier to protect the bases of the piers from scour.

6. Engels, H., 1894. Schutz der Strompfeilerfundamente gegen Unterspulung. (German) (Protection of the Foundation of Piers Against Underscouring) Zeitschrift fur Bauwesen, 1894, p. 407.

Model experiments were conducted on scour protection of piers. It was proposed that foundations of piers could be protected with riprap or rock fill before scouring occurred. The study indicated that efficient and simple protection could be effected by placing a horseshoe shaped rock fill around the pier with the open end downstream. Triangular and rectangular shaped piers and rock fills were also tested. The laboratory study indicated that the deepest scour occurred at the front or nose of the pier.

7. Kennedy, R. G., 1895. The prevention of silting in irrigation canals. Proceedings of Institution of Civil Engineers, Vol. 119, 1895, pp. 281-290.

Kennedy advanced his theory that the bed width of the channel had no place in the equation connecting the depth $D$ and the mean velocity $V$ . He gives $V = cD^m = 0.84\ D^{0.64}$ in which he calls $V$ the critical velocity being that at which for a given depth $D$ silting is just prevented. The coefficient $c$ and exponent $m$ may vary slightly from one canal system to another but that the variation will be small. Sediment in a flowing canal is kept in suspension solely by the vertical components of the constant eddies, which can always be observed in any stream, boiling up to the surface. It is assumed that the quantity of silt a stream will support will be proportional to the width of the bed, all other conditions remaining the same.

8. Anonymous, 1897. Die Gesetze der Bewegung des Geschiebes (German). (The laws of the motion of debris) Oesterr Monatschr f d Oeffent Baudienst., Feb. 1897.

A brief discussion is presented on the motion of stones and debris in mountainous torrents with investigations as to the erosion and modification of channel profiles. The term erosion is used in a general sense.

9. Flammant, A., 1900. Affouillements qui en sont la conséquence. (French) (Scour around bridge piers as a consequence of the reduction of the section), Hydraulique, Chapter V, Paris, 1900, pp. 281-282.

In this textbook on hydraulics, a brief discussion is presented on the experimental work of Durand-Claye. In the experiments, three shapes of bridge piers were tested: rectangular, semi-circular nose and tail, and triangular nose and tail of the pier. The experiments showed that the rectangular shaped pier caused the deepest scour, and comparatively reduced depth of scour was was noted for the other two shapes. The triangular nose pier caused little or no scour at the nose although scour occurred at the sides. Durand-Claye presented his opinion that a streamlined shaped pier nose would be most efficient based upon his observations of experiments. The author, Flammant, concluded from Durand-Claye's report that a triangular shaped pier nose and a semi-circular tail would be the most effective shape to reduce scour around bridge piers.

10. Spring, F. J. E., 1903. River training and control of the guide bank system. Railway Board, Government of India, New Delhi. Tech. Paper No. 153, 1903.

The author suggests that contraction of rivers with 18 inches of fall per mile or less should be limited to that which will cause an over fall mean scour between abutments of from 8 to 16 ft for bed material consisting predominantly of from very coarse (16 mesh) to very fine sand (100 mesh) respectively.

To calculate scour depth it is suggested that Kutter's or the Mississippi formula for velocity be used to first prepare a chart of velocity versus depth of flow. Estimate the scour and calculate by trial and error a new cross section. Use the deepest point and determine the permissible river contraction. By experience the author states that the deepest scour may be from 20 to 30 percent greater than calculation shows. Use this knowledge and assume another section and recalculate permissible contraction. Establish a guide bank (also commonly called a spur dike in the United States) at each abutment, depending upon location. The spur dike should be 10 percent longer than the length of the bridge.

11. Anonymous, 1906. Silt and scour. Engineer, London, Oct. 19, 1906, pp. 391-2.

The existing theories of silting and scour are discussed briefly and their errors are pointed out. No new theory is presented.

12. Gilbert, G. K., 1914. The transportation of debris by running water. U.S. Geological Survey Prof. Paper No. 86. Washington 1914, 155 p.

The primary purpose of this experimental investigation was to develop the relationships which control the movement of bed load; especially to find how the quantity of load is related to stream slope and discharge and the extent of movement of the debris.

Competent slope limits transportation for a given combination of discharge, width, and grade of debris. For each combination of width, slope and sediment size and distribution, there is a competent discharge. For each combination of width, slope and discharge there is a limiting fineness of debris below which no transport occurs. The ratio of depth to width (form factor) significantly affects the capacity and for a particular value of this ratio transport will be a maximum.

Attempts to measure bed velocity were unsuccessful thus mean velocity was utilized. With variations of width, slope and discharge the capacity varies with some power of velocity.

In general, debris composed of particles of a single size is moved less freely than debris containing particles of many sizes.

Modes of transportation are labeled as:

(1) Movement of particles; slide, roll, skip, leap (saltation)

(2) Collective movement

(a) Small bed load--ripples and dunes

(b) With increased bed load--plane bed

(c) Further increase--antidunes.

The energy of the stream is measured by the product of total discharge, slope and gravitational acceleration. Sediment load affects energy is three ways:

(1) it adds to the mass of water increasing the stock of energy

(2) its transport involves work at the expense of stream energy

(3) its presence restricts the mobility of water, in effect increasing its viscosity and thus consuming energy.

As a result the sediment load reduces the turbulent velocity of the stream.

The level of maximum velocity may have any position in the upper three-fourths of the flow depth. In sediment laden streams its position is higher as the load increases.

13. Soldan, 1918. Uber die Berechnung des Brückenstaues (German) (Computation of backwater at bridges) Zentralblatt der Bauverwaltung, 1918, p. 422.

Calculation of backwater due to piers is discussed.

14. Lane, E. W., 1919. Experiments on the flow of water through contractions in an open channel. Am. Soc. of Civil Engrs. Proceedings, Vol. XLV, pp. 715-774.

The theory of flow through contractions is developed from consideration of the continuity equation and discharge formulae of Weisbach and D'Aubuisson. A general discharge formula is presented for contraction of short length with free expansion. The experiments are used to prove the general discharge formulae already developed Also noted in the experiments is the unstableness of the discharge jet downstream from the contraction as the jet swings from one side of the channel to the other.

15. Lindley, E. S., 1919. Regime channels Proceedings, Punjab Eng. Congress, Vol. 7, 1919, pp. 63-74.

Kennedy's study of regime canals is reviewed. Using the same data, two equations for velocity are given

$$V = 0.95\ D^{0.57}, \quad \text{and} \quad V = 0.57\ B^{0.355},$$

from which

$$B = 3.8\ D^{1.61}$$

The variation in exponent and coefficient from Kennedy's equation exists because there is some latitude in velocity between incipient deposition and incipient scour. If two canals carry the same discharge but different sediment charge then the greater silt bearing canal will adopt a wider and shallower cross-section and the slope would be steeper. Some typical channel dimensions are presented in the appendix.

16. Rehbock, Th., 1919. Zür Frage des Bruckenstaues, (German) (On the question of backwater at bridges) Zentralblatt der Bauverwaltung, 1919, p. 197.

Analysis of the backwater problem leads to the following equation for computing the afflux at a bridge crossing due to piers:

$$z = \beta\,\alpha\,k_o$$

where

$z$ = afflux
$\beta$ = pier shape coefficient
$\alpha$ = channel contraction ratio
$k_o$ = velocity head downstream from the pier.

For bridge piers of slender form the backwater may be computed with sufficient accuracy by assuming $\beta = 1.0$. For bridge piers with blunt leading edges the stagnation height at the pier may be about doubled or, $\beta = 2.1$.

17. Krey, Hans, 1923. Der Widerstand von Einbauten in Flussen und anderen offenen Gerinnen auf das stromende Wasser. (German) (The resistance to the flow of water of structures built in levees and other open channels). Bautechnik, 1923, p. 415.

A resistance equation is derived for an obstruction in an open channel. The equation is derived on the basis of impulse using the difference in pressures and water surface levels upstream and downstream of the obstruction. The result is for computation of hydraulic characteristics only, and no attempt is made to relate resistance to scour.

18. Holmquist, F. N., 1925. Behavior of debris carrying rivers in flood. Engineering News-Record, Vol. 94, 1925, pp. 362-365.

The author's theory is that wide, steep rivers at flood stage, excavate a deep channel over only a portion of their width, depositing the excavated material in the shallower parts of the channel a short distance downstream. He believes that a deep channel tends to approach the outside of the bends; thus the material may cross from one side of the river channel to the other. The constant shift of the channel position is believed to result from side erosion.

19. Soorovzef, V., 1926. To the question of the calculation of scour and silt movement. Translated by the U.S. Bureau of Reclamation, Denver, from Russian. Irrigation News Bulletin (Russian), No. 11, Nov. 1926, pp. 43-45.

General scour rather than local scour is the subject of discussion. However, it may be of interest to note the method of determining scour and deposition. It is assumed that scour is a function of velocity alone. Actual field measurements are made of changes in river cross section in a uniform reach during varying stages and discharge to determine the scour or deposition at the section. An average value of scour or deposition is calculated for the cross section, hence a relationship between measured mean velocity and average scour is established. The method and results apply only to the specific section and only within the range of flows studied. It does not apply for determination of scour depths in general. The actual analysis involves volumes rather than depth at the cross section. However since the author assumes a uniform section, the results are the same in his analysis. The theory of errors applied to the data is utilized in establishing the final relationship of scour depth to velocity.

20. Fortier, S. and Scobey, F. C., 1926. Permissible canal velocities. Transactions, Am. Soc. of Civil Engrs., Vol. 89, 1926, pp. 940-984.

The authors state that there is a broad range of velocities between the velocities that can no longer maintain silt in motion and those that will scour a canal bed. A higher velocity is required to start scour than to continue it once it is started. The nature of the silt carried by the water affects erosion, as some fine silts penetrate and solidifies canal beds while coarse silts tend to start erosion. Silting and scouring involve two fundamentally different processes. In one case the force opposing is gravity, in the other it is cohesion or friction. Scour depends on the pressure which the water is able to effect on the particles, on the size and weight of the particles, on the surface exposed to the water action and on the tenacity with which one particle clings to another. Smoothness or roundness or the grain will dimish the pressure but will also decrease the tenacity. A mixture of various sizes will diminish the area on which the water can bear and thus decrease scour.

21. Griffith, William Maurice, 1927. A theory of silt and scour. Minutes of Proceedings, Instn. of Civil Engrs. Vol. 223, 1926-1927, pt. 1, pp. 243-314.

The silt transporting power of a stream varies with the vertical velocity distribution since the difference in velocities of horizontal filaments in the flow creates vertical eddies, instrumental in suspending the sediment, and the change in velocity gradient is clearly a function of both depth and mean or average velocity. R. G. Kennedy's relationship $V = cD^m$, ($V$ - regime velocity, $c$ = a coefficient varying from 0.84 to 1.09 depending upon the quantity and character of the silt being transported, $m = 0.64$), which was developed from data taken from canals, is applied to rivers to explain scour and deposition. From Kennedy's equation to the Chezy equation a line of reasoning is established to show that if $m$ is less than 0.5, the river would tend to be deep and narrow and if $m$ is greater than 0.5, the opposite would be true. At river contractions, the local water surface slope increases with flood because of the afflux created at the contraction, the velocity will increase, hence $D$ must increase as depth is proportional to velocity in the Kennedy equation, thus local scour occurs. The process of degradation at contractions is also discussed from the Kennedy formula. Pier foundations must obviously be set below the degradation level at the contraction, also noting that there is additional local scour to be expected around the piers due to change in direction of flow at the piers. No method is given for calculating the local scour around piers. It is also mentioned that skewed flow can cause greater scour than normal flow.

22. Schmidt, 1927. Einsturz des Widerlagers der Allnerbrücke bei Siegburg. (German) (Failure of the abutment of the Allner Bridge at Siegburg) Bauingenieur, 1927, p. 605.

A description of the abutment failure and consequent loss of the Allner Bridge is given. No significant data are contributed and no new theory is advanced on causes for abutment failure.

23. Gostev, A., 1928. On scouring velocities. A translation from Russia by the U.S. Bureau of Reclamation. Irrigation News Bulletin (Russian) No. 1, January 1928, pp. 65-69.

The paper is directed towards determining the velocity at which movement of the bed particles (scour) begins by considering the resistance against movement and the forces which cause movement. An equation is developed to determine the velocity as a function of Chezy C and sediment diameter assuming uniform resistance in a cross section. Recognition is given to the fact that in the practical case the resistance across a river bed is not uniform but since it is not possible to determine the variation in resistance at a cross section, it would be treated with an average value.

24. Bottomley, W. T., 1928. New theory of silt and scour. Engineering, Vol. 125, No. 3244, March 16, 1928, p. 307-8.

Silt is lifted from the stream bed by eddies and vortices created at the bed. Silt-supporting force is dependent upon the number and strength of the vortices and therefore, it depends on the frictional resistance or roughness of the bed. Frictional resistance can be determined from the hydraulic gradient and hence silt transport is related to the hydraulic gradient. For streams to establish regime, their gradients must be uniform and equal to the prevailing slope of the country. An equation is developed for relating bed roughness to velocity, depth and fluid density. The writer discusses the various theories of Kennedy, Griffith and Wood. Whether silting or scour will occur depends on whether the percentage of silt carried by the flow is greater or less than that which it can sustain due to the gradient.

25. Engeln, Oscar Diedrich von, 1929. Falling Water. Sci. Monthly, Vol. 28, pp. 422-429. Illus. May 1929.

The discussion is confined to erosive action of falling water (water falls) on rock.

26. Engels, H., 1929. Experiments pertaining to the protection of bridge piers against undermining. Hydraulic Laboratory Practice, Chapter V. Edited by John R. Freeman, Am. Soc. of Mech. Engrs., New York, 1929.

Studies conducted in 1893 on pier scour are summarized. The most significant result of that study was to show that where formerly it was anticipated that maximum scour occurred at the downstream end of the pier, it was observed that maximum scour occurred at the upstream nose. Some investigation was made towards pier protection with the conclusion that rip rap placed at the base of the pier from the nose around both sides of the pier would provide adequate protection. Sizes and thickness of rip rap, for varying geometry and flow characteristics were not delineated.

27. Lacey, Gerald, 1929. Stable channels in alluvium Minutes of Proceedings, Instn. of Civil Engrs. Vol. 229, pt. 1, pp. 259-384.

For given discharge and silt factor, the Lindley theorem is correct, that is, the cross-sectional area, wetted perimeter and slope of a stable channel are uniquely determined. The wetted perimeter of a stable channel varies as the square root of the discharge and is independent of the type of silt transported. All stable channels of the same discharge have the same wetted perimeter and the silt factor determines the shape. The minimum stable width of active waterways of large alluvial rivers in flood varies approximately as the square root of the discharge and is virtually independent of the silt factor.

The maximum depth of scour below water surface at bridge sites and other constricted areas can be calculated from:

$$D_{max} = C R$$

where C depends upon the cross section of the river at the bridge and may vary from 1 to 2.

R is the hydraulic radius of the section.

28. Rehbock, T. H., 1929. Transformations wrought in stream beds by bridge piers of various shapes of cross section and experiments on the scouring action of the circular piers of a skew railroad bridge across the Wiesent River for the Nüremberg Railroad (1921). Hydraulic Laboratory Practice, edited by John R. Freeman. Am. Soc. of Mech. Engrs., New York, 1929.

Models of circular, square, rectangular and pointed arch-nosed piers constructed of wood to a scale of 1:100 were tested in the laboratory in an alluvial flume. It was ascertained from the tests that the greatest scour in a stream bed takes place upstream of the pier nose and was attributed to the cross-currents generated there. It was found that the amount of scour (hence depth of scour) depended upon the velocity of flow, materials composing the bed, shape of the pier and duration of a flood. The studies were conducted in the years of 1920-21.

29. Robertson, James, 1929. Bridge repair and strengthening work in Lanarkshire. Surveyor, V. 75, No. 1953, June 28, 1929, p. 648.

To prevent scouring action on foundations of existing bridge piers, many of which are comparatively shallow, deeper foundation by underpinning, together with construction of masonry or concrete training walls or by sheet piling alongside the river banks both upstream and downstream of the bridge section may be adopted. The training walls serve to confine the water to mid channel. Paved aprons between bridge piers may be used, provided that the elevation relative to the stream bed is not too shallow. Placement of the apron too high could cause erosion and undercutting at the downstream end, and eventually cause failure.

30. Schwartz, K., 1929. Comparative experiments on the influence of the size of particles of a river bottom on the depth of excavation occurring in the vicinity of bridge piers. Hydraulic Laboratory Practice, edited by J. R. Freeman, 1929, p. 201.

Experiments conducted from December 1924 to July 1925 are described. Pier models at a scale of 1:100 were placed in a flume 0.5 m wide. Models of 2 piers with pointed ends having a length of 20 m and width of 4 m were placed symmetrically in the flume. Model discharge of 10 litres per second at a depth of 0.05 m were used. Three sizes of sand were used successively, varying from about 0.2 mm to about 0.5 mm. The scour rates were measured beginning with a level bed. The initial scour rates varied for the different sand sizes, but the maximum scour depth was observed to be about the same; hence it was concluded that maximum scour depth was independent of sediment size. Sediment was not recirculated in these tests.

31. Timonoff, V. E., 1929. Experiments on the spacing of bridge piers in the case of parallel bridges. Hydraulic Laboratory Practices, Chapter X, edited by John R. Freeman. Am. Soc. of Mech. Engrs., New York, 1929, p. 359-361.

Studies conducted in 1911 in the hydraulic laboratory in Leningrad are described. The flume used was 29 m wide. The sand bed was 25 cm thick. Each test was continued to establish maximum scour depth. The experiments showed that the upstream ends of the piers play the most important part in scour. The shape of the downstream ends has little effect on the scour action. New bridge piers in the case of parallel bridges should be in the immediate proximity of the old piers along the same axes. If the old bridge is safe, build the new bridge downstream and if the old is considered unsafe the new bridge should be constructed upstream.

32. Rehbock, Th., 1930. The prevention of harmful erosion in the beds of sluices and weirs. Translated from Der Bauingenieur, 1928. "Flussbaulaboratorium," of the "Technische Hochschale." Karlsruhue.

This article describes the reduction of erosion of the channel beds at sluices and weirs by the use of dentated sills at the ends of the aprons, according to the research of Dr. Leuscher in Switzerland, and experiments at Karlsruhue. Effective action of the dentated sills is also attained when the water stream on the apron has a shooting character. The level of the apron necessary to create a hydraulic jump can be calculated in the usual manner.

33. Yarnell, D. L. and Nagler, F. A., 1931. A report upon a hydraulic investigation of North Carolina standard reinforced concrete bridge pier number P-401-R and modifications thereof. Iowa Institute of Hydraulic Research University of Iowa, Iowa City, December 1931.

Hydraulic experiments were conducted on a standard North Carolina bridge design. Tests included observation of flow pattern and eddies around the pier and resulting scour at the base. The theory of obstruction caused by bridge piers is explained, with description of pier models and test procedures. The investigation also included a study of different pier shapes on the basis of hydraulic efficiency. The most efficient shape of pier it was concluded, was a lense shaped nose with straight sides and a semi-arc tail.

34. Butcher, A. D. B. and Atkinson, J. D., 1932. The causes and prevention of bed erosion, with special reference to the protection of structures controlling rivers and canals. Minutes of Proceedings, Inst. of Civil Engrs., Vol. 235, 1932-33, p. 175-222.

Models were used to simulate flow and scour conditions at regulating structures and results are compared to prototype. In both prototype and model a negative vortex, i.e., a reverse current at the surface, was observed to be invariably associated with scour, while a positive vortex tended to pile up bed material against the the regulating works. Hence the obvious method to prevent scour is to prevent negative vortices.

35. Keutner, Chr., 1932. Stromungsvorgänge an Strompfeilorn von verschiedenen Grundriss formen und ihre Einwirkung aur die Flussohle. (German) (The flow around bridge piers of different shapes and its effect on the river bed). Die Bautechnik, Vol. 10, No. 12, March 15, 1932 (Translated from the German by E. F. Wilsey, April 22, 1937. U.S. Bureau of Reclamation report HYD-19, Translation No. 40.)

Keutner conducted experiments in a flume 0.6 m. wide, and with sand bed thickness and flow depth of about 8 in. The model pier was 0.4 ft thick. Discharge and depth were maintained constant while two time units of 150 and 480 minutes were used. The experiments were qualitative and results were compared relatively.

It was observed that greatest scour occurred at the front of the pier. Water surface profiles were taken along the centerline of the pier, and along the surface of the pier and transverse to the pier. Scour depth was measured as a function of the angle which the shape of the nose prescribed with the centerline of the pier, and it was found that scour was greatest for a semicircular nose. As observed by Engel, shape of the end of the pier had no influence on the depth and extent of scour. Skew piers from 5 to 27 degrees were studied and found that scour at both upstream and downstream ends of the piers were affected at 27° skew. Scour depth was twice that for 0° skew. The area of scour increased with increased skew. A fish shaped pier was found to produce about 30 percent less scour with normal flow. It was concluded that the transverse water surface slope from the piers created rollers about a horizontal axis which caused scour and further that the transverse slopes depended upon the shape of the pier nose.

36. Ho, Chitty, 1933. Determination of bottom velocity necessary to start erosion in sand. Ph.D. Thesis, University of Iowa, Iowa City, June, 1933.

Various theories of transportation by suspension are discussed: (1) relative velocity, (2) rolling, (3) continuous upward flow, (4) vortex and eddy, and (5) turbulence. Also two theories of transportation by traction are mentioned: (a) bottom velocity and (b) slope-depth (tractive force). Experimentation at Iowa University and analysis of results yielded equations for critical bottom velocities: (i) $V_{0.05} = 3.85\,\partial^{0.48}$ where $V_{0.05}$ = velocity at 0.05 ft above the bed and $\partial$ = size of bed materials. (ii) $V_{0.025} = 2.83\,\partial^{0.42}$ and (iii) $V_{0.00} = 2.07\,\partial^{0.35}$. The critical mean velocity was a function of bed material size and depth of flow. For uniform channel, critical mean velocity was $V_m = 5.1\,\partial^{0.494}\,y^{0.129}$ where $y$ = depth of flow and for non-uniform channels, the critical mean velocity was $V_m = 3.9\,\partial^{0.467}\,y^{0.215}$. It is believed that the bottom velocity determines the stability of river channels and it is bottom velocity rather than mean velocity that training and regulating works should be designed to control.

In order to perform successful model studies the following condition should be maintained:

$$\frac{V_B = K\sqrt{2g\,\partial\,(s_p-1)}}{v_B = k\sqrt{2g\,\partial_m(s_p-1)}}$$

where capital letters are for prototype and lower case letters for model. $V_B$ and $v_B$ are bottom velocities and K and k are constants depending upon the shape of the particles of the bed material.

37. Hendrickson, B. H., 1934. The choking of pore space in the soil and its relation to runoff and erosion. Trans. Am. Geo. Union, Section of Hydrology, 1934, p. 500.

This article is concerned with raindrop and general surface erosion rather than local scour. The purpose of the paper is to discuss the process by which raindrop impact with the earth with the earth suspends fine material in the flow which tends to clog pore spaces in the soil and hence, increase runoff. Experiments were conducted as proof.

38. Kessler, Lewis Hanford, 1934. Experimental investigation of the hydraulics of drop inlets and spillways for erosion control structures. Bulletin of the Univ. of Wisc. Engrg. Exp. Sta., Series No. 30, pp. 1-66.

This bulletin presents the results of an analysis of hydraulic characteristics of certain types of concrete conduits, flumes and spillways and with earth fill, soil saving dams for erosion control. Square inlets, square and round pipes, and stilling basins are discussed. Erosion control here means control of gullying.

39. Kramer, H., 1934. The practical application of the duBoys tractive forces theory. Trans. Am. Geo. Union, part II, 1934, pp. 463-466.

The use of duBoys equation $\tau_o = \gamma$ DS is discussed in reference to determination of $\tau_o$, the shear force from size analysis of the bed material. From 24 sets of data of different bed material from many experimenters, it is determined that $\tau_o = \frac{100}{6}\,\frac{\partial}{M}\,(\gamma_1-\gamma)$ where $\tau_o$ = critical, tractive force in gm/m², $\partial$ - grain diam. in mm $\gamma_1-\gamma$ = effective density and M is the modulus of uniformity, or measure of the variation of sizes from average. The equation is reduced to $\tau_o = 27.5\,\frac{\partial}{M}$ in the metric system or $\tau_o = \frac{1}{7}\,\frac{\partial}{M}$ in English units. This method is developed to determine beginning of motion but not depth or extent of local scour.

40. Lacey, G., 1934. Uniform flow in alluvial rivers and canals. Minutes of Proceedings, Inst. of Civil Engrs., Vol. 237, 1933-34, pt. 1, pp. 421-453.

In a previous paper (Ref. 27) the author advanced a theory of silt transport based on hydraulic observations on irrigation canals in India intended for design engineers. In this paper there is a collection of observations from rivers and canals and a more rigorous analysis is developed on a general theory of flow applicable to channels flowing uniformly in incoherent alluvium.

In all regime channels in incoherent alluvium of the same grade, $V \propto \sqrt{D}$ , $S \propto \frac{1}{\sqrt{D}}$ or $S \propto \frac{1}{V}$ , $V = K\,R^{3/4}\,S^{1/2}$ where $V$ = velocity, $D$ is depth, $S$ is slope, $K$ is a constant and $R$ is hydraulic radius. Also, $V = f(R^2S)^{1/3}$ irrespective of silt grade, and the criteria for similarity in channels is an absence of distortion in the developed wetted surface.

41. Ramser, C. E., 1934. Dynamics of erosion in controlled channels. Trans. Am. Geo. Union, 1934 Sec. of Hydrology, p. 488.

Kennedy's equation is erroneously applied to ditches and gullies. The ditches in question are small steep-sloped ditches resulting from land erosion and gullying, which are not in regime. The discussion proceeds to Chezy's formula and concludes that it is in reality an involvement of many factors that must affect the dynamics of the erosion process. Mechanics of sediment movement is not actually developed or discussed.

42. Straub, L. G., 1934. Effect of channel contraction works upon regimes of movable bed streams. Trans. Am. Geo. Union, pt. II, pp. 454-463.

The general transport theory proposed by the author is reviewed, where the theory was developed some years previously. In brief, the general transport equation is

$$G = \psi \frac{s^{1.4}}{C^{1.2}} Q^{3/5}\ Q^{3/5} - Q_c^{\,3/5} ,$$

where $G$ - quantity of sediment transported along stream bed in pounds per unit width of channel $Q$ - discharge per unit width, $Q_c$ - discharge at which transport begins, $s$ - stream slope, $C$ - roughness coefficient, $V = C\,R^{2/3}\,s^{1/2}$ , $R$ - hydraulic radius, $\psi$ - sediment characteristics, an exponential coefficient depending upon size, specific gravity and mechanical composition of the sediment. The transport equation together with a relationship of depth at a contraction provides for the condition of equilibrium in a contraction where scour depth will reach a maximum. The development assumes general scour across the width and length of contraction and presumes the transport equation to hold for the particular geometric condition.

43. Yarnell, David L., 1934. Bridge piers as channel obstructions. U.S. Dept. of Agriculture, Division of Drainage and Soil Erosion Control, Bureau of Agricultural Engineering Tech. Bull. No. 442, Nov. 1934.

The paper describes studies conducted at the University of Iowa Hydraulics Laboratory. The study was confined to rigid boundary hydraulics and principally to determination of the most reliable backwater formulas to use among those existing and used in practice at that time. The formulas of D'Aubuisson, Weisbach, Nagler and Rehbock are compared with test data collected from the study and it is concluded that none of the formulas are applicable for the entire range of flows from low to high velocities. This observation however, is limited to fixed boundary conditions. Yarnell observed that the height of backwater due to bridge piers varied directly as the depth of the unobstructed channel and increasing the length of the pier had better effect on hydraulic efficiency. A new formula for backwater is not proposed but a discussion of some basic principles involved in the hydraulics of bridge piers are discussed. This discussion does not, however, include local scour.

44. O'Brien, M. P. and Rindlaub, B. D., 1934. The transportation of bed load by streams, Trans. Am. Geo. Union, 15th Annual Meeting. (Reprint)

The paper is a result of a critical survey of available data made to determine whether a quantitative prediction of bed movement is possible. Theory of duBoys which relates bed movement to tractive force is discussed, also that of Strickler. Data of Engels, Kramer, Gilbert and MacDougall are used in the analysis. It is concluded that none of the existing equations for critical tractive force or rate of bed load movement is sufficiently reliable for design. Theory of Krey and Schoklitsch appear most satisfactory, and need for new transport equation is expressed.

45. Lane, E. W. and Bingham, W. F. Protection against scour below overfall dams. Engrg. News-Record. March 14, 1935, pp. 373-378.

Four general conditions of hydraulic jumps determine the form of spillway and type of apron required to protect the river bottom against scour. Need for model study is emphasized and the possibilities for savings in construction costs therefrom are indicated.

46. Bartrum, J. A., 1935. Erosion at Arapuni. New Zealand Journ. Sci. and Technology. Vol. 17, No. 1, pp. 391-397, July, 1935.

The reference is one related more to the geomorphological viewpoint of erosion, and is concerned with formation of pot holes, sinks, notching and slotting of rocks and wave-out benches on the shores of Lake Arapuni.

47. Bouyoucos, G. J., 1935. The clay ratio as a criterion of susceptibility of soils to erosion. Am. Soc. Agron. Journal, V. 27, pp. 738-41.

The suggestion is made that an index designated as the clay ratio $(\frac{\text{sand + silt}}{\text{clay}})$ in soils as a possible criterion for judging the relative susceptibility of soils to erosion. Such criterion may apply to land erosion but it would seem unadaptable to the local scour in river beds.

48. Hjulstrom, Filip, 1935. Studies of the morphological activity of rivers as illustrated by the river Fyris. Uppsala Univ. Geol. Instn. Bull, Vol. 25, pp. 221-528, Sweden, 1935.

The investigation bears upon a determination of the ratio of mechanical and chemical denudation within the Fyris river basin north of Uppsala in central Sweden. Chapter 2 gives an account of the theories on the influence of the hydrodynamic upthrust and the "Austauch" process. The knowledge in meteorology on turbulence is applied to water in a river channel. Chapter 3 discusses some problems of erosion (general), transport and deposition. From previous and recent investigations a new relationship is developed for erosive velocity as influenced by depth of flow. Erosion of rock, and erosion through cavitation are discussed as well as transportation of different materials over stream beds, in terms of dunes, ripples and capacities. The problem of stability is applied to motion of bed load.

49. Schoklitsch, A., 1935. Kolkabwehr und Stauraumver-landung. (German) (Prevention of scour and energy dissipation). Berlin, Julius Springer, pp. 17-183. Translation from the German by Edward F. Wilsey, U.S. Bureau of Reclamation, Denver, 1937, 86 p.

This is a treatise on hydraulic jump below dams and sluice gates and equations are developed to determine conjugate depths. Design of stilling basins of various kinds are discussed which depend upon condition of overfall or shooting flow. Depths of scour for various apron designs are given graphically but no formula for their estimation is given.

50. Inglis, C. C. and Joglekar, D. V., 1936. Investigations carried out by means of models at the Khadakwasha Hydrodynamics Research Station near Poona in connection with the protection of the Hardinge Bridge which spans the river Ganges near Paksey, East Bengal Railway, Public Works Department; Bombay, India, 1936, Tech. Paper No. 55.

Same information published in the Central Irrigation and Hydrodynamics Research Station reports. See reference Nos. 59, 65, 75, 76.

51. Khosla, Rai, Bahadur, A. N., Bose, N. K., and Taylor, E. M., 1936. Design of weirs on permeable foundations. Central Board of Irrigation, India. Publication No. 12, Simla, September 1936, p. 131.

This article assumes that depth of local scour is proportional to regime depth, and the constant of proportionality is strictly a function of the geometry of the obstruction. Lacey's equation for regime depth is used which includes a silt factor. No figures are given for computing depth of local scour for specific cases.

52. Shields, A., 1936. Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. (German) (Applications of similarity principles and turbulence research to bed load movement.) Mitteilungen der Preussischen Versuchanstalt fur Wasserbau und Schiffbau. Berlin, Heft 26, 1936. Translation of the German Paper on file in the Engineering Societies Library. 16 p., 1936.

Experiments with bed movement and tractive force are described in which several different lightweight particles are used. A correlation of moveable bed models to prototype is attempted. The relationship of the effective force of water parallel to the bed, to the resistance of a layer of grains is a universal function of the ratio of grain size to the thickness of the laminar boundary layer. It is concluded that the kinematic viscosity of the flowing fluid $\nu$, in the term $\frac{V_* d}{\nu}$ is the principal factor in the formation of ripples. The following expression for the coefficient of the critical tractive force is expressed:

$$\frac{\tau_o}{(\gamma_1 - \gamma)} = f\left(\frac{V_* d}{\nu}\right)$$

where $V_* = \sqrt{g\ RS}$ and $f\left(\frac{V_* d}{\nu}\right)$ is a function which can be described graphically.

53. Terzaghi, Karl V., 1936. Failure of bridge piers due to scour. Int. Conf. in Soil Mech. and Found. Engrg. Proc., Vol. 2, 1936, p. 264.

From very limited data, the author arrives at the conclusion that in soils with little or no cohesion, the depth of scour is likely to assume values of 3 or 4 times the rise of the water level in the stream.

54. Wright, Chilton A., 1936. Experimental study of the scour of a sandy river bed by clear and by muddy water. Journ. of Research of the Nat. Bureau of Stds. Vol. 17, No. 2, Aug. 1936, pp. 193-206.

An experimental comparison was made of the scour produced in a bed of fine sand in a sloping flume by muddy water and by clear water in attempted simulation of the conditions existing in the Colorado River at Boulder Dam before and after construction. Critical velocities of water were determined for incipient movement of the sand bed in the form of ripples and were found to be greater for muddy water, that is, water containing an appreciable amount of clay in suspension, than for clear water. With the muddy water an increase of about 10 percent on mean velocity was necessary to scour out the same amount of Colorado sand as was scoured by clear water under otherwise similar conditions. For coarser sands the increase in velocity was greater. It was concluded that when clear water is discharged at the Boulder Dam it will cause greater scouring away of the sand bed than did the muddy water under previous conditions.

55. Rubey, W. W., 1937. The force required to move particles on a stream bed. U.S. Geological Survey Professional Paper 189-E, U.S. Department of the Interior, 1937.

Based on Gilbert's experiments the author finds that the data tends to substantiate the "sixth-power law" for coarse sand and gravel, but for fine particles the law of critical tractive force holds. When particles are relatively small compared to the thickness of the laminar flow the force of the current is less efficient so that "bed" velocities higher than those indicated by the "sixth-power law" are required to start movement; when the particle radii are from 1 to 13 times as great as the thickness of the laminar film, the current is considerably more effective; and when the particles are relatively large compared with the thickness of the laminar film the current is of intermediate efficiency. The sixth-power law measures only the size of the larger particles moved and has nothing to do with the total load or amount of debris moved.

56. Schulits, S., and Corfitzen, W. E., 1937. Bed-load transportation and the stable channel problems. Trans. Am. Geo. Union. 18th Annual Meeting 1937, p. 457-467.

A general review of the formulas for computing bed load and tractive force in use at the time is presented.

57. Tison, L. J., 1937. Affouillement autour des piles de ponts en riviere. (French) (The washing out round bridge piers in rivers). Academie Royale de Belgique, Bulletin de la Classe des Sciences, 5 e Série XXIII, 1937.

It is shown from the equation

$$y_B + \frac{p_B}{\gamma} - \left(y_A + \frac{p_A}{\gamma}\right) = \frac{1}{g}\int_A^B \frac{v^2}{\rho}\, ds$$

(h = elevation, p = pressure, $\gamma$ specific weight, v = local velocity, $\rho$ radius of curvature of streamline, ds = length element taken along a curve orthogonal to the streamline) that the velocity has a downward component which increases with the curvature of the streamlines and the non-uniformity of the velocity distribution in the vertical direction. These conclusions are verified by model studies on piers of various shapes (lens shaped) and with beds of two different roughnesses to change the velocity distribution.

58. Burns, R. V., and White, C. M., 1938. The protection of dams, weirs and sluice gates against scour. Institution of Civil Engrs., London Journal, Vol. 1, Nov. 1938. pp. 23-46.

Various model experiments of scour below dams are discussed as well as various methods tried with end sills to prevent scour. Modelling techniques and fundamental hydraulics are discussed. Graphical plots of scour depth created by particular end sills are shown as a variable with tail water depths.

59. Gales, R., 1938. Principles of river training for railway bridges and their application to the case of the Hardinge Bridge over the lower Ganges at Sara. Journ. of the Instn. of Civil Engrs., December 1938, Paper No. 5167.

Method of river training consists of making use of the river section at a bend and during floods to assess the extent to which the bridge section can be allowed to develop. The principle centers on the assumption that a river in flood creates conditions at river beds not totally unlike conditions which are created at bridge constrictions. By observing the river sections during floods, some guidance can be established for expected river behavior at bridge sections. Some general recommendations are given regarding computation of scour depth at heads of guide banks, and length of bends relative to bridge lengths.

60. Inglis, C. C., 1938. The use of models for elucidating flow problems based on experience gained in carrying out model experiments at the hydrodynamic research station, Poona. National Institute of Science, India, Proceedings, Vol. 4, No. 4, pp. 419-439.

Model studies conducted at Poona for the clarification of flow problems are described and discussed. Regime models in which the conditions of flow are maintained constant with complete freedom as regards silting and scour is also included.

61. Ishihara, T., 1938. Experimental study of scour at bridge piers. (Japanese) Trans. Japanese Soc. of Civil Engrs., Vol. 24, No. 1, pp. 28-55, 1938.

The difficulty and lack of conformity between model and prototype of alluvial channels are recognized. Because of the "imperfections" in the law of similarity no accurate conclusions for the prototype is to be obtained from the results discussed in this paper. The stability of a river bed is discussed to some detail, (including review of previous significant literature) primarily from two viewpoints: (1) on the impulse theory of velocity near the bed and (2) on the tractive force theory. Effect of pier shape on scour was studied experimentally, and it is proposed that a pier with a sharp nose and tail is best with regards to minimum scour and backwater. It was concluded that scour depth at the pier front is a function of its shape and is independent of the length of the pier and the downstream shape.

62. Schmitt, E. E., 1938. To eliminate pier scour. Engrg. News-Record, Vol. 120, No. 26, June 30, 1938, p. 894.

This article appears as an editiorial. Apparently some time in 1938 the Milwaukee Olympian (train) was wrecked on the Custer Creek bridge with tragic loss of life. It is the editor's opinion that the high speed traffic of these times requires more consideration to safety. Scour of piers was considered to be the reason for the bridge failure. No detailed technical data are given.

63. Chang, Y. L., 1939. Laboratory investigations of flume traction and transportation. Trans. Am. Soc. of Civil Engineers, Vol. 104, 1939, p. 1246.

The investigations are divided into three parts: (1) tractive force required for incipient movement of the bed particles, (2) tractive force applied to transportation, and (3) suspended sediment transport. Tractive force on the bed of an alluvial channel of infinite width and uniform flow may be expressed as $\tau_o = \gamma DS$ . If the width is finite but the channel irregular, then $\tau_o = \gamma SR$ and for non-uniform flow, $\tau_o = \frac{\gamma S}{2}\left(y + \frac{2V^2}{g}\right)$. Critical tractive force is given as $\tau_c = C\left[(S-1)\delta o^{1/3}\right]^{\beta}$. In these formulae, $\tau_o$ = bed shear,

$\tau_c$ = critical shear for movement, D is uniform flow depth, S = slope of bed, R = hydraulic radius, $\gamma$ = unit weight of water, y = variable flow depth, V = average velocity, g = gravitational acceleration, $\partial$ = mean sediment diameter, C = constant, s = specific gravity of the sand particle, O = ratio of longest to smallest diameter of particle, $\beta$ = experimental exponent.

From experimentation an equation similar to du Boys (reference 4) was found to fit the data best: $G = \frac{C_1 n}{\tau_c^2} \tau_o(\tau_o - \tau_c)$, G = transport rate, $C_1$ = constant, n = Manning's roughness. It is also concluded that the force required to lift a particle from the bottom of a stream is about 40 percent greater than that required to keep the particle in motion.

64. Dewey, H. G., Jr., 1939. An analytical and experimental analysis of energy dissipation and scour prevention. U.S. Bureau of Reclamation, Hydraulic Lab Report No. 54., Denver.

A study was conducted to check structure No. 4 in the Sunnyside Main Canal. Models were used to determine the protection necessary downstream of the stilling basin to prevent excessive scour.

65. Inglis, C. C., Thomas, A. R., and Joglekar, D. V., 1939. The protection of bridge piers against scour. Annual Report of Work Done During 1938-39. Central Irrigation and Hydrodynamics Research Station, Poona, Research Publication No. 2.

This article reports results of model experiments on the Hardinge Bridge piers. Geometrically similar scales were used to model bridge piers. Scales of 1:40, 1:65, 1:105, 1:210 were used with various discharges. It is recognized that scour was deepest at the nose of the pier, and reasoned that the secondary circulation of flow at the nose of the pier caused the cup-shaped scour holes. Data for scour depths are given. Tests were made with the sand bed level initially in all cases. The smallest discharge was first tested, then larger discharges successively without relevelling the bed. No sediment was recirculated. The various models gave similar scour depths with the same bed material size. From these studies it was concluded that scour depth could be calculated from

$$\frac{D_s}{b} = 1.70 \left(\frac{q_c^{2/3}}{b}\right)^{0.78}$$

where $D_s$ - scour depth, b - width of the pier, $q_c$ - discharge per ft upstream of the pier.

66. Rouse, H., 1939. Experiments on the mechanics of sediment suspension. Proceedings. Int. Congr. Appl. Mech. Cambridge Man., 5th Congress, pp. 550-554.

An equation is developed for the relative concentration of sediment at any point above some arbitrary reference level. Experimental data are collected to prove the equation and to satisfy a proportionality factor. In form the equation appears as:

$$\ln \frac{c}{c_a} = - \frac{w}{c'} \int_a^y \frac{dy}{v'\ell}$$

where c - concentration at level y , $c_a$ = line at level a , w = settling velocity, c' = a proportionality factor, v' = mean absolute magnitude of transverse velocity fluctuations $\ell$ = mixing length.

67. Rouse, H., 1939. An analysis of sediment transportation in the light of fluid turbulence. U.S. Dept. of Agr., Soil Cons. Serv. SCS-TP-25, 1939. (Mimeographed).

Analysis of sediment problems as a whole will become possible when bed load and suspended load are expressed as functions of the same flow parameters. An equation is derived for computation of sediment transportation. Computation of bed load and suspended load are explained and then the possibility of determining the total load by using just one method is determined. Distribution curves for suspended load is a function of the material characteristics at the reference level, the height of the reference level is its ratio to total depth, the friction velocity and the distribution of turbulent eddies. Emphasis is placed on the need for experimental data to provide numerical constants to satisfy the developed functional relationship and to test the validity of assumptions.

68. Straub, L. G., 1939. Approaches to the study of the mechanics of bed movement. Presented at the 1st Hydraulics Conference at Iowa City.

A moveable bed channel in contrast to a rigid bed channel tends toward condition of equilibrium within itself which is dependent upon bed load for different conditions of flow. In regard to the non-silting, non-eroding condition, it is important to recognize that both the sediment load and discharge passing various sections in a continuous channel must be constant. It is the bed load which must be of primary importance in defining the stability of a channel in contrast to the frequently expressed concept that it is the suspended load.

69. Stewart, R. W., 1939. Safe foundation depths for bridges to protect from scour. Civil Engrg., Vol. 9, No. 6, June 1939, pp. 336-337, and Indian Roads No. XVIII, December 1939.

This article is a documentary of bridge failures in California. Pictures of bridges are shown, table of failures, type of structure, character of bed and proposed causes of failure are listed.

70. Tison, L. J., 1939. Erosion at the bottom of river beds. Translated from French. Washington Meeting of the Inter., Assoc. of Hydrology, Vol. 1, 1939. Translated for the Soil Conservation and River Control Council by the Translation Service, Dept. of Internal Affairs, Wellington, New Zealand. August 26, 1952.

It is generally assumed that erosion is a consequence of velocity, expressed by various formulae and diagrams, but they cannot be all-expressive of the other factors facilitating or retarding erosion. The laboratory tests show two factors influencing erosion: (1) water level and (2) plane curvature. Increasing water level causes increased velocity at which scour begins, but at a certain water level erosion velocity will decrease with increase in water level because the velocity distribution changes from shallow to deep water. Curvature of stream lines around obstacles causes increased velocities locally and hence, erosion of sand. The thicker the obstacle, the greater the scour, as proved by experimentation. If velocity distribution in the vertical is pronounced, scour would be greater. If material size is not uniform scour will be greater for a given median size, and therefore, material size influences depth of scour. Whirlpools (local eddies) are not strictly an erosive agent.

71. Rouse, H., 1940. Criteria for similarity in the transportation of sediment. Proc. Hydr. Conf., Univ. of Iowa Studies, Studies in Engrg. Bull. 20, March 1940, p. 33.

It is not safe practice to combine all pertinent variables by simple dimensional analyses, for the pi-theorem presumes motion of a homogeneous fluid, which leads to a term such as $\frac{\partial}{D}$ being significant. There is no dimensional analysis available for sediment-water movement, and fall velocity should be used instead of $\partial$. Criteria for similarity are found by geometry, flow and fluid characteristics and also sediment properties. If size of sediment relative to some length parameter is significant then use only size-frequency property as similarity criteria, geometric mean diameter and geometric standard deviation from the mean being most significant. If $\partial$ is approximately equal to the thickness of the laminar sublayer, the ratio $\frac{\partial}{\delta}$ is fundamental. If $\partial$ is much larger than the thickness of the laminar sublayer then neither viscosity nor $\partial$ is significant. Fall velocity is the significant sediment characteristic provided the model scale is large enough that the sand grain diameter does not approach the order of magnitude of other flow dimensions. Use of coarse low density materials in model studies of scour produces a condition of transport similar to bed load phase, whereas in nature scour is often predominantly a phenomenon of suspension. From systematic experiments with a submerged two-dimensional jet of clear water, it was found that the scour depth increases as an exponential function of time. Two distinct zones of flow were observed to occur, viz. zones of maximum and minimum jet deflection.

72. Tison, L. J., 1940. L'érosion et le transport de matéreaux solides dans les cours d'eau. (French) (Erosion and transportation of sediment in water courses). Reports and papers for the postponed meeting of the Int. Assoc. for Hydraulics Structures Research, Stockholm, 1939. Paper No. 3, pp. 71-90.

Local scour results from development of secondary circulation due to curvature in the stream lines around a pier. By applying a form of the Bernoulli equation to two-dimensional flow, it is shown that because the water flow is not parallel to the bed, secondary circulation is created and the diving flow attacks the stream bed. Local scour depth depends on the magnitude of the vertical velocity component. Experimental confirmation of the analysis was provided using different shapes of piers but with the same cross sectional pier length and width. As reported by others, streamlined piers produced less scour than square cornered piers. See also reference 73.

73. Tison, L. J., 1940. Erosion autour de piles de ponts en rivière. (French) (Erosion around bridge piers). Annales des travaux publers de Belgique, Vol. 41, No. 6, Dec. 1940, pp. 813-71.

Subject matter presented in references 57 and 72 are discussed again herein. Any object placed in the path of parallel flow produces curvature of the flow lines which takes two successive forms: (1) divergence upstream of the object and (2) convergence downstream of the object. Upstream there is a diving flow due to divergence and downstream flow is upwards and both causes scour. Velocity of the stream is not necessarily the chief reason for scour at any point, as compared to the angle of the diving and upward flows. Through experimentation it is advocated to place piles upstream of the piers to retard scour. Since curvature of the the flow lines is the chief source of diving or upward flow, the flatter the curvature, the less the scour.

74. White, C. M., 1940. The equilibrium of grains on the bed of a stream. Proceedings, Royal Society, A. 174, 1940, pp. 332-338.

The author discusses the conditions under which movement of sand grains on a loose flat granular bed begins. It is stated that incipient motion depends not only on the velocity but also upon the nature of the stream; viscous motion, inviscid motion and turbulent motion acting somewhat differently, and the velocity necessary to dislodge grains differ appreciably. With slow velocities and small grain sizes the viscous forces acting tangentially are important while at high velocities and large grain sizes the tangential drag becomes relatively unimportant and drag due to pressure differences become dominant. These forces are concerned with local motion. If the flow in the main stream is turbulent the forces on the grains fluctuate irregularly. In a part of the experiments where the flow was turbulent and the velocity was less, the bed was extremely active despite the fact that the mean drag was negligible. Form drag apparently enables the bed to withstand a greater drag force, while turbulence and non-uniformity of flow have the opposite effect.

75. Inglis, C. C., Thomas, A. R., and Joglekar, D. V., 1941. Part II, Specific experiments - Scour at nose of the outer banks of the new approach channel at Sukkur. Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication No. 5, Annual Report (Technical) of Work Done During 1940-41.

The Hardinge Bridge model studies (Ref. 65). determined that scour at bridge piers could be calculated from the equation:

$$D_s = 1.7\, q^{0.52}\, b^{0.72} \text{ or, } \frac{D_s}{b} = 1.7 \left(\frac{q^{2/3}}{b}\right)^{0.78}$$

where $D_s$ - scour depth from water surface, q - unit discharge upstream, b - width of pier. A similar form of equation was developed for scour at the nose of a guide bank (Spur dike is the terminology used by some U.S. State Highway Departments). The equation is:

$$\frac{D_s}{b_m} = 1.32 \left(\frac{q^{2/3}}{b_m}\right)^{0.70} \quad \pm 6\%$$

where $b_m$ is an average width of the dike measured at the top and at the base.

76. Inglis, C. C., Thomas, A. R. and Joglekar, D. V., 1941, Part III Basic experiments in connection with research into specific problems - scour. Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication No. 5. Annual Report (Technical) of Work Done During 1940-41, p. 35.

Additional experiments of general application with the scale model of the Hardinge Bridge is discussed. The studies are concerned with development of a criteria for depth of protective stone around the base of bridge piers. An empirical equation is developed which is based upon the discharge causing failure of the protective layer for various levels of the water surface. No field data are given to support the laboratory studies.

77. Inglis, C. C., Thomas, A. R. and Joglekar, D. V., 1941. Scour at spurs in river models. Central Irrigation and Hydrodynamic Research Station, Poona. Research Publication No. 5, Annual Report (Technical) of Work Done, 1940-41.

Experiments were conducted with 1:40 and 1:30 scale models of the Watrak River at Kaira and it was found that the shape of the bed and side slopes of the piers had considerable influence on the subsequent flow pattern and scour. Verification of river models is necessary. Also that adjustment of Q to obtain scalar depths of scour is not a suitable method of the discharge scale because the flow patterns may be dissimilar.

78. Krumbein, W. C., 1941. Measurement and geological significance on shape and roundness of sedimentary particles, Journal of Sedimentary Petrology, Vol. 11, No. 2, pp. 64-72, August, 1941.

The author presents Wadell's definiton of sphericity, $\psi = \sqrt{\dfrac{\text{volume of particle}}{\text{volume of circumscribed sphere}}}$ where the volume of the particle is in terms of a sphere of the same volume. The diameter, $\delta$, of that sphere = nominal diameter or, $\psi = \frac{\delta}{a}$ Where a = the largest diameter. The author then presents the intercept sphericity,
$\psi = \sqrt{\dfrac{\text{volume of ellipsoid}}{\text{volume of circumscribed sphere}}} = \sqrt[3]{\dfrac{\frac{\pi}{6}abc}{\frac{\pi}{6}a^3}} = \sqrt[3]{\dfrac{bc}{a^2}}$, and justifies his method on the basis that statistically they may be approximated by such form. Curves are developed for $\frac{b}{a}$ vs $\frac{c}{b}$. These curves may be used to arrive at the sphericity.

79. Broadfoot, H. L. and Chalkley, W. A., 1942. Bridge piers encases against scour. Engrg. News-Record, April 9, 1942, p. 90.

The protection of the bridge piers of the Illinois Central Railroad Bridge against scour is discussed. Protection was achieved by encasing the piers in sheet steel piles which were driven to bed rock and were then capped with concrete.

80. Morris, Brooks T., 1942. Scour control and scour resistance design for hydraulic structures. Trans. Am. Geoph. Union, August, 1942, Part 1, p. 60.

The mechanics of the scour flow pattern are discussed. Scour may be considered to be the removal of sediment due to local and variable excess of entrainment over deposition. The significant factors which control the ability of a stream to scour are: (1) the amount of sediment which is brought into the region of scouring action by the stream, (2) the sediment-carrying capacity of the flow in the downstream channel, (3) the resistance of the bed and bank materials to dislodgment and entrainment, (4) the mixing or sediment suspending power of the eddies produced in the scour-zone, and (5) the velocity of flow through the scour zone. The experiments performed are also discussed.

81. Anonymous, 1942. The effect of high level pitching layed round bridge piers on the depth of downstream scour. Tech. Annual Report of the Central Board of Irrigation, India, Publication No. 29, pp. 17-19.

A scour hole 216 feet below high water level was observed in September 1938 downstream of the spans of the Hardinge Bridge. Experiments were conducted to verify the magnitude of of the scour and to determine the reasons for the scour. It was found that scour depends on the curvature of the flow upstream of the structure, flow pattern at the nose of the piers, depth of flow, velocity, relation of the upstream and downstream water levels to each other and width of bed downstream. In this particular case the scour was due to high level pitching around the bridge piers.

82. Engeln, Oscar Diedrich von, 1942. Geomorphology. New York, MacMillan Company, 665 pp. illustrated.

This textbook on geomorphology contains several chapters on erosion cycles, stream patterns, meanders, work of streams, etc. The geologic concept of scour is presented.

83 Inglis, C. C., Thomas, A. R., and Joglekar, D. V., 1942. Remodelling Son Anicut. Scour at the noses of divide walls, upstream and downstream of the Anicut and undersluices. India Irrigation and Hydrodynamic Research Station, Poona, Res. Publication 5, pp. 19-21.

The scour problem is stated and the model studies are described. It was found that the upstream divide walls should have their noses sloping up gradually at about 1 to 10 in order to prevent concentration of flow at the point. The divide wall constructed between the high and low crested weir portions were provided with arched openings to minimize the effect of curvature of flow. By so doing scour was reduced in one case by 18 feet. Stone pitching downstream of the baffle was recommended. The placing of the stone apron was described.

84. Inglis, C. C., Thomas, A. R., and Joglekar, D.V., 1942. The protection of bridge piers against scour. India Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication 5, pp. 35-38.

The limiting discharge per unit width, $q_{lim}$ is correlated with $D$, the depth of channel upstream of the pier, and $D_p$, the depth of stone below water level at the time when failure begins. It was found that stones should be layed at the lowest practicable level to avoid the formation of high mounds of stone which tend to obstruct the waterway of the bridge and cause dangerous scour downstream. A rough indication of the discharge which will cause failure at the nose of the pier is given by the formula:

$$q_{lim} = 2.3\, g^{1/2}\, (W/\gamma\, S)^{1/6} (S-1)^{1/2} b^{1/12} D^{2/3} D_p^{\,1/4},$$

where $W$ = weight of protection per stone, $\gamma$ = weight per unit volume of water, $S$ = specific gravity of stone, and $b$ = width of pier. Other factors being the same, the higher the bed level upstream of the pier the more severe is the attack. The greater the depth of the stone the more stable it is.

85. Inglis, C. C., Thomas, A. R. and Joglekar, D. V., 1942. Scour at nose of outer bank of the new approach channel at Sukkur in prototype and models, India Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication 5, pp. 12-13.

The experiments using prototype and models to determine the relative scour and to relate this with scour around piers are described. It was found that $\frac{D_s}{b} = a\left(\frac{q^{2/3}}{b}\right)^m$ where $d_s$ = maximum depth of scour upstream of the nose of the pier, $b$ = thickness of the pier, and $q$ = the discharge intensity in the normal channel upstream of the nose of the pier, $a$ and $m$ are experimental coefficients.

86. Ishihara, T., 1942. Experimental study of scour at bridge piers. (Japanese) Trans. of Japanese Society of Civil Engineers, Vol. 28, No. 9, pp. 787-821.

The effect of the angle of skew between the centerline of flow and the pier axis is discussed. It was found that the skewed pier has greater scour and the scour hole is more irregular. When the skew angle is small the pier tends to collapse towards the pier nose but when the angle is large the pier has a tendency to collapse towards a direction perpendicular to the pier axis. The author says backwater caused by a pier is considered as having serious effect on scour at the nose of a pier, but scour is also governed by the eccentricity of the flow at the pier nose. If the ratio of the opening to the pier width is not extremely small this eccentricity of flow has no evident effect. The author states that "backwater should be considered in pier construction but it does not seem important from the point of scour." Greater scour occurs around a pier located at the center of a river than one located near the bank. This means there is close relationship between the flow velocity and the scour.

87. Ishihara, T., 1942. Experimental study of scour at bridge piers. (Japanese) Trans. of Japanese Society of Civil Engineers, Vol. 28, No. 11, pp. 974-1007.

The effects of pier shape, model scale and skew angle on scour for different bed materials under different critical conditions are fairly similar. Scour is mainly caused by eccentricity (divergence or convergence) of flow and the non-uniformity of velocity, and its magnitude is closely related with $\frac{1}{g}\int_A^S \frac{V^2}{\rho}\, ds$. If scour depth is proportional to scour force, then the scour depth is proportional to the radius of curvature. The author's opinion is that scour is caused by horizontal eddies from the tip of the pier nose (this agrees with Tison and Keutner), which results from flow eccentricity and the non-uniformity of the velocity distribution, but a rise in stage is only due to flow eccentricity. Eventually the degree of flow eccentricity, and shape of pier nose is the main term controlling scour. Scour is related to pier shape, model scale, critical conditions and the characteristics of the bed material. Scour at the nose of the pier is independent of pier length and tail shape.

88. Lane, E. W., 1942. Scour protection below overfall dams. C. V. Davis, Handbook of Applied Hydraulics, pp. 347-351.

This article discusses the erosion below spillways, end sills, blocks, etc. No new theory is presented.

89. Mockmore, C. A., 1943. Flow around bends in stable channels. Proceedings, Am. Soc. of Civil Engrs., Vol. 69, No. 3, March, 1943.

A study of the flow conditions in the bend of an open channel was performed. An attempt was made to observe the direction and magnitude of the angular velocities of particles in suspension as the water moved through the channel bend, and to compare these with the theoretical analysis made under assumed flow conditions. The observed rotation of the suspended particles corresponded, in general, with the theoretical analysis based on the assumed conditions. The path taken by a particle on its way around a bend closely approximates that of a spiral. In the experimental channel the cross currents moving along the stream bed from the outside to the inside of the bend were amazingly strong compared to the average velocities in the stream. At about 3/4 of the way around the bed there was a tendency for the development of an eddy, or slack water, along the inside of the bank due to the spiral motion, which is conducive to the deposition of suspended matter and the formation of a bar.

90. Borhek, R., 1943. Scouring of foundations as a cause of bridge failure. Roads and Bridges, August, 1943, p. 33.

As a rule, highway bridge foundations are not as deep as railway bridges. This indicates that very little is known about scour, erosion and channel changes and research in these problem areas is encouraged. In a survey of railway bridge failures in the United States and Canada it was estimated that only a few of the bridges could have been saved by annual maintenance. Most of the failures from scour occurred during a flood and not from scour over long periods of time. The author believes in the 6th power law, that is, the weight of particles that can be moved by a stream varies with the 6th power of the velocity. He recommends dredging upstream and downstream of bridges to prevent scour. Emphasis is also placed on scour across the whole waterway, not just at bridge piers and abutments. Flexible mats are likened to the tree roots and the author advocates placing them across the entire waterway. No equations are given, but only a discussion of what the author thinks should be done in terms of research and design.

91. Quraishy, M. S., 1943. The critical shear stress. Reprinted from the Journal of the University of Bombay, Vol. XII, Part III, November 1943.

The shear stress on the channel bed created by the moving fluid is proportional to the fall velocity of the particles.

92. Rittenhouse, G., 1943. A visual method of estimating two-dimensional sphericity. Journal of Sediment Petrology, Vol. 13, No. 2, 1943.

Two-dimensional sphericity of sands and other fine-grained particulate materials may be determined rapidly by visual comparison with a standard chart. The chart is devised in such a way that by making microscopic observations of individual sand grains the shape of the particle can be compared to one of many shown on the chart. Sphericity indices between 0.45 and 0.97 are shown for various general shapes and the index is related to a circle.

93. Fadum, R. E., 1944. Some factors to consider in the design of bridge foundations. Proceedings 30th Annual Road School, Engineering Bulletin, Purdue University, Extension Series No. 56, January, 1944, pp. 25-37.

At sections of rivers where the change in velocity is great as compared to normal flow, the quantity of material scoured out during flood stage will exceed that which is replaced simultaneously by transport. The rise in the stage of a stream at such locations does not reflect the total increase in size of the stream channel. From studies of bridge failures due to scour the following conclusions were reached: (1) cohesionless soils are particularly subject to erosion, (2) the depth of erosion below a normal stream bed may exceed considerably the rise in stage of a stream during flood flow, and (3) scouring action is particularly acute at locations of changes in width and alignment of a channel, or at locations obstructed by piers and abutments.

94. Inglis, C. C. and Joglekar, D. V., 1944. Maximum depth of scour at heads of guide banks and groynes, pier noses and downstream of bridges. Indian Waterways Experiment Station, Poona, Annual Report (Technical) of Work Done During Year 1944, pp. 74-83.

Deep scour occurs at (1) noses of piers due to diving flow, (2) ends of guide banks and groynes due to concentrated flow swinging around their extremities, and (3) downstream of bridges due to eddies shed from high pavements or stone protection placed around bridge piers. In all 3 cases, the scour is due to the bed velocity being far in excess of that which is natural for the discharge, so that $\frac{V^2}{d}$, which is related to turbulence, is very high. It was found that scour was much higher than estimated by Lacey's equation, $D = 0.47\left(\frac{Q}{f}\right)^{1/3}$. The maximum depth of scour occurring around some bridge piers and groynes and the steps taken to reduce the scour action are discussed. At several of the sites the original cause of scour was said to be due to form drag later believed to be caused by the flow pattern around the obstruction.

95. Anonymous, 1944. Protection of bridge piers against scour and minimum safe level at which to lay stone around piers. India Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication 6, 1944, p. 12-13.

This is a continuation of an earlier paper on the same subject, see pp. 33-40 of Annual Tech. Report for 1939-40. The conclusion is that where stone pitching is laid around a pier at too high a level, failure may occur due to stones being undermined at the tail of the pier. Normally, failure occurs at the nose. Scour is due to "drag" which depends on the rate of change of velocity in the immediate vicinity of the bed; where curvature of flow is a major factor, "drag" may have little connection with surface velocity

96. Inglis, C. C., Reid, J. S. and Joglekar, D. V., 1944. The effect of high level pitching laid round bridge piers on the depth of downstream scour. India Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication 6, pp. 31-32.

This article deals with the relation between the height of pitching around piers and consequent downstream scour. Model results are compared to known scour at the Hardinge bridge. Scour downstream of a bridge depends on 4 factors: (1) curvature of the flow upstream, (2) flow pattern at the nose of the pier, (3) the depth-velocity relation upstream and downstream of the pier, and (4) the material of the bed downstream. It was found that the scour hole in the prototype was approximately reproduced in the model and that high-level pitching at piers in the prototype was responsible for the deep scour hole downstream of the piers.

97. Inglis, C. C., Reid, J. S., and Joglekar, D. V., 1944. Scour around piers. India Central Irrigation and Hydrodynamic Research Station, Poona, Research Publication 9.

Scour downstream of the North Western Railway bridge over the N.W. Canal at mile 18/13-4 near Ruk-Sind is discussed. Experiments were carried out to evolve a suitable design of pavement and side expansion to induce accretion. See also reference 98.

98. Anonymous, 1945. Deep scour downstream of the North Western Railway Bridge over the N.W. Canal at mile 18-13-4 near Ruk-Sind. The Central Board of Irrigation, Annual Report 1945, p. 46.

A model investigation showed that the deep scour downstream of the bridge was due to return flow at the banks, leading to the formation of "bellies." The return eddies at the banks restrict the waterway and so cause jetting. If the bellies are prevented from forming much less scour will occur. The bellies can be eliminated by "juck work" (brush groynes) and accretion will then occur in the bed of the scour hole provided at a suitably low level to induce a return bed roller.

99. Inglis, C. C., and Joglekar, D. V., 1945. Maximum depth of scour at heads of guide banks and groynes, pier noses and downstream of bridges. The Central Board of Irrigation Annual Report 1945.

Scour is classified into three groups (see references 94 and 96). A form of Lacey's formula for determining the maximum depth of scour at bends is given.

100. Lacey, G. L., 1945. Scour at barrages. The Central Board of Irrigation. Annual Report 1945, Government of India Press, Simla.

Beginning with the depth and velocity equations the author derives formulas for the depth of scour upstream and downstream of barrages in terms of the critical depth of flow. He arrives at the equation $D_s = 1.40 \left(\frac{q}{f}\right)^{1/3} D_c$ for upstream scour where $D_s$ = depth of scour from the water surface, $f$ = silt factor, $D_c$ = critical depth through the barrage computed from $q = 0.333\ Q^{1/2}$ and $D_c = \left(\frac{q^2}{f}\right)^{1/3}$. For the downstream scour he arrives at the equation $D_s = 3.00\ D_c$.

101. Erickson, E. L., 1946. Some measurements of velocities and scour at a Mississippi River bridge pier. Highway Research Board, Proceedings, 1946, pp. 124-128.

In the spring of 1938 observations were made at piers of the Mississippi River bridge at Baton Rouge, Louisiana. Measurements indicated velocities of between 5 and 7 feet per second with the higher velocities around the sides of the piers. Between 30 and 40 feet of scour was measured. Flexible mattresses of ballast and rip rap stone was used to prevent further scour.

102. Rao, J. S. N., 1946. History of the Hardinge Bridge up to 1941. Railway Board Government of India. New Delhi, Tech. Paper No. 318, 1946.

See reference nos. 50, 76, 81 and 96.

103. Ewing, M. A., 1947. Scour and settlement problems. California Highways, Division of Bridge Department, California Bridge maintenance practice, 1949, pp. 25-28.

Several correction procedures are recommended for bridges that have been damaged because of scour at the base of piers and abutments. Some general statements are made as to the cause of scour, such as general degradation of the stream bed, brush collection, vegetation growth, and shape of piers. No information is given for calculating scour depth. For maintenance the author recommends construction of a sacked concrete lining on a slope below the footings of the piers and abutments and jacking up the superstructure to line and grade. When necessary if sacked concrete cannot be provided because of water, then sheet piles should be driven around the pier foundations and, if head room does not permit sheet piling to be driven then rip rap is the only course. In gravel foundations, when settlement is caused by finer material passing through the spaces of larger particles it is recommended that gravel be used to fill the voids and thus make a solid foundation.

104. Kalinske, A. A., 1947. Movement of sediment as bed load in rivers. Trans. Am. Geo. Union, Vol. 28, August 1947, p. 615.

The movement of sediment along the bed of a river or flume is analyzed theoretically in terms of the properties of the sediment grains and the hydraulic characteristics of the flow. The critical tractive force is evaluated for any grain size and related to the mean acting force. By utilizing the boundary layer and turbulence theories, the equation for sediment transport is given as

$$G = \frac{2}{3} f\left(\frac{\tau_c}{\tau_o}\right) j \partial \gamma_s \sqrt{\frac{\tau_o}{\rho}}$$

, where $G$ is the rate of transport, $\tau_c$ is critical shear on the bed, $\tau_o$ is shear for the flow, $j$ is portion of bed exposed to shear, $\partial$ is sediment diameter, $\gamma_s$ is unit weight of sediment and $\rho$ is fluid density.

105. Matthes, Gerard H., 1947. Research study of underscour at bridges, piers and abutments. Am. Assoc. of State Highway Officals, Convention Group Meetings Papers and Discussions, 1947, pp. 179-186.

Underscour at piers and abutments nearly always takes place during flood stages when general deepening of a river bed is also usually in progress. During rising stages, it is normal for erodible beds to exhibit a tendency towards overall deepening as a result of bed materials being set in motion either in suspended form or by rolling and bouncing. The deepening so affected is usually temporary, and upon subsidence of high stages is followed by prompt rebuilding of the bed to its former level, due to deposition of material in transit. Steambeds composed mostly of fine materials such as sand or mud, are more susceptible to deeping than are coarse gravel or cobblestone beds. Stream beds which obtain a high degree of compaction, due to the presence of clays or organic matter, are less erodible. Underscour appears to be a distinct phenomenon, the negative pressures of which are created by flow rotation akin to vortex motion.

106. De Beer, E., 1948. Settlement record of bridges founded on sand. Proceedings of the 2nd International Congress on Soil Mechanics and Foundation Engineering Vol. II, Rotterdam, June 21 to 30th, 1948, pp. 111-121.

This paper is concerned only with soil mechanics and the computation of the settlement of bridge piers by the methods of soil mechanics.

107. Fisher, K., 1948. The foundation of the Rotunda Bridge in Vienna. Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering, Vol. IV. Rotterdam, June 21 to 30th, 1948, pp. 22-27.

The soil mechanics aspect of founding shallow bridge footing is discussed.

108. Blench, T., Ahmad, Mushtaq and Ahmad, Nazir, 1948. Scour in alluvium below falls. Proceedings of the International Association for Hydraulic Research, 2nd Meeting at Stockholm, 1948, pp. 341-350.

Experiments were conducted with the object of determining how vorticity damping, and satisfactory flow distribution can be achieved with minimum length of masonry work beyond hydraulic jumps. For a given discharge and drop, the scour depth is independent of chute slope provided the horizontal floor length, and its depression, are the same in all cases. If a uniform horizontal floor is used, the scour depth does not decrease below floor level when depth of water exceeds 1.25 E $f_2$ (energy of flow beyond the jump in masonry work). Velocity distribution can be improved by two double rows of staggered blocks. The upstream set (impact block) throws the line of maximum velocity upwards, while the downstream set (deflector blocks) further improves velocity distribution and create a bed roller that deposits mobile material against the toe-wall.

109. Bose, N. K., and Pramanick, H. R., 1948. Scour below weirs. 2nd Meeting of the Intern. Assoc. for Hydraulic Structures Research, pp. 351-360.

The results of the model experiments conducted for the undersluice section of the proposed Mor barrage in connection with the Mor project in Bengal is described. As the scale of the model is reduced, the point of maximum scour moves further away from the end of the floor. The maximum depth of scour tends to decrease slightly with an increase in the model scale ratio. There was no definite trend for the maximum depth of scour to increase or decrease with the scale of the model when there are staggered blocks on the downstream floor.

110. Framji, K. K., 1948. Scour below weirs. 2nd Meeting of the Intern. Assoc. for Hydraulic Structure Research, pp. 361-375.

Prototype and model data of depths of scour below weirs are analyzed. A close comparison of results of model tests against prototype behavior shows conformity to a degree when the model is operated correctly. Scour downstream of weirs occurs due to one or more of the following reasons: (1) excess energy of hypercritical flow when insufficiently dissipated by a standing wave, (2) an unstable standing wave forming below the toe of the glacis and shifting beyond the rigid floor, and/or (3) the pavement level being too high, making the bed velocity abnormally high and causing violent eddies to be shed from the downstream end of the pavement. Predominant factors determining the maximum depth of scour downstream of structures like barrages and bridges over wide rivers are discharge intensity and turbulence (as indicated by $\frac{V^2}{d}$). The effect of sides being negligible, other important factors are flow pattern and grade of bed material. The maximum scour downstream of bridges is of the order of $4\ D_L$; while below weirs, having greater waterway than Lacey's minimum stable waterway, the maximum scour will vary from 1.25 $D_L$ to 2 $D_L$ depending on concentration and intensity of turbulence.

111. Hathaway, G. A., 1948. Observations on channel changes, degradation and scour below dams. 2nd meeting of the Intern. Assoc. for Hydraulic Structures Research, pp. 287-307.

This paper concerns the general significance of sediment transportation as related to channel changes below hydraulic structures. When water is released from a storage reservoir, the sediment-free water in the downstream channel will act upon the channel bed and quickly pick up a new sediment load. The load will be proportional to the ability of the flow to transport the type of material present in the bed, and to the susceptibility of the bed to erosion. The hydraulic properties of a stream section determine the competency of the flow to erode and transport the load whereas resistance offered by the bed to the erosive and transport action of the stream is determined by the composition and formation of the bed. Channel changes downstream of the John Martin Dam on the Arkansas, Conchas Dam on the South Canadian, Denison Dam on the Red River, and Fort Peck Dam on the Missouri are discussed.

112. Hellström, B., 1948. Measures to reduce scour below dams. 2nd Meeting of the Intern. Assoc. for Hydraulic Structures Research, pp. 309-315.

The model test of a dam and apron in Malaya are described. It is explained how the discharge was directed towards the center of the river downstream of the dam in order to prevent erosion of the banks of the channel. The results of the passage of a flood through the prototype, which confirmed model results, are described.

113. Hickox, G. H., 1948. Prevention of erosion below TVA dams. 2nd Meeting of the Intern. Assoc. for Hydraulic Structures Research.

The model tests of methods of preventing scour downstream of the TVA dams are discussed.

No quantitative results are presented. The success of the methods employed are described.

114. Lane, E. W., 1948. An estimate of the magnitude of the degradation which will result in the Middle Rio Grande Channel from the construction of the proposed sediment storage basins and contraction works and sample computations showing method of computing degradation or aggradation on the Middle Rio Grande River. Report No. HYD-290 Bureau of Reclamation.

According to some reports, evidence seems to point out that it is not uncommon for the bottom of a stream to lower twice as much as the water surface rises in a flood. The author questions this statement pointing out that suspended sediment samples do not bear this out, nor does evidence of sediment accumulated in settling reservoirs. He points out that all of the cases where the bottom was lowered were either at bridges where the presence of piers would induce scour, or at stations where the river was narrow because measuring stations are usually located where the river is narrow. That these narrow sections scour out during floods seems very reasonable, but it appears that they deposit the load at the next wide section downstream and it is not carried on down the river. The author indicates that this explanation corresponds to observed data

115. Scimeni, E., 1948. On the scour which can appear along the downstream face of a dam. 2nd Meeting of the Intern. Assoc. for Hydraulic Structures Research, pp. 493-496.

The effect of the shape or profile of a dam on the scour on its surface is discussed.

116. Stanley, J. W., 1948. Effects of dams on channel regimen. Proceedings, Federal Inter-Agency Sedimentation Conf. Washington, D.C.

The author discusses the effect dams have on the regime of the stream. When a dam is installed, sediment deposits in the reservoir above the dam and clear water released from the dam creates increased scour of the downstream channel. Initially, the slope directly below the dam is decreased and the effect of degradation moves downstream with time until a slope roughly equivalent to the original occurs. If bed material becomes progressively finer downstream or if the depths to coarse material increase with distance downstream from the dam, the ultimate slope in the scoured area will be less steep than initially. A river, free of sediment load, will tend to maintain a relatively straight channel. Also, suspended load carried by rivers vary approximately as the square of the discharge, other variables remaining constant.

117. Tison, L. J., 1948. Transport de materiaux de fond, et erosion a l'aval des barriages. (Transport of bed material and erosion downstream of dams). Association Internationale des Travaux Hydrauliques, Stockholm, Sweden, 1948, pp. 65-76.

Scour equations are developed on an energy concept, concluding that the diving flow attacks the bed and causes scour.

118. Posey, C. J., 1949. Why bridges fail in floods. Civil Engineering, Vol. 19, February, 1949, pp. 42-90.

Model experiments on scour action were performed in a 6-foot wide flume using graded fine sand for the bed and a one-litre glass tube as the pier. By the use of mirrors placed inside the glass tube, below the bed level, the general bed level, scour level, Kolk action, and vortices could be observed while the experiment was in progress. The movement of sand picked up by the vortex at the front of the pier was downward next to the model pier. The vortex around the pier picked up sand. The shape of the scour hole was the result of the sand sliding when at the angle of repose. A second vortex near the water surface was also noted. This vortex was in the opposite direction and carried no sand.

119. Blaisdell, F. W., 1949. Flow through diverging open channel transitions. United States Department of Agriculture.

Experiments were performed to determine the feasibility of using diverging channel sections at the entrance to the St. Anthony Falls type stilling basin in order to increase the Froude number. By increasing the Froude number the efficiency of operation of the stilling basin would be increased and this would make it possible to decrease the length of the stilling basin thereby creating a savings on the construction costs.

120. Inglis, C. C., 1949. The behavior and control of rivers and canals. Central Water Power Irrigation and Navigation Report, Poona Research Station, Research Publication 13, Part I and II, 1949, pp. 327-248.

Bridge piers deflect current as at bends, if the depth of scour $D_s$ at the bridge pier is proportional to Lacey's regime depth $D_L$. The following equations are recommended for design:

$D_s = 4\ D_L$ (maximum scour downstream of bridges)

$D_s = 3.8\ D_L$ (spur heads on steep slopes)

$D_s = 2.25\ D_L$ (spur heads on gentle slopes)

$D_s = 2.75\ D_L$ (at long radius spur heads)

$D_s = 2\ D_L$ (at bridge piers)

$D_s = 1.7$ to $3.8\ D_L$ (at spurs along river banks)

$D_s = 1.7 \left(\frac{q^{2/3}}{D}\right) 0.78$ where $D$ = width of pier.

121. Inglis, C. C., 1949. The effect of variations in charge and grade on the slopes and shapes of channels. Proceedings of the International Association for Hydraulic Structures Research, 3rd Meeting, Grenoble, France. 1949.

The paper explains the mechanism of change which controls and maintains a dominant state of equilibrium in regime channels, and describes the factors which maintain this control, and how the shapes and slopes of channels can be modified by controlling the quantity and grade of material entering their heads.

The development of the regime formulas of Kennedy (1895), Garrett (1913), Lindley (1919), Lacey, G., (1929) and Inglis (1947) is reviewed. The gradual elaboration of the formulae to facilitate the design of regime canals is shown. A regime channel is defined as that which changes little from year to year but may have changes within a given period. It is explained that the change in Manning's n is due to the reduction in size of the bed material exposed because of silting during floods, and the opposite during clear water flows. When charge increases, the slope must increase and some broadening takes effect. If excess charge enters a canal system it has to be accommodated within the system, hence, it is important to design the headworks to admit only the designed charge. Excluders and ejectors are discussed briefly. It is mentioned that the slope and shape of canals depend upon the overall dominant relationships between discharge, and grade and charge of bed materials.

122. Wilson, W. S., 1949. Subsidence in bridge foundations. The Surveyor, Vol. 108, August 12, 1949, pp. 491-492.

The primary causes of subsidence of bridge piers and abutments are (a) underground mineral workings, (b) earth movements, (c) river scour, and (d) excessive pressure on foundations. Periodic maintenance should eliminate any serious effects from scour. Whatever the reason for settlement, it can be corrected by the cementation of the foundation by grouting after blocking off an area around the pier with sheet piling and then grouting inside the frame work.

123. Anonymous, 1950. Bank protection: How retards save bridges. Louisiana Highways, Vol. 4, No 2, February 1950, p. 1, 4-5.

This article tells of the use of retards to protect bridges by causing eddies to form behind the retards and these eddies in turn cause sediment to be deposited along the banks and thus protect the banks. The retards attempt to force the channel into the stream center, hence, flow is directed through bridge openings.

124. Appel, D. W., 1950. Flexible mats may reduce scour at piers of small bridges. Engrg. News-Record, Vol. 144, No. 21, May 25, 1950, p. 43.

The mat principle is envisioned as being adaptable for use at piers of small railroad and highway bridges where unpredictable amounts of scour continue to pose an unsolved problem and where more expensive preventive methods are not justified. Comparison of scour around a model pier with and without mats showed that a mat on the downstream side of the pier scour below the average bed level is prevented and on the upstream side the scour was greatly reduced. The mat was made of link-chain. The primary function of the mat is to reduce the velocity of flow at the bed; below that required to produce scour. On the upstream side of the pier the increased head due to the decrease in velocity of the oncoming flow causes flow downward through the mat, which accounts for scour that does occur there. See also reference number 134.

125. Anonymous, 1950. Rosport-Ralingen barrage. Report of the Hydraulic Laboratories of the M.A.N. Conern. Gustavsberg, Germany, November, 1950.

This report describes model studies of the Rosport-Ralingen barrage undertaken in an attempt to discover a means of alleviating the scour problem downstream of the paved apron. It was decided to place a sill at the downstream end and thus create a roller to prevent undercutting of the paved apron. Photographs and dimensions of the structure are shown.

126. Anonymous, 1950. Road bridge across the Gautami-Godavari River at Alamaru below Rajahmundry-Madra Province. Central Board of Irrigation, India, Publication No. 50, p. 205.

A model was used to finalize the site of the bridge, its orientation, length, and the required protection works. Lacey's scour formula, $D_s = 0.473 \left(\frac{Q}{f}\right)^{1/3}$, was used to calculate the depth of scour below high flood level. For scour at the pier nose the depth calculated by the formula should be multiplied by 2, and 1/2 of this result should be added for extra footing depth of the bridge piers. Similitude of scour depth between model and calculated values did not occur, however, it is believed that qualitatively the scour patterns should be similar. The depth scale was calculated from average depth and width prototype and model, using a discharge scale = $L^2$. Different sizes of sand were used in the model. Lacey's roughness coefficient was used to calculate the model and prototype depth of flow. The time scale was calculated from

$$\text{T-scale} = \frac{\text{work done}}{(w)\ (vel)} = \frac{LwD}{wv} = LD^{1/2} \quad \text{if} \quad v \propto D^{1/2}.$$

127. Albertson, M. L., Dia, Y. B., Jensen, R. A., and Rouse, H., 1950. Diffusion of submerged jets. Trans. Am. Soc. of Civil Engrs., Vol. 115, 1950, pp. 639-697.

The approximate characteristics of the corresponding mean flow pattern of a submerged jet is derived and experimental data is presented to verify the analysis. Algebraic expressions and plotted curves are presented in dimensionless form to give the distribution of velocity, volume flux, and energy flux in the zone of flow establishment and the zone of established flow for submerged jets from both slots and orifices. A qualitative treatment of the variation in mixing characteristics and a generalized diagram of the mean flow pattern are given.

128. Carter, A. C., and Carlson, E. J., 1950. Critical tractive forces on channel side slopes. Revised Edition, U.S. Bureau of Reclamation Hydraulic Laboratory Report No. HYD-295.

The magnitude of the tractive forces exerted by flowing water which will cause impending motion of coarse non-cohesive material comprising the sloping side of a channel is derived in this paper. They arrive at the expression

$$\frac{T_s}{T_L} = \cos \phi \sqrt{1 - \frac{\tan^2 \phi}{\tan^2 \theta}}$$

for the ratio of the force on a sloping side to that on a level surface necessary to cause impending motion where $\phi$ is the angle of inclination of the sloping side and $\theta$ is the angle of repose of the material. A diagram with values of the ratio for various values of $\phi$ and $\theta$ is presented.

129. Doddiah, Doddiah, 1950. Comparison of scour caused by hollow and solid jets of water. Master's thesis. Colorado A and M College, pp. 1-156.

With relatively uniform bed material the depth of scour depends on the area and the velocity of the jet, the mean fall-velocity of the material, the depth of water over the material, and the duration of the scouring action. A state of equilibrium in the process of scour cannot be expected either at any depth or after any period of time. The magnitude of scour decreases with a decrease in the ratio of jet velocity to fall velocity approaching zero as this ratio approaches unity. Scour increases with an increase in the depth of water over the erodible bed until the depth reaches a critical value. Any further increase in depth will diminish the resulting scour. For a given area of jet, the comparison of the scour resulting from the two types of jets appears to indicate one trend. See also reference 159.

130. Einstein, H. A., 1950. The bed-load function for sediment transportation in open channel flows. United States Department of Agriculture, Soil Conservation Service Tech. Bull. No. 1026. September 1950.

The study included suspended load as well as bed load. The analysis assumes uniform flow in a reach of stable channels. The resistance to flow is divided into two parts, that due to grain roughness and that due to form roughness of the bed configuration. It is assumed that turbulence near the bed caused by the grains of sand affects the transport of the sand grains, but the turbulence due to form roughness does not since it occurs a significant distance above the bed of the channel.

Using turbulence and boundary layer theories in a equation for calculating suspended load is derived, which is believed to be valid from the water surface down to a close proximity of the bed. By applying further the theory of probability for exchange of particles between the bed and the suspended loads, and from large quantities of flume and field data, a bed-load equation is developed. Since the development is partly empirical, computational procedure for the bed-load function requires use of empirical graphical functions. The bed-load function is reasonably satisfactory for a specific range of small bed particles but the equation deviates from measured data when sediment size becomes large.

131. Harned, C. H., 1950. Foundations for highway bridges and separation structures on unconsolidated sediment. Applied sedimentation - a symposium edited by P. D. Trask, 1950, pp. 169-180.

Bridge foundation requirements, personnel requirements, foundation study tools, exploration procedures, footing foundations, and pile foundations are discussed.

132. Henry, H. R., 1950. Discussion of diffusion of submerged jets. Trans. Am. Soc. of Civil Engrs., Vol. 115, 1950, pp. 665-697.

The author gives an analysis of the efflux from a submerged sluice gate and concludes that the method of experimental attack as applied in reference 127 is of great value in investigating any type of submerged jet.

133. Sugimoto, S. and Inada, Y., 1950. Study of hydrodynamics of flow around piers. (Japanese) Transactions of the Japanese Society of Civil Engineers, Vol. 36, No. 10, pp. 2-12.

Conformal transformation is utilized to transform a streamlined pier shape into a circle. The objective of this exercise is to obtain the pressure distribution to establish the flow direction and estimate the scour. Results inferred from the theoretical calculations agree with the experimental observations of Engels (see reference 26), Keutner (reference 35), and Ishihara (references 61, 86 and 87). A direct method of calculating the scour depth is not given. Two dimensional potential flow of an ideal fluid is assumed in the calculations.

134. Anonymous, 1950-1951. River control work and investigations, lower Colorado River Basin. Report, Bureau of Reclamation, U.S. Department of the Interior, Boulder City, Nevada, Vol. 1, pp. 7-9.

Erosion of the Colorado River below Hoover Dam is discussed. Charts are shown to indicate progressive erosion with time.

135. Anonymous, 1951. Platte River near Ashland, Nebraska - flood characteristics at the three overflow outlets on U.S. Highway 6 East of the main channel. U.S. Geological Survey Water Resources Division, Surface Water Branch, Lincoln, Nebraska, January 10, 1951.

The study was made to determine the hydraulic adequacy of the highway bridges across the Platte River near Ashland, Nebraska. Floods in 1944 and 1949 damaged the main and relief bridges localized at the same site parallel to the highway. The highway bridge is downstream of a railroad bridge. The flood of 1949, with velocities of about 9 feet per second, scoured the bed beneath the main bridge about 6 feet. The conclusion was reached that under present conditions (1951) the bridges are safe but with deterioration of a guide levee, the river may change and cause the main flow to be directed towards one of the relief bridges which would then be unsafe.

136. Newton, Carroll T., 1951. An experimental investigation of bed degradation in an open channel. Journal of the Boston Society of Civil Engineering, Vol. 38, No. 1, January, 1951, pp. 28-60.

Experiments were conducted in a 30-foot-long flume, one foot wide and 2 feet deep to determine the rate of degradation of the channel bed from given equilibrium conditions when the sediment supply was suddenly terminated. The experiment represents a dam constructed on a river with the reservoir collecting the sediment supply. It was found that the degradation rate, called scour, conformed to analytical expectations expressed in the computations for Garrison Dam. This study showed that the rate of degradation decreased asymptotically to zero with time.

137. Anonymous, 1951. Prepact protects old bridge piers. Western construction, Vol. 26, No. 10, October 1, 1951, pp. 80-81.

This article discusses the jetting of fines from the river bed gravels around the piers of a 32-year-old bridge and the stabilization of the remaining material with an intruded grout.

138. Laursen, E. M. and Toch, Arthur, 1951. Model studies of scour around bridge piers and abutments. Second Progress Report, State University of Iowa Reprints in Engineering. Reprint No. 107, Reprinted from Highway Research Board Proceedings, December, 1961.

See references 140 and 151.

139. Blench, T., 1951. Hydraulics of sediment-bearing canals and rivers. Evans Industries, Vancouver B.C., Canada, 1951.

See reference 204.

140. Laursen, E. M., 1951. Progress report of model studies of scour around bridge piers and abutments. Research Report No. 13-B, Highway Research Board, 1951.

The process of scour and the experimental methods of the study are discussed. Scour is caused by a disturbance of the stream's sediment-transport capacity in a limited area such that the capacity to transport is greater than the amount of material supplied. As the bed material normally at rest is placed in motion by the local increase in capacity, a scour hole develops which in turn alters the flow pattern. The tendency will be for the rate of scour to decrease with time; that is, as the size of the scour hole increases, the velocity and therefore, the transport capacity at the bottom of the scour hole decreases. The exact pattern of movement varies with the geometry of the pier or abutment.

141. Posey, C. J., Appel, D. W., and Chamness, E., 1951. Investigation of flexible mats to reduce scour around bridge piers. Highway Research Board Report No. 13-B, 1951.

The nature of the scour pattern and the possibility of using flexible mats around piers as a means of preventing scour are discussed. It was found that the two greatest hazards to the effective function of mats were: (1) the tendency of upward currents to move material up through the mat, and (2) the tendency of the mat to bridge or buckle due to bottom irregularities, thus creating under channels through which bed material is easily transported. The best protection was afforded by a heavy completely flexible mat with comparatively small openings. The flow patterns and scour formation are illustrated in this paper. See also reference 124.

142. Schneible, D. E., 1951. An investigation of the effect of bridge-pier shape on the relative depth of scour. Master's thesis, State University of Iowa, June, 1951.

The effect of pier shape and arrestors on the depth of scour and extent of scour around bridge piers was investigated. It was determined that of the elongated piers the lenticular-shaped pier produced the least depth of scour. A comparison of the relative depth of scour around elongated and circular piers of equivalent cross-sectional area, in which the angle of attack was 30° or less, shows that the depth of scour was greater around the circular pier. It was also determined experimentally that a single disk around a pier at or below the surface approximately 1/2 the pier diameter was very effective in reducing the depth of scour. No quantitative results are presented and all variables except pier shape were held constant.

143. Boyce, E. R., 1952. High water means deep scour. Minnesota Highway, Vol. 1, No. 5, March, 1952, p. 2.

The heavy rains and runoffs occurring in District 12 around Rochester, Minnesota caused damage to bridges. The use of masonry walls, timber fences, and crib construction in the past to try to prevent the loss of roads and bridges is described. Heavy rip rap is proving effective in reducing erosion and preventing loss of structures.

144. Leopold, Luna B., and Maddock, Thomas, Jr., 1952. Relation of suspended-sediment concentration to channel scour and fill. Proceedings of the Fifth Hydraulic Conference, State University of Iowa, Iowa City, Iowa, June 9-11, 1952.

An analysis was made of concurrent values of suspended sediment load and width, mean depth, mean velocity, and discharge at a number of gaging stations. From the data analyzed it appeared that fairly definite relations exist between the variables. These are $B = a\,Q^b$, $V = k\,Q^m$, $D = c\,Q^f$, and $L_s = p\,Q^j$ where a,b,c,f,j,k,m and p are empirical coefficients and exponents, $B$ = width of water surface, $D$ = mean depth, $V$ = mean velocity, $L_s$ = suspended sediment load in the stream in tons per day. For constant discharge and width, a decrease in suspended-sediment load is accompanied by a decrease in velocity and increase in depth. Changes in the bed occur simultaneously with a variation in the rate of suspended-sediment concentration. At constant discharge the suspended sediment load appears to be related to the quantities--width, velocity, and depth. It was noted that at constant width and discharge increases in the suspended-sediment load would be associated with increased velocity. An increase in suspended load tends to decrease channel resistance and thus causes an increase in velocity.

145. Anonymous, 1952. Report of committee on surface drainage of highways. Highway Research Abstracts, Vol. 22, No. 6, June 1952, p. 11.

Work during the past year (1951) has been with a model pier placed in a flume equipped with a sand-feeding mechanism which enables the simulation of bed-load movement as it occurs in a river with a movable bed. Indications are that the depth of flow has more effect on the depth of scour than does the velocity of the flow.

146. Lane, E. W., 1952. Progress report on results of studies on design of stable channels. U.S. Bureau of Reclamation Hydraulic Laboratory Report No. HYD-352, Denver, Colorado, June, 1952.

This paper discusses the work done on a tentative method of designing unlined earth canals to insure freedom from scour and the development of an analysis of the channel shape for certain conditions involving minimum excavation. It classifies unstable channels as: (1) those which scour but have no objectionable deposits, (2) those having objectionable deposits without scour, and (3) those having both deposition and scour. With sediment-free water only the first type can occur. Every canal flowing at design discharge has a definite maximum capacity to carry sediment of a certain size range. The author discusses the history of stable channel knowledge. Scour takes place when particles composing the bed of the canal are acted upon by forces sufficient to cause them to move. Tractive force is defined as not the force on a single particle but rather the force exerted over a certain area of the bed or banks. An advantage of using tractive force analysis rather than limiting velocity approach for the design of large channels is that it indicates why higher velocities are safer in large canals than in small ones. Probably the most important factor in the design of clear water canals in coarse noncohesive material is the limiting tractive force which the various types of material will stand. In designing canals that will be free from scour while carrying relatively clear water, one of the most important factors is the material through which the canal passes. Sinuous canals scour more readily than straight ones. The scour in bends can be reduced by lowering the velocity of flow. See also reference 161.

147. Lawrie, W. G. A., 1952. The effects of scour on military bridge design. The Royal Engineers, Vol. LXVI, No. 3, September, 1952, pp. 256-269.

See references 154 and 163.

148. Caldwell, J. M., 1952. Supersonic sounding instruments and methods. Trans. Am. Soc. of Civil Engrs., 1952, p. 44.

Supersonic frequency sounders are preferred to those operating at sonic frequencies because of better definition of the bottom resulting from a smaller sound cone and because the comparative freedom from interference from extraneous noises. Readings of false bottoms in areas with soft muddy bottoms may be recorded. The author believes sounders are more accurate and consistent than are soundings made by lead lines. Examples of readings indicating bottoms by use of electronic sounders are compared to readings by lead lines.

149. Halbronn, G., 1952. Etude de la mise en regime des écoulements sur les ouvrages a forte pente. (French) (Study of the establishment of flow regime on a hydraulic structure with a steep slope.) La Houille Blanche, No. 1, 1952, pp. 21-40.

This is a theoretical study of free surface fluid flow over a long spillway taking viscosity into account. Local velocities and depths in laminar and turbulent flow regimes are calculated. There exists a critical point where turbulent action becomes noticeable on the surface and air entrainment becomes possible. The analysis is verified by experiment.

150. Laursen, E. M., 1952. Observations on the nature of scour. Proceedings of the Fifth Hydraulic Conference, State University of Iowa, Iowa City, Iowa, 1952.

Scour is defined as the enlargement of a flow section by the removal of material composing the boundary through the action of the fluid in motion. The amount of material the fluid can move in a unit time is termed the capacity of the flow. The following general characteristics which should be the basis of any detailed analysis of local scour were deduced: (1) The rate of scour will equal the difference between the capacity for transport out of the scoured area and the rate of supply of material to that area. (2) The rate of scour will decrease as the flow section is enlarged. (3) There will be a limiting extent of scour, and (4) this limit will be approached asymptotically. The equation of scour is given as $\frac{d}{dt}(f(\bar{D})) = g(\bar{D}) - L$ where $\bar{D}$ is a mathematical description of the boundary so that $\frac{d}{dt}(f(\bar{D}))$ = rate of scour, $g(\bar{D})$ is the capacity of the flow to transport sediment, function of the boundary position, and L = rate of supply. To apply the equation to a specific situation the capacity of flow (as it varies with boundary position) and the rate of supply must be known. In experiments with a submerged jet at the beginning the vertical dimensions of the scour hole and the downstream dune, or deposited material, increased faster than the horizontal dimensions. At the beginning, sand moved as bed load but when the upstream face of a dune reached the angle of repose the mechanism of transport changed to suspension. By analysis, it is shown that the depth of scour should increase with the depth of flow. By using an appropriate experimental capacity function the differential equation of scour was integrated and was confirmed by experimental data.

151. Laursen, E. M. and Toch, A., 1952. Model studies of scour around bridge piers and abutments - second progress report. Proceedings of the 91st Annual Meeting, Highway Research Board.

The authors describe the second phase of the scour investigation at the University of Iowa. The primary criterion in the design of piers for minimum scour is that the pier should present a minimum flow obstruction. The possibility of inhibiting scour by the use of arrestors around the pier is described. Laboratory investigations in the second phase of the program revealed that for any pier in a steady flow, there is an equilibrium depth of scour which increases with increasing depth of flow but is not affected appreciably by a change in velocity. Under unsteady flow conditions, however, greater depths may be attained, because of an apparent lag in the establishment of transport equilibrium. An electronic scour meter was used to determine the depth of scour.

152. Posey, C. J., 1952. Tests of erosion around models of submersible oil-storage and well-drilling barges. Rocky Mountain Hydraulic Laboratory, Allenspark, Colorado, in cooperation with the Bethlehem Steel Company, Shipbuilding Division, Beaumont, Texas.

Tests were performed on submergible oil storages and drilling barges which are set on the bottom of the bay but which extend above the water. It was found that round and slant-sided square barges are subject to as much erosion as are vertical-sided square models. Of three positions tested of the square model with vertical sides, that facing the current squarely causes the greatest amount of erosion, but the differences noted are not significant. Half-buried barges are almost as seriously eroded beneath as are fully exposed barges. The method by which the experimental model is placed on the sand seems to have little effect. Columns at the edges of the barge have a slight effect on increasing the scour depth; the deepest scour ordinarily occurs under the upstream edge or under the corner projecting into the flow. No scour occurs under the downstream edge, and very little under the downstream half or the sides. If the current shifts 90 or 130 degrees after a scour hole is created, a new scour hole is formed, but the first will not be filled up rapidly. It was found that a T-V graded filter provided good protection about the drilling barge.

153. Anonymous, 1952. Scouring velocities in tidal rivers. Central Board of Irrigation and Power, India, Annual Technical Report.

Experiments were performed to determine the velocities at which bed material would be moved by the ebb tide in the tidal rivers of lower Bengal. The problems experienced with the model are discussed.

154. Lawrie, W. G. A., 1953. The effects of scour on military bridge design. Civil Engineering and Public Works Review, Vol. 48, No. 562, April, 1953, pp. 342-344.

The author uses the equations of Spring (reference 10) and Inglis to develop an equation for depth of scour, $d_s$ , in terms of the meander length of a stream. $M_L = 27 \sqrt{Q_{max}}$ where $M_L$ = meander length, Lacey's $D_s = 2 \times 0.473 \left(\frac{Q}{f}\right)^{1/3}$ or $D_{s_{max}} = 0.1 \frac{M_L{}^{2/3}}{f^{1/2}}$ and, assuming $f = 1$ , $D_{s_{max}} = \frac{M_L{}^{2/3}}{10}$ which gives the scour depth independent of $Q$ but gives $D_s$ from measurable $M_L$ on maps for military engineers. From calculation and using selected data the author finds that $D_s$ (calculated) = $\frac{D_s \text{ (observed)}}{0.72}$.

It is recommended that a military engineer should:

(1) Choose a site for a bridge where the river is straight and flow is smooth.

(2) Design the bridge with a minimum number of piers and avoid construction in the main channel.

(3) Calculate $D_s$ from $D_{s_{max}} = \frac{M_L{}^{2/3}}{10}$

(4) Check $D_s$ by other methods.

Since there is an element of unknown involved, the piers should be placed 1/2 again as deep as calculated from (3) in the active channel.

See also reference 163.

155. Romita, Pier Luigi, 1953. Erosioni d' alveo al piede delle pile di Ponte. investiti obliquamente dalla corrente.(Italian) (Bed scour around bridge piers with the axis skewed to the stream flow). L' Energia Electtrica, No. 4 e 6, Aprile, Giugno, 1953.

The study of the influence of the angle of attack on bed scour around bridge piers skewed to the stream flow, was systematically studied in the hydraulic laboratory at the Politecnico of Milano. The experiments are described and the results are analyzed, with particular reference to the maximum depth of scour around the pier. Some general directions for construction are deduced as a conclusion of the study. The equation developed is similar to that of L. J. Tison.

156. Anonymous, 1953. A plan of channel erosion control, Five Mile Creek, Riverton project, Wyoming. Hydrology Branch Project Planning Division, U.S. Bureau of Reclamation, Sedimentation Section, April 1953.

Proposed method of controlling bank erosion of Five Mile Creek by brush groins is presented.

157. Ahmad, Mushtaq, 1953. Experiments on design and behavior of spur dikes. Proceedings, Intern. Assoc. for Hydraulic Research, 6th Meeting, September 1-4, 1953, pp. 145-159.

The problem of scour depth at a spur dike was subjected to dimensional analysis to delineate terms important in the study. The effects of discharge, sand grade, flow concentration, and angle of attack on scour depth and pattern were investigated. A formula for scour depth was determined to be of the form $D = K q^{2/3}$. Ultimate scour was unaffected by a change in the grade of bed material and the rate of development of scour was believed to be much more rapid with fine than with coarse sand. Polar diagrams of scour around various types of spur dikes at varying angles with respect to the flow are shown.

158. Ahmad, Nazir, 1953. Mechanism of erosion below hydraulic works. Proceedings, Intern. Assoc. for Hydraulic Research, 6th Meeting, September 1-4, 1953, pp. 133-143.

The mechanism of erosion below hydraulic works is described. Low spillways only were studied. On the basis of data from several model studies the author concludes that the depth of scour holes below hydraulic works can be expressed as $\frac{R}{q^{2/3}}$ or $\frac{R^{3/2}}{q}$, a constant, irrespective of stable conditions, sand grade, discharge, and flow length. $R$ is hydraulic radius and $q$ is unit discharge. The constants of proportionality account for the effect of each parameter.

The mechanism of erosion below hydraulic works is due to the formation of eddies and the shedding of same. The collective effect of the eddies on the erodible bed is such that scour profiles of equal depth, developed by different discharges are similar irrespective of sand grade. Longitudinal profiles developed with a given discharge in the same sand, with different apron lengths, are different.

159. Doddiah Doddiah, Albertson, M. L. and Thomas, R. K., 1953. Scour from jets. Proceedings. Inter. Assoc. for Hydraulic Research, September 1-4, 1953, pp. 161-169.

A study of scour resulting from circular jets issuing vertically downward onto a bed of alluvial material by Doddiah, and Thomas' study of two-dimensional jet scour are reported. The study by Doddiah is reported independently in reference 129 and that by Thomas in reference 168. The circular jet study is developed from dimensional considerations, and conclude that scour is directly proportional to a geometric progression of time. The magnitude of scour decreases with a decrease in the ratio of the jet velocity to fall velocity, approaching zero as this ratio approaches unity. Scour increases with an increase in the depth of water over the bed up to a critical value, thereafter scour decreases. There are limitations in application to size of bed material. Much the same conclusions were reached for the two-dimensional study. The important conclusion from both studies is that scour progresses geometrically with time.

160. Homma, M., 1953. An experimental study of water fall. Proceedings. Intern. Assoc. for Hydraulic Research, September 1-4, 1953, pp. 477-481.

The study is concerned with establishing the differences in flow pattern between submerged jets and free falling jets of water. There is some difference to be expected for instance because of the entrained air. Through experimentation, it was determined that free falling jets of water cannot be separated into quasi-distinct zones of flow, such as has been observed for submerged jets (see reference 127). The rate of deceleration of the jet, was observed to be much larger for the free falling jet, hence scour potential is much less. Although scour is not treated specifically in this publication some interesting experimental observations on jets are noted.

161. Lane, E. W., 1953. Progress report on studies on the design of stable channels by the Bureau of Reclamation. Proceedings. Am. Soc. of Civil Engrs., Vol. 79, Separate No. 280, September 1953.

See abstract of USBR Lab Report No. Hyd-352, 1952, reference 146.

162. Laursen, E. M. and Toch, A., 1953. A generalized model study of scour around bridge piers and abutments. Intern. Assoc. for Hydraulic Research, September 1-4, 1953. pp. 123.

Four classes of variables are involved in a study of scour around bridge piers: (1) geometry of the piers, (2) flow characteristics, (3) sediment characteristics, and (4) geometry of the site. The first three variables were studied and for equilibrium flow conditions with a uniform sand, velocity and mean sediment diameter do not affect scour depth. The depth of flow is the determining factor. Hence, a model-prototype scale depends only on the flow depth. No scaling of the sediment transport was involved. Prior to reaching equilibrium depth, the greater scour depths achieved (with sediment transport) was explained by the concept of active scour and the imbalance between sediment supply and rate of scour. In the scour hole the angular velocity of the spiral roller is the chief transporting agent. The roller velocity is a function of the mean velocity of the flow and since the mean velocity is a function of the flow depth, equilibrium scour should be a function of depth only. An increase in mean velocity means an increase in the angular velocity of the roller. Therefore, an increase in the transport of sediment from upstream should be balanced by increased sediment transport in the scour hole with no change in the depth of scour. Also, an increase in flow depth means a decrease in the bed velocity with consequent decrease in sediment transport and therefore an increase of scour in order to maintain a balance of sediment transport.

163. Lawrie, W. G. A., 1953. The effects of scour on military bridge design. Road Abstracts, Vol. 20, No. 10, October 1953, p. 154.

See reference 154.

164. Danel, P., Durand, R., and Condolios, E., 1953. Introduction a l'etride de la saltation. (French) (Introduction to the study of saltation). La Houille Blanche, Vol. 8, No. 6, December 1953, pp. 815-829. Translation No. 319, U.S. Department of Interior, Bureau of Reclamation, Design and Construction Division, Technical Library, Denver, Colorado.

In this study the authors found that saltation was a fundamental process which, by its true nature, permitted development of other processes such as the simple sliding of grains. The observations of Gilbert and Bagnold in addition to those of the authors are used to further the theory of saltation. They explain that an upward motion is imparted to sand grains when in the field of turbulent fluctuation, the wake downstream and the roller upstream from the grain near the bed do not have time to develop with the same rhythm and the grain acts almost as if it were in a perfect fluid. Gilbert's explanation of grain take-off was centrifugal force because of the rapid rotation of the particles. The principle cause of saltation is the rapid increase in the hydrodynamic force acting on the grain. The wearing rate of grains depends on the intensity of the saltation action, therefore on the magnitude of the discharge.

165. Kindsvater, C. E., Carter, R. W., and Tracy, H. J., 1953. Computation of peak discharge at contractions. Geological Survey Circular 284, Washington 25, D.C.

The discharge equation for flow through a contraction as derived on the basis of the Bernoulli energy equation and the continuity equation. Several design curves for different types of contractions and of different contraction ratios are given.

166. Lane, E. W. and Borland, W. M., 1953. River-bed scour during floods. Proceedings. Am. Soc. of Civil Engrs., Vol. 79, Separate No. 254, pp. 1-13.

See reference 172.

167. Leopold, L. B. and Maddock, T., 1953. The channel geometry of stream channels and some physiographic implications. U.S. Geological Survey, Professional Paper 252, Washington, D.C.

Some hydraulic characteristics of stream channels - depth $D$, width $B$, velocity $V$, and suspended load $L_s$ are measured quantitatively. They vary with discharge, $Q$ as simple power functions at a given river cross section. Similar variations in relation to discharge exist among the cross sections along the length of a river under the condition that $Q$ at all points is equal in frequency of occurrence. The function derived for a given cross section and among various cross sections along the river differ only in the numerical values of the coefficients and exponents; $B = a\,Q^c$ ; $D = c\,Q^f$ ; $V = k\,Q^m$ ; $L_s = p\,Q^j$ . See reference 144.

168. Thomas, Robert K., 1953. Scour in a gravel bed at the base of a free overfall. Master's Thesis, Colorado A and M College, 1953.

The author found that the depth of scour below a free overfall increased rapidly following an increase in discharge, and slowly as the height of fall increased. Scour depths increased as the tailwater depth increased for high tailwater until a critical value was reached, beyond which further increases in the tailwater depth resulted in smaller scour depths. At low tailwater depths an optimum depth of tailwater occurred which resulted in a minimum depth of scour. At tailwater depths less than optimum, the downstream deposits were limited in height and the crest was rounded. The depth of scour increased with a geometric progression of time. An equilibrium depth of scour did not occur. The depth of scour was determined by using the Schoklitsch equation. An equation for the depth of scour was developed experimentally with the aid of dimensional analysis, using the following parameters $\frac{d_s}{h} = \Phi\left(\frac{h}{d_s}, \frac{qt}{H^2}, \frac{Hw}{q}, \sigma_w\right)$ where $d_s$ = depth of scour from the original bed surface, $h$ = tailwater depth, $H$ = height of fall from crest of drop to original bed, $q$ = rate of flow, $t$ = time of test, $w$ = geometric mean fall velocity of the bed material, $\sigma_w$ = geometric standard deviation of the fall velocity from $w$ . See also reference 159.

169. Schneible, D. E., 1954. Some field examples of scour at bridge piers and abutments. Better Roads, Vol. 24, No. 8, August 1954.

Three types of scour are defined: (1) Local scour occurring in the immediate vicinity of the pier or abutment as a result of a disturbed flow pattern around the structure; (2) general scour occurring in the vicinity of the entire bridge as a result of increased velocity caused by contraction of the flow area, and (3) stream-bed scour as a result of upsetting of the equilibrium of the stream flow. All three types of scour may occur simultaneously or separately. From model studies these conclusions result: (1) local scour action around a pier is the result of two factors, the increased velocity resulting from an obstruction in the flow, and the spiral eddy (roller) occurring across the upstream face of the pier. As the scour hole progresses, the roller becomes the active scouring agent. (2) As a result of the roller action, the upstream part of the scour hole has the approximate shape of an inverted cone, with the greatest depth just upstream from the face of the pier. (3) At a two-shafted pier the scour hole is deeper at the upstream shaft when the pier is aligned with the flow, or when the angle of attack is small. (4) At a webbed pier the scour depth increases with greater angles of attack. The area of deepest scour expands across the upstream part of the pier. (5) At an abutment the deepest scour occurs at the upstream corner of the abutment. (6) In the vicinity of an abutment the scour hole deepens with increasing contraction ratio (width of flow cut off by approach fills to the unrestricted width of flow) for the same discharge. (7) If unrestricted, the scour hole will increase in size until there is a balance between sediment transport into and out of the scour hole; thereby a condition of equilibrium is obtained. (8) When the scouring mechanism is active and equilibrium conditions have been attained, depth of flow rather than velocity of flow is a primary factor in the determination of the depth of scour.

170. Ditbrenner, E. E., Laursen, E. M., and Toch, A., 1954. Discussion of proceedings - separate 254, Am. Soc. of Civil Engrs. River-bed scour during floods. Proceedings, Am. Soc. of Civil Engrs., Vol. 80, Separate No. 479, August, 1954, p. 40.

Author Ditbrenner observes that all streams with a steep slope regardless of the sediment in which the channel is formed are flat-bottomed, wide and shallow. He also states that where bridge crossings on a stream are at a pool there is no build-up around the piers but where the bridge is built across the stream at a bar there is a build-up around the piers. The stream determines the dimensions of its channel. Only if a major change in regime occurs will the shape and size of the channel change.

Authors Laursen and Toch attempt to relate their approximate analysis of the magnitude of scour to be expected at a contraction, to river-bed scour during floods.

171. Hawthorne, W. R., 1954. Secondary circulation about struts and airfoils. Journal of Aeronautical Science, Vol. 21, p. 588.

Theoretical methods are developed to determine the relative magnitude of secondary flows. The theory assumes that the fluid is inviscid and incompressible and that the flow is a small disturbance of the two-dimensional potential pattern appropriate to the profile. Tests were run on piers in an alluvial channel and the author states that "it seems likely that the changes in river beds which occur around obstructions, and the depressions found in snow at the windward side of a tree or telegraph pole are caused by the scouring effect of the secondary flow."

172. Lane, E. W. and Borland, W. M., 1954. River-bed scour during floods. Transactions Am. Soc. of Civil Engrs., Vol. 119, 1954, p. 1069.

As a result of their studies the authors concluded that during floods the bed of the Rio Grande scours at the narrow sections and that most of the material is deposited in the next wide section downstream. This action causes the wide sections which may cause the stream to attack the banks. It was also concluded that the common opinion that there is a general lowering of the bed of such streams in flood is unsound.

173. Leliavsky, S., Bose, N. K., Nizery, and Braudeau, 1954. Discussion of proceedings - separate No. 280, Am. Soc. of Civil Engrs., Progress report on studies on the design of stable channels by the Bureau of Reclamation. Proceedings. Am. Soc. of Civil Engrs., Vol. 80, Separate No. 522, October 1954, 30 p.

Mr. Leliavsky indicates that stable channels are basically three dimensional and depending on the specific circumstances of the canal, diagonal tractive force might or might not be more important than parallel forces. He mentions that the granular bed in a diverging flume was noted by Professor White to be extremely active despite negligble mean drag. He believes that stable channels should be designed with consideration to the cross-current pattern.

Mr. Bose suggests that more attention should be given to inclusion of suitable sediment characteristics when considering stable channel problems.

174. Laursen, E. M. and Hubbard, P. G., 1954. Model - prototype comparison and bridge pier scour. Proceedings of the County Engineers Conference Iowa State College of Agriculture and Mechanical Arts, Ames, Iowa, 1954, pp. 30-45.

The effect of stream and sediment characteristics on scour were studied by models. It was found that after an active period of scour an equilibrium depth of scour was established as a temporal mean. This equilibrium depth of scour was not dependent on the velocity of flow or the sediment size, but was determined by the geometry of the pier and the depth of flow. The rate of scour during the active period was dependent on the velocity of flow and sediment size as well as geometry of the pier and depth of flow. During the active scour period, depths of scour in excess of the final equilibrium depth can occur. The observations and conclusions were rationalized by the concept of scour as an inbalance between the capacity for sediment movement in an area and the rate at which sediment is supplied to that area. If the capacity exceeds the supply rate, scour will occur. A good comparison was obtained between model and prototype on the simple basis of geometric depth ratio.

175. Anonymous, 1955. Causes leading to failure of the bridge on Yeshwantpur river and design of the new bridge. Central Water and Power Research Station, Poona, India, Technical Annual Report.

The causes leading to the failure of the railway bridge on the Yeshwantpur river and the new bridge are discussed. Four spans of the bridge (20 feet each span) collapsed on September 27, 1954. The river was 300-500 feet wide and the bridge was skewed about 30° from normal to the center line of the river. The foundations of the piers and the drop walls were not sufficiently deep. Using Lacey's regime depth multiplied by two and adding 1/2 of that depth from high flood level to determine the pier depth, the model study showed the inadequacy of the waterway and the shallow piers.

176. Ahmad, Mushtaq, 1955. Effect of scale distortion, size of model bed material and time scale on geometrical similarity of localized scour. Proceedings. Intern. Assoc. for Hydraulic Research. The Hague, Netherlands.

Use is made of a number of model investigations over a period of time in order to obtain data to study the geometric similarity of localized scour in relation to scale distortion, change in the size of bed material in the model and time scale.

The distortion of the model is calculated from the localized scour. The distortion $\delta = \frac{l}{D_r} = \frac{\tan \theta}{\frac{D_p}{L_p}}$, where l is the length scale, $D_r$ is the depth scale, $\theta$ is the angle of repose of the bed material, $D_p$ is the prototype depth, and $L_p$ is the prototype length. The time scale was calculated empirically from models.

177. Einstein, H. A. and Ning Chein, 1955. Effects of heavy sediment concentrations near the bed on velocity and sediment distribution. Institute of Engineering Research, University of California, in cooperation with the U.S. Army Corps of Engineers, Missouri River Division, MRD Sediment Series No. 8.

The assumption that suspended sediment has no effect on flow or sediment distribution is erroneous. Sediment distribution is highly skewed towards the bed. Turbulence, which keeps sediment in suspension is generated essentially at the bed and, therefore, the locally high sediment concentration near the bed naturally plays an important part in molding the turbulence pattern. This results in a flow which is completely different than that of clear water. The authors establish a preliminary theory of sediment transport using the effects of sediment concentration, velocity, and sediment distribution.

178. Hallmark, D. E., 1955. Scour at the base of a free overfall. Master's Thesis, Colorado A and M College, 1955.

The investigation concerned armor plating as a means of decreasing or preventing scour below a free overfall. The movement of particles from the scour hole was a function of unit discharge and tailwater depth. The use of armorplating materials considerably decreased the rate of scour. The greatest decrease was obtained by using graded gravels rather than a uniform size. The depth of scour continued to increase with a geometric progression of time. Only a relatively small amount of armorplating material was necessary to effect large decrease in the rate of scour. The rate of scour decreases with a decrease in the size of the armorplate material when the armorplate material remains larger than the largest particle size of the bed material. The rate of scour decreases with an increase in the amount of armorplate placed in the scour hole.

179. Hubbard, P. G., 1955. Field measurement of bridge-pier scour. Proceedings Highway Research Board, Washington, D.C., pp. 184-188.

An instrument which depends on the difference between the electrical conductivity of the stream and the bed material was developed. A series of electrodes were placed on a vertical line on a support near a bridge pier. These electrodes extended downward to below the maximum expected scour depth. Alternating current was then passed from each of these electrodes to a nearby common ground. The impedance to the flow of current through the bed is much greater than the impedance of the water, so that a continuous record of impedances at all measuring points will show a distinct difference at the bed level. A relationship between scour depth and water depth as predicted on the basis of earlier laboratory investigations was found.

180. Kindsvater, C. E. and Carter, R. W., 1955. Tranquil flow through open channel constrictions. Transactions Am. Soc. of Civil Engrs., Vol. 120, 1955, pp. 955-991.

The authors experiments and efforts to determine the discharge coefficients through contracted openings in open channels are reviewed. Consideration is given to different degrees of opening, varying degree of channel roughness and the effect of edge conditions of the contraction.

181. Lane, E. W., 1955. Design of stable channels. Transactions Am. Soc. of Civil Engrs., Vol. 120, 1955, pp. 1234-1260.

Mr. Lane summarized previous work in which limiting velocities for various non-cohesive and cohesive sediments are presented as the criteria for stable channel design. A safe tractive force is recommended as a basis for stable channel design. For channels in cohesive soil, tabular values of the tractive force are presented as determined by previous investigators.

182. Laursen, E. M., 1955. Model-prototype comparisons of bridge-pier scour. Proceedings, Highway Research Board, Vol. 34, 1955, pp. 138-193.

The second phase of a laboratory project concerned with the effect of stream and sediment characteristics on scour is reported. After an active period of scouring, an equilibrium depth of scour is established as a temporal mean. This equilibrium depth appears to be independent of the velocity of flow and sediment size, varying only with the form and size of pier and the depth of flow. The rate of scour during the active period, however, is dependent on the velocity of flow and the sediment size as well as pier characteristics and flow depth. In the laboratory it was found that during the active period, depths of scour in excess of the final equilibrium depth could occur. Quantitative comparisons of scour around bridge piers and abutments have indicated that the same patterns of scour can be expected in the field as in the laboratory. The concept of scour in this report is the inbalance between the capacity for sediment movement in an area and the rate at which sediment is supplied to that area.

183. Leliavsky, S., 1955. Basic scour criteria: Pick-up velocity, drag, and lift. An introduction to Fluvial Hydraulics, 1955, pp. 35-68.

The text book provides a review of the important investigations on scour up to the date of the publication.

184. Leliavsky, S., 1955. Irrigation and Hydraulic Design. Vol. 1, Chapman and Hall, London, 1955, p. 204.

Scour is discussed and also methods of computing works to protect against it. The equation of Bligh, $B = 10\ c\left(\sqrt{\frac{H}{10}}\right)\left(\sqrt{\frac{q}{75}}\right)$ where $B$ = overall width of works protecting the bed against scour, $c$ = a coefficient of the material of the channel, $q$ = unit discharge and $H$ = height of fall from crest to downstream water level is used. The formula by Khosla (first suggested by Lacey) $D_s = 2.74\ q^{0.61}$ where $D_s$ = depth of scour as measured from the water surface is also given. When a barrage or a weir is built across a river the depth of extra scour resulting from the additional turbulence caused by the new obstruction is proportional to the value of $D_s$. Some computations are checked with measured values.

185. Anonymous, 1956. Unique willow mattress to protect pier construction. Roads and Streets, Vol. 99, No. 1, January 1956, p. 86.

A 3-1/2 acre mattress of woven willows was ballasted with rock and placed at the base of bridge piers of a bridge in New Orleans to prevent scour.

186. Anonymous, 1956. Willow mattress sunk to river bed. Construction methods and equipment, Vol. 38, No. 1, January 1956, p. 82.

See reference 185.

187. Anonymous, 1956. Flood provides formula covering bridge scour. Cuts and Fills (Conneticut), Vol. 14, No. 4, April 1956. p. 4.

See references 203 and 215.

188. Anonymous, 1956. Mission-Matsqui bridge protected from erosion. Construction World (Canada) Vol. 11, No. 7, May 1956, p. 62.

Steel reinforced concrete tiles eleven-foot square by ten inches thick were laid on the bed of the Fraser River to combat erosion at the bridge site. A mattress of brush bundles were placed across the Fraser beyond the concrete work and these were covered with three feet of rock. See also reference 189.

189. Anonymous, 1956. River bed is paved. Engineering News-Record, Vol. 156, No. 18, May 3, 1956, p. 70, 72.

In July of 1955 scour caused a pier of the Mission-Matsqui bridge to fail and a 150 foot section of the steel bridge fell in to the Fraser river. The scour hole at the pier was reportedly ninety-feet deep. To prevent further erosion, one-hundred feet downstream and sixty feet upstream of the bridge was paved with concrete blocks eleven-foot square and ten-inches thick. At the downstream end of the concrete paving brush mattresses loaded with rock were placed to prevent scour and undermining of the seventy-two foot steel piles used.

190. Laursen, E. M. and Toch, A., 1956. Scour around bridge piers and abutments. Iowa Highway Research Board Bulletin No. 4, May 1956.

Experimental studies were made at the Iowa University Hydraulic Laboratory to study the effect of pier and abutment geometry on scour. Scour arrestors were also studied and some debris tests were made. Skewed piers were included in the investigation. It was found that scour depth is closely related to flow depth and the degree of local disturbance. Streamlining is effective only for aligned flow. Scour arrestors must extend laterally as well as forwards. Debris collects on the upstream nose of the piers and is equivalent to a wider pier, causing deeper scour and a larger scour hole.

There is no effect of flow contraction on pier scour if the piers total less than 10 percent of the flow width. Since depth of flow is the only significant influence on scour, the scour depth scale in the model is strictly a geometric scale. Equilibrium depth in the model can be equated to maximum depth in the field. Some examples for design and design curves are given.

191. Chabert, J. and Engeldinger, P., 1956. Etude des affouillements autour des piles de ponts (French). (Study of scour around bridge piers). National Hydraulic Laboratory, Chatou, France, Series A, October, 1956.

Studies were performed in a laboratory flume to study scour around bridge piers. The investigation was divided into three main parts: (1) tests on circular piers, (2) tests of different pier shapes, and (3) tests on scour protection devices. The important conclusion of this investigation was that scour depth reached a maximum for velocities approximately corresponding to beginning of bed transport (dunes). Empirical relationships were found for the equilibrium depth of scour around piers but could not be related to the prototype because of the lack of a similarity relationship. Protective devices to retard scour were studied. Among those providing greatest success were piles placed upstream of the piers. These piles caused scour and the material was deposited at the base of the pier downstream.

192. Khaskind, M. D., 1956. K teorii nanosov, o dvizhenij tyazheloi chastitsy v turbulentnom potoke (Russian). (About the theory of sediment movement of heavy particles in turbulent flow). Akademiya Nauk SSSR, Izvestiya. Otdelenie tekhnicheskikh Nauk n, II November 1956, pp. 28-39.

The theory of alluvium formation; motion of heavy particles in turbulent flow; forces acting on a particle; slow pulsations of turbulent flow; progressive motion of particles under conditions of the quadratic law of resistance; and the lift properties of a particle are presented in this article.

193. Posey, C. J. and Warnock, R. G., 1956. Tests of erosion around models of submerged oil-drilling barges. Rocky Mountain Hydraulic Laboratory, Allenspark, Colorado, in co-operation with Bethlehem Steel Company, Shipbuilding Division, Beaumont, Texas, November, 1956.

See reference 152.

194. Anonymous, 1956. River control for bridges and their protection works. Manual on River Behaviour, Control and Training, Chapter VI, Central Board of Irrigation and Power, Publication No. 6, New Delhi, December 26, 1956.

The chapter discusses location of bridges, determining lengths of bridges and guide banks to the bridge. The studies of Spring and Gale are cited.

Spring estimated scour depth to be: normal scour - 30 to 40 feet, abnormal scour - 60 to 100 feet, extraordinary scour - 80 to 120 feet. (See also reference 10).

Gales estimated scour depth to be 0.33 to 2.5 times the regime depth in unobstructed channels. (reference 59) The recommended criteria for calculating maximum pier scour is $D_s = 2D_L = 2(0.47)\left(\frac{Q}{f}\right)^{1/3}$ which is two times the Lacey regime depth where f is silt factor, $D_s$ is scour depth and $D_L$ is Lacey regime depth.

195. Glauert, M. B., 1956. The wall jet. Journal of Fluid Mechanics, Vol. 1, 1956, pp. 625-643.

The flow due to a jet spreading out over a plane surface, either radially or in two dimension is considered. For laminar flow the velocity distribution across the jet is obtained, and for turbulent flow predictions are made about the rate of growth of the wall jet. The theory is developed for a radial jet and the modifications necessary to analyze the plane wall jet are noted.

196. Iwagaki, Y., and Tsuchiya, Y., 1956. Fundamental study of critical tractive force, Part I Hydrodynamical study on critical tractive force (Iwagaki). Part II On the critical tractive force for gravels on a granular bed in turbulent stream, (Tsuchiya). (Japanese). Transactions of the Japanese Society of Civil Engineers, No. 41, 1956.

In Part I, the basic idea of the author's theory is to visualize the equilibrium condition using the forces which are acting on a spherical grain of sand, i.e., gravity, fluid resistance, pressure gradient, and to evaluate these forces. Considering velocity fluctuation in the process, the concepts of the mixing length of turbulence and the minimum scale of eddies in turbulence theory are utilized.

A dimensionless function of critical tractive force is developed from the analysis and an experimental constant, named as the sheltering coefficient, is introduced to this function to agree with experimental results obtained with a small water tunnel having a uniform and square cross section. On the basis of the experimental results and theoretical relationships, a new formula for critical tractive force is developed and compared with the empirical formulas proposed by many investigators.

Part II. Theoretical considerations on the incipient motion of spheres on a fixed granular bed are made by means of the same treatment as in Part I. The dimensionless critical tractive forces are expressed as a function of the roughness Reynolds number with respect to granular beds, and the ratio of the diameter of the sphere to bed material. The developed function appears to represent satisfactory agreement with the experimental data. Critical tractive force for mixed sand and gravel is discussed.

197. Laursen, E. M., 1956. River-bed scour at bridge foundations. Proceedings of the Symposium on Geology as Applied to Highway Engineering, 1956, pp. 36-44.

This article compares the geologists concept of equilibrium to the engineer's concept. Lowering of the stream bed in the vicinity of piers and abutments can be ascribed to three causes; local scour due to distortion of the flow pattern by the pier itself, general scour due to disturbance of the flow pattern by the overall bridge-crossing geometry, and any degradation of the stream which may occur whether natural or caused by the works of man. For turbulent flow such as is found in a river, the boundary geometry will determine the flow pattern around an obstruction such as a pier. A spiral roller within the scour hole is the active agent of erosion and transportation. Until the scour holes from adjacent piers meet, the contraction of the flow does not appear to have any influence on the depth of scour. If the pier is not aligned with the flow, the scour depth at zero angle of attack is multiplied by a factor greater than one, which factor depends on the attack and the length to width ratio of the pier. Only if the pier is aligned with the flow can the effect of a rounded or streamlined pier shape be considered. Basically all scour phenomena are similar in that for any flow pattern there will be an equilibrium bed configuration so that at every point the capacity for transport is exactly equal to the rate at which sediment is supplied. General scour at a bridge crossing differs from local scour only in the factors which affect the flow pattern, or more specifically the pattern of sediment-transport capacity. Cutoffs or stream straightenings will cause degradation upstream approximately equal to the slope of the stream multiplied by the reduction in the length of the stream. Any disturbance of the normal functioning of a stream which effectively increases the capacity for transport or decreases the sediment supply will result in a tendency for degradation. Successful application of the proposed method of predicting local scour and of its anticipated counterpart for general scour depends on an understanding of the general nature of the scour phenomenon, an ability to visualize flow patterns, and a knowledge of the behaviour of the individual stream.

198. Lighthill, M. J., 1956. Drift. Journal of Fluid Mechanics, Vol. 1, 1956, pp. 31-53.

It is shown how secondary flows can be evaluated by use of a "drift function," $t$, such that material surfaces initially at right angles to the stream, drift into shapes expressible by equations $t$ = constant. Drift past a sphere is computed and illustrated and the secondary vorticity field is tabulated. A detailed study is also made of the asymptotic form of the secondary velocity field in flow past any body.

199. Livesey, J. L., 1956. The behavior of transverse cylindrical and forward facing total pressure probes in transverse total pressure gradients. Journal of Aero Science, Vol. 23, p. 949.

This paper gives the result of the investigation of the effect of transverse total pressure gradients on the displacement of the effective center of a total pressure probe toward the higher total pressure. An estimate of the error is given for the transverse cylindrical type of probe, and the error due to the position of the hole, depth of the hole, and the wall proximity with this type of probe. It was found that errors due to the position of the hole will be negligible if the hole is at least 2.1 diameters of the probe distance from the end of the probe.

200. Anonymous, 1957. How derrick stone is specified for Oahe. Engrg. News-Record, Vol. 158, No. 8, February 21, 1957, p. 239.

For a distance of seventy-five feet downstream from the spillway, ten-foot thick boulders are specified, which must be square rectangular or oval in cross section with the least dimension not less than 1/3 the greatest dimension. The stones must weigh at least 160 pounds per cubic foot.

201. Witzigman, F. S., 1957. Degradation below Garrison Dam, observations in 1954. U.S. Army Engineer Division, Missouri River, Corps of Engineers, Omaha, Nebraska, M.R.D. Sediment Memorandum No. 3, April 1957.

Degradation of the Missouri River below Garrison Dam was investigated and related to the operation of the reservoir. Graphs of the changes in the river bed and the cumulative scour are given.

202. Anonymous, 1957. Spur dikes at bridge ends streamline flow. Better Roads, Vol. 27, No. 7, July 1957, p. 42-46.

An elliptic spur dike or guide bank is recommended to be placed at the upstream side of bridge abutments to reduce scour at the abutments and to increase the efficiency of waterway through the bridge.

203. Moulton, L. K., Belcher, C., and Butler, B. E., 1957. Report on investigation of scour at bridges caused by floods of 1955. Highway Research Abstracts, Vol. 27, No. 8, September 1957, pp. 14-31.

The authors discuss the loss of bridges in the floods of 1955. Losses were attributed to: undermining of the foundations, debris blocking the flow area, impact and vibration by the flood waters, and rip rap and slope paving failures. The shape of the waterway area of the bridges relative to the shape of the approach channel was concluded to have a definite effect on the depth of scour. The equilibrium depth of scour is independent of both the velocity of flow and the sediment particle size. However, the rate of scour is dependent on both of these factors. If the approach flow to a bridge is not carrying a load of sediment equal to its transport capacity potential, scour may result under the bridge, even if the change in transport capacity at the bridge is insignificant. The authors present an analysis of scour and develop some equations and design curves.

204. Blench, T., 1957. Regime Behaviour of Canals and Rivers. Butterworths Scientific Publications, London and Toronto.

If a river engineer estimates the scour to be expected at a bridge for which there is no discharge records he can guess the peak flood 30 percent wrong and be only 10 percent wrong in the estimated scour, while if he tries to deduce the probable peak flood of a river from observations of the scoured depth, the error due to selecting a depth 30 percent wrong may give 100 percent error in estimating the flood. The author's rule for determining the maximum scour depth found in a freely meandering channel, without obstacles that interfere in any way with normal meander curvature, is 1.70 times the regime depth of the approaching straight channel. The facts show that bed-material size is relevant to scoured depth. There is reason to believe that charge, up to a limit, does not reduce the scour at an obstacle such as a spur nose. A procedure is outlined for the placing of an apron to prevent scour. The horizontal extent of the scour hole in a model is N times the horizontal extent of the prototype, where N is the vertical exaggeration in the model. The theory and applicability of model results to prototype are discussed.

205. Lighthill, M. J., 1957. Corrigenda to drift. Journal of Fluid Mechanics, Vol. 2, 1957, p. 311.

Corrections to be made to equations presented in reference 198, due to further study.

206. Liu, H. K., Bradley, J. N., and Plate, E. J., 1957. Backwater effects of piers and abutments. Colorado State University Report No. CER57HKL10, 1957.

The experimental data from models of wing wall, spill through and vertical board abutments and with piers are analyzed. For the vertical board it was found that $\left(\frac{y_1}{y_n}\right)^3 - 1 = 4.83\, F^2 \left[\frac{1}{\alpha^2} - \frac{2}{3}(25 - \alpha)\right]$ where $y_1$ = depth of flow at section 1 with the model in place, $y_n$ = normal depth in the channel with the model removed, F = Froude number at normal flow with the model removed, $\alpha = \frac{B-b}{B}$ = the ratio of the width of opening between abutments to the width of the channel upstream of the abutments. For wing wall and spill through models it was found that the effect of abutment geometry on the maximum backwater changes with the Froude number, F . For skew angles of less than $15^{\circ}$ the flow depths at the two upstream stagnation points were not affected appreciably. For eccentric crossings the maximum backwater was not affected for the vertical board model. Data were analyzed from the viewpoints of fluid mechanics and of the practicing engineer.

207. Mostafa, M. Gamal, 1957. River-bed degradation below large capacity reservoirs. Transactions, Am. Soc. of Civil Engineers, Vol. 122, 1957, pp. 688-695.

The author computes the rate of degradation (below a dam) by a trial and error method. A section, distance "L" from the dam which is assumed to be the range of scour during the first time interval, then the sediment-transport ability of the existing hydraulic condition is computed. A certain amount of scour is assumed at the chosen section, the volume of which should be equal to the difference between load passing the section during the interval and the load entering the section. The section is then re-analyzed for transportability. The author suggests use of Straub's equation, reference 68, for the trial computations. The sediment diameter which should be used is the mean size for the first time period and gradually increased, reaching from 90 to 98 percent finer, for the last time period in which degradation appears to approach asymptotically its maximum value for equilibrium.

208. Posey, Chesley J., 1957. Flood erosion protection for highway fills. Transactions, Am. Soc. of Civil Engrs., Vol. 122, 1957, p. 531.

Tests were made using T-V gradation rock blankets on highway fill embankments and found to function well until submerged under considerable water. Tests were then made using the T-V gradation blankets covered with "rock sausages," (sacks of wire screen filled with rocks). These devices worked rather well. The reasons for some bridge failures, the value of low approaches to the bridges, and methods of remedy are discussed.

209. Smith, G. L., 1957. An analysis of scour below culvert outlets. Master's Thesis, Colorado State University, pp. 1-152.

It was found that the depth of scour below culvert outlets continues with a geometric progression of time, the volume of scour increases proportionally to the logarithm of the energy of the jet as it strikes the tailwater surface. The scour rate is the same at all tailwater depths less than the "critical" tailwater depth. For all tailwater depths above critical a given increase in jet energy will produce a smaller volume of scour than for a tailwater depth which is less than critical. For tailwater depths below critical, experimental data indicates the volume of scour is independent of discharge and tailwater depth, provided the jet energy is held constant.

210. Smith, G. L., 1957. Scour and energy dissipation below culvert outlets. Report of the Department of Civil Engineering, Colorado A and M College, pp. 1-122.

See reference 209.

211. Tison, L J., 1957. Essais sur modele reduit pour la prise d'eau sur la Leviro (French) (Congo Belge) (Model study for the water intake from the Leviro) International Association for Hydraulic Research, General Assembly, September 1957.

Theoretical basis for designing a small water intake is presented in this paper. Model tests were made to study the skewed flow distribution and confirmed the bed-load transportation theory. A vertical roller caused by a discontinuity in the plan of a structure plays an important role in the bed-load transportation.

212. Laursen, E. M., 1958. The total sediment load of streams. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 84, No. HY1, February, 1958.

The author discusses methods currently (1958) in use in sediment transport. The shortcomings of these methods are listed and an equation is developed by the use of qualitative analysis of original experiments of a specialized nature and use of supplementary data from other sources. The developed equation is

$$\bar{c} = \Sigma p \left(\frac{\partial}{\partial D}\right)^{7/6} \left(\frac{\tau_o}{\tau_c} - 1\right) f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right) \text{ where } \bar{c} =$$

mean concentration, $p$ = fraction of bed material of diameter $\partial$ , $\tau_o$ = boundary shear associated with sediment particles, $\tau_c$ = critical tractive force for beginning of movement, $\tau_o$ = boundary shear at stream bed ($\sqrt{y}$ s), $\partial$ = diameter of sediment particle in feet, $y$ = depth of flow in feet, $f$ = Weisbach resistance coefficient, $\rho$ = density of water, $w$ = fall velocity of sediment particle. The author checks the equation with field data obtained from several sources. He also gives a curve of the equation.

213. Anonymous, 1958. Scouring eliminated in Yarmouth harbour. Engineering (Great Britain), Vol. 185, No. 4810, May 16, 1958, p. 625.

Serious undermining of the foundations of a bridge at the entrance to Great Yarmouth harbour caused scour below the piers. Experiments at Wallingford indicated that curved pier noses would solve the problem of scour.

214. Moulton, L. K., Belcher, C., and Butler, B. E., 1958. Report on an investigation of scour at bridges caused by floods. Civil Engineering and Public Works Review (Great Britain), Vol. 53, No. 624, June 1958, p. 669.

See reference 203.

215. Inglis, C. C. and Kestner, F. J. T., 1958. Changes in Wash (Bay) as affected by training walls and reclamation works. Institution of Civil Engineers, Proceedings, Vol. 11, Paper No. 6340, p. 435-466, December 1958, (discussion), Vol. 13, July 1959, p. 393-407.

This paper describes the changes that have taken place in the loose boundary of the Wash in historic times, with particular reference to the effects of engineering works constructed to reclaim land to train navigation channels, or to improve farmland drainage. Field studies to determine current changes are described. The results of these studies have been linked with observations of suspended sediment concentrations from different stations in the Wash. The mechanism of scour and accretion, and the marked accelerating effect of engineering works on the rate of accretion are also discussed.

216. Iwagaki, Y., Smith, G. L., and Albertson, M. L., 1958. Analytical study of the mechanics of scour for three-dimensional jet. Presented at Am. Soc. of Civil Engrs. Hydraulics Conference, Atlanta, Georgia, August 20, 1958, Colorado State University Research Foundation, Fort Collins, Colorado.

See reference 250.

217. Reddoch, A. F., 1958. River control work in non-tidal section of Hunter River and its tributaries. Institution of Engineers, Australia, Journal, Vol. 29, No. 10-11, October-November, 1952, p. 241-247.

The methods used in attempting to control bank erosion of the Hunter River is discussed. Willow mats, tree tops, rock passages, planted willows and other things were used. The failure of most of these methods by undermining or outflanking is told. The policy now is to attempt to control the alignment of the stream and then protect the river banks wherever they are eroding.

218. Davies, R. W., 1958. Turbulent diffusion and errosion. Journal of Applied Physics, Vol. 23, 1952, pp. 941-948.

This paper is a mathematical treatment of turbulent diffusion and a one-dimensional model of the mass transport phenomena. A steady-state suspension of particles in a turbulent stream is treated like an atmosphere. Dimensional arguments are used to retain the most relevant physical entities in a linear theory. It is shown that the bed-load and wind-stream suspension of a muddy stream cannot be treated separately. A qualitative theory of sand rippling is explained in terms of the instability of a flat sand bottom under certain turbulence conditions. The advantage of the theory is that all the statistical coefficients are averages of familiar dynamical quantities.

219. Izzard, C. F. and Bradley, J. N., 1958. Field verification of model tests on flow through highway bridges and culverts. Proceedings of the 7th Hydraulic Conference, Iowa, 1958, pp. 225-243.

This is mostly a discussion of the applicability of model results to prototype structures. Scour studies at Colorado State University and Iowa University are discussed. Constriction of a channel by spur dikes appears to produce practically no alteration in the shape of stream lines near the center of the channel, but the lines are deformed and close together near the abutments indicating concentration of flow. The areas adjacent to the abutments is most vulnerable to attack by scour. Curves for degree of channel constriction versus $\frac{z_1}{z_3}$ ($z_1$ = rise of water upstream of constriction, $z_3$ = fall in water surface downstream of constriction) are given. Regardless of the degree of constriction, the deepest scour occurs at the abutments and along the upstream face of the embankments. The angle the scour hole sides make with the horizontal appears to depend on the size, gradation and cohesive properties of the material composing the bed, and on the geometry of the abutment used. From model and field data the authors present an equation for the depth of scour, $d_s = 1.40\ q^{2/3}$ where $q$ = unit discharge.

220. Laursen, E. M., 1958. Scour at bridge crossings. Iowa Highway Research Board Bulletin No. 8, prepared by the Iowa Institute of Hydraulic Research, pp. 1-53.

Scour depth equations are developed for abutments of a bridge which are near the main channel banks. These equations are based on the concept of scour in a long contraction using Laursen's total sediment load equations (reference 212). The assumptions are:

(a) flow in the approach channel and the contracted region are uniform,
(b) sediment transport in the overbank is negligible,
(c) sediment transport equations of Laursen apply,
(d) roughness in the approach main channel and constricted regions are the same,
(e) depth ratios are independent of the sediment transport mode,
(f) assume streamlines further than $2.75\ d_s$ from the abutment are unaffected by the abutment, where $d_s$ is scour depth,
(g) depth of scour in a long contraction of a bridge section can be represented by $\frac{1}{r} d_s$.

The equations are limited to scour holes at abutments which overlap, when discharges on the overbank is not significantly larger than the flow along the main channel and to streams where sediment transport exists in the main channel. The equations developed are:

$$\frac{Q_o b}{Q_b y_o} = 2.75 \frac{d_s}{y_\sigma}\left[\left(\frac{1}{\gamma}\frac{d_s}{y_o} + 1\right)^{7/6} - 1\right]$$ General (bed transport only) where $\tau_o >> \tau_c$, (suspended sediment transport largely)

$$\frac{Q_o b}{Q_b y_o} = 2.75 \frac{d_s}{y_o} \left[ \frac{\left(\frac{1}{\gamma} \frac{d_s}{y_o} + 1\right)^{7/6}}{\left(1 - \frac{1}{t}\right)^{1/3+a}} - 1 \right] ,$$

$$t = \frac{\tau_o'}{\tau_o} = \frac{(Q_o + Q_b)^2}{120\ b^2\ y^{7/3}\ d^{2/3}} .$$

221. Dunn, I.S., 1959. Tractive resistance of cohesive channels. Journal of the Soil Mechanics and Foundations Division, Proceedings, Am. Soc. of Civil Engrs., June, 1959.

A submerged jet was utilized to determine the tractive resistance of cohesive sediments. In the tests, the surface of a cohesive soil sample was subjected to the erosive action of a jet. The head of water on a nozzle placed vertically above the sample was increased until an initial erosion of the sample took place. It was found that initial scour occurred a short distance away from the center line of the jet and that this location was unaffected by a change in the head on the nozzle or by a change in the elevation of the nozzle above the sample. The magnitude of the tractive force causing scour was measured by replacing the soil particles and having a shear plate at the position of the initial scour. The critical shear stress was then related to the shear strength of the soil as determined from a vane test.

222. Stiefel, R. C., 1959. Scour at relief bridges. Master's Thesis, State University of Iowa, Iowa City, Iowa, August 1959.

Clear-water scour is discussed in this paper. The author found that the final or equilibrium depth of clear-water scour is dependent upon the mean velocity of flow, the particle size in the vicinity of the abutment, and the geometry of the abutment. The equilibrium depth of clear-water scour increases as the mean velocity of flow increases, the particle size in the vicinity of the abutment decreases, and the length of the abutment increases. No effect of the depth of flow on the equilibrium depth of clear-water scour could be found. The capacity curve for scour found for the case where sediment is supplied can be extrapolated to the equilibrium condition of clear-water scour.

223. Karaki, S. S., 1959. Hydraulic model study of spur dikes for highway bridge openings. Report CER59SSK36, Colorado State University, Fort Collins, Colorado, September, 1959.

A qualitiative study was made in the laboratory to determine length, location, shape and riprap protection required for spur dikes at the entrance to bridge openings to reduce local scour there. A quarter ellipse with major to minor axis ratio of 2-1/2 = 1 with 2:1 side slopes and riprap protection around the nose to be desirable.

224. Poreh, M. and Cermak, J. E., 1959. Flow characteristics of a circular submerged jet impinging normally on a smooth boundary. Paper prepared for the Sixth Annual Conference on Fluid Mechanics held at the University of Texas, Austin, Texas, September, 1959. Colorado State University Report No. CER59MP-JEC67.

The transverse velocity distributions outside the boundary layer for a circular jet impinging normally on a flat plate, both for the zone of established flow in the direction of the jet and in the zone of radial flow are derived.

225. Smerdon, E. T. and Beasley, R. P., 1959. The tractive force theory applied to stability of open channels in cohesive soils. Missouri University Agricultural Experiment Station Bulletin 715, October 1959, 36 p.

The tractive force theory was applied to the study of stability of open channels in cohesive soils. Tests were performed in which soil samples were placed in the bottom of a flume. Water was allowed to flow through the flume and over the sample until bed failure was noted. The bed was considered to have failed when the tractive was large enough to cause general movement of the bed material. For the soils tested, the initial tractive force was related to such properties as the plasticity index, disperison ratio, mean particle size, and percentage of clay.

226. Elevatorski, E. A., 1959. Erosion below dams. Hydraulic Energy Dissipators, 1959, p. 204-208.

The inadequacy of stilling basins, erosion below dams, and the failures due to erosion are discussed.

227. Iwagaki, Y. and Tsuchiya, Y., 1959. Boundary layer growth in wall jets issuing from a submerged outlet. (Japanese) Proceedings of the 9th Japan National Congress for Applied Mechanics, 1959.

The boundary layer growth in wall jets is analysed and interpreted with the assistance of the momentum equation. The characteristics of the diffusion of a wall jet, boundary layer growth and resistance laws are discussed on the basis of the experimental wall jets issuing from a submerged outlet. The comparison of experimental results with theory indicate satisfactory agreement.

228. de Sousa Pinto, Nelson, L., 1959. Rip rap protection against scour around bridge piers. Master's Thesis, State University of Iowa, Iowa City, Iowa, 1959.

Experiments were performed to determine the feasibility of preventing scour around piers by the use of a graded filter. The effect of the lateral extent of the filter, depth below the bed level, and shape of the filter were studied. It was concluded that the T-V graded filter will adequately prevent erosion around piers if the proper conditions are met. The equation $\frac{a}{b} = k \frac{(d_s - p)}{b}$ was derived, where a = lateral extent of the protective layer, b = diameter of the pier, $d_s$ = depth of scour without protection, p = depth of the layer below bed level, and k = a constant, in the case of this study, 1.8. Only one thickness of filter was used during these tests.

229. de Sousa Pinto, Nelson, L., Sybert, J. H. and Posey, C. J., 1959. Model tests of rip rap scour protection. Report on tests made at the Rocky Mountain Hydraulic Laboratory under the sponsorship of the Standard Oil Company of Texas and the California Research Corporation, Report No. 23, Allenspark, Colorado, December, 1959.

The results of laboratory tests on scour around submersible oil-drilling platforms are discussed. Coal dust was used in some of the tests in order to achieve sufficient sediment movement. It was found that adequate protection could be obtained around the platform if a T-V graded filter was placed around the piers in such a way as to cover the extent of the scour hole which would develop without the filter protection.

230. Poreh, M., 1959. Flow characteristics of a circular submerged jet impinging normally on a smooth boundary. Master's Thesis, Colorado State University, Fort Collins, Colorado, 1959.

The diffusion of a circular submerged jet impinging on a solid smooth boundary normal to the jet axis is characterized by the deflection of the jet through the action of the boundary, thus dividing the space into various zones with distinct patterns of flow and diffusion. The flow may be divided into natural zones of flow establishment, established flow in the direction of the jet axis, deflection, and established radial flow. In the zone of established flow in the direction of the jet axis the velocities are proportional to the distance from the origin. The velocity distribution in the transverse plane agrees with the theoretical solution by Goertler. Experimental data can be represented by the error function. In the neighborhood of the stagnation point the flow is almost identical with that computed on the basis of irrotational flow. Here the velocities and pressures are related by Bernoulli's equation. In the region of boundary layer development the radial velocity deviates from the approximating jet profile. The representation of the velocity profile in the region where $z > \delta$ by an error function is also satisfactory.

231. Laursen, E. M., 1960. Scour at bridge crossings. Journal of the Hydraulics Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY 2, Paper No. 2369, February, 1960, pp. 39-54.

For local scour at highway embankments extending to the edge of the main channel, with no sediment transport in the overbank flow, and overlapping of the scour holes at the abutments, the maximum depth of local scour is equal to four times the depth of scour due to a long contraction. If there is no overlapping of scour and the embankment extends into the main channel, the local scour may be twelve times the general scour.

Local scour depends only on the normal depth of flow and the geometry of the obstruction. It is independent of sediment size and flow velocity. Therefore, flow intensity is insignificant to scour. See also references 220 and 290.

232. Anonymous, 1960. Rock blanket for Blythe Bridge-32 years ago and now. Southwest Builder and Contractor, March 11, 1960.

The method used to construct a flexible rock mattress for each of the piers of the new bridge across the Colorado River at Blythe is presented. Half-inch wire cable on 3 foot centers was first placed, both parallel and perpendicular to the flow direction. Fourteen gage 4" x 4" wire mesh was then fastened to these cables. Boulders weighing from 75 to 150 pounds were placed on top of the cables to a minimum depth of one foot and three inches. Wire cable and wire mesh were then placed on top of the boulders and the top and bottom wire mesh were fastened together. The mattresses were intended as a precautionary protection measure for the footings.

233. Parker, P. I., 1960. Pahlavi Foundation Bridge. Civil Engineering and Public Works Review, Vol. 55, No. 644, March 1960, pp. 384-386.

The specifications of the bridge and the foundations are given.

234. Blench, T., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulics Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY5, May, 1960, pp. 193-194.

The writer indicates that Laursen's work appears to follow the regime theory equations. Blench believes that bed load is more effective in determining the depth of scour than total load.

235. Bradley, J. N., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulics Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY8, Part 1, August, 1960, pp. 69-70.

Model results are not valid for application to rivers in the United States because in the model, with ideal conditions imposed, the velocity is uniformly distributed and scour is concentrated at the abutments but in rivers with non-rectangular cross sections the velocity is is non-uniformly distributed and maximum scour is most likely to be found in a portion of the channel where the depth of flow and velocity are greatest.

236. Whipple, W., 1960. Arkansas River plan. Proceedings, Journal of the Waterways and Harbors Division, Am. Soc. of Civil Engrs., Vol. 86, No. WW3, Part 1, September 1960, pp. 15-28.

The revision of the development plan for the Arkansas River for navigation purposes is discussed. The plan is to dredge portions of the channel and contract these sections in order to maintain the sediment transport capacity. By so doing navigable depths of water can be obtained. This will help eliminate three proposed dams which were at first considered necessary for obtaining the navigable depths. The bed material load was computed by the equation $\frac{Q_s}{Q} = D^{1.1} S^{2.3}$ where $Q_s$ = bed material load, $Q$ = discharge, $D$ = mean depth, $S$ = slope.

237. Herbich, J. B., 1960. The effect of spur dikes on flood flows through bridge constrictions. Preliminary paper prepared for presentation to the ASCE Convention in Boston, October 14, 1960, Hydraulic Division Report, Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University, Bethlehem, Pennsylvania.

The scour damage which occurred to bridges in Connecticut in 1955 are cited. Experimental studies were conducted to determine the required shape and size of dikes necessary, for generalized conditions at a bridge, using a rigid bed flume. A rigid flume was justified because several variables were eliminated from the study. The studies amounted to improvement of flow through a two-dimensional contraction. Only small openings were considered.

238. Colby, B. R., 1960. Average scour and fill in sand-bed streams. Watershed Technology Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, USDA, Research Report No. 336, October 25, 1960.

The principles of scour and fill are discussed. If there is no tributary inflow of sediment to a channel reach, scour or fill is caused by a change in the load of bed material as the flow moves through the reach and not by the magnitude of the load at any particular cross section. Such a change can result either from a change in the carrying capacity or from an increase in the load of bed material in a stream that was not already carrying its capacity load of bed material. If the carrying capacity is high, a small percentage increase or decrease in that capacity as the flow moves along the channel can cause rapid scour or fill. The flow through a contraction and the reason for scour is discussed. It is mentioned that local scour, while flow is increasing, and local fill during the recession of a flood rise, are frequently observed at narrow sections of a channel.

239. Ahmad, Mushtaq, 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY9, Part 1, November 1960, pp. 144-151.

It is demonstrated that Laursen's equations are essentially the same as the writers'. The writer does not agree with Laursen however that the depth of scour does not depend on the degree of flow concentration. He does agree with Laursen that there is a limiting or equilibrium depth of scour.

240. Bauer, W. J., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY9, Part 1, November, 1960, pp. 132-133.

The application of the results presented by Laursen to a particular approach to waterway design is discussed.

241. Joglekar, D. V., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY9, Part 1, November 1960. pp. 129-132.

The writer agrees that scour at bridge piers is closely related to the river conditions upstream and downstream, the meandering tendency of the river, whether the river is flowing in its alluvial plain or has its sides and beds resistant to scour, whether the river is flashy or has sustained floods, and the constriction of the river section caused by the bridge. In the case of cohesive bed material, it is difficult to estimate the maximum depth of scour. Hydraulic model experiments are unable to reproduce this scour. Field data, therefore, must be used. The studies of Spring and Gales is also mentioned.

242. Romita, P. L., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. HY9, Part 1, November 1960, pp. 151-152.

The writer discusses his previous model investigations of the effect of angle of attack of the stream on the depth of scour at a pier.

243. Thomas, A. R., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY9, Part 1, November, 1960, pp. 142-143.

The writer shows that data from the Hardinge Model Study does not correspond to Laursen's conclusion that scour depth is dependent only on flow depth. It is suggested that the difference may be due to sediment charge. The relationship between depth of scour at the nose of the pier and depth of the channel upstream is not the most suitable one for the comparison of full-scale data, nor for practical application of a design formula, because the upstream depth during a maximum flood is often not known before hand and would have to be calculated. An error in assuming this depth would lead to a corresponding error in estimating the level to which scour is liable to occur.

244. Tison, L. J., 1960. Discussion of scour at bridge crossings. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 86, No. HY9, Part 1, November 1960, pp. 134-137.

A brief derivation of Tison's theory of scour is given (see reference 57) along with a list of references to Tison's publications.

245. Bata, G., 1960. Erozija oko novosadskog mostovskog stuba (Serbian) (Scour around bridge piers). Insitiut za vodoprivreder, Jaroslav Cerai Beozrad Yogoslavia, 1960. English translation by Markovic filed at Colorado State University, Civil Engineering Department, Fort Collins, Colorado.

The author states that the vertical velocity in the downward direction created at bridge piers is the cause of local scour. A method of calculating the vertical velocity component by successive approximations is presented for particular points near the pier. Strong vertical velocities which increase downward exist at a distance of from 3 to 4 times the radius of the pier, ahead of the pier. The order of magnitude of the veritcal velocity is about 1/2 of the average velocity and represents the principal cause of scour upstream of the pier. By dimensional analysis, $\frac{d_s}{D} = f\left(\frac{V}{\sqrt{gD}}, \frac{V}{\sqrt{g}}, \frac{VD}{\nu}\right)$ where $\frac{d_s}{D}$ expresses relative scour in relation to depth of water, and $\partial$ = diameter of sediment particle. From laboratory experiments it was found that the influence of the Reynold's number is practically negligible. It was also concluded that a change in the diameter of the sediment particles did not have a significant influence on the magnitude of scour. The author is certain that the magnitude of scour, $\frac{d_s}{gD}$, is a linear function of the approach velocity squared $\left(\frac{V^2}{gD}\right)$. He arrives at a form of Jaroslavans formula

$$\frac{d_s}{D} = 10\left(\frac{V^2}{gD} - \frac{3\partial}{D}\right).$$

246. Bradley, J. N., 1960. Hydraulics of bridge waterways, Chapter VII, Effect of scour on backwater. U.S. Department of Commerce, Bureau of Public Roads, Washington 25, D.C., pp. 28-37.

The nature of scour at bridge sections is discussed briefly. It is indicated that it is difficult to predict the magnitude and location of scour at field structures because of variations in the flow depth.

247. Duckstein, L., Iwagaki, Y., Smith, G. L., and Albertson, M. L., 1960. Analytical study of the mechanics of scour for two-dimensional jet. Engineering Research, Colorado State University, Report No. CER60GLS12.

An elementary theoretical analysis of the mechanics of scour caused by a two-dimensional jet issuing from submerged and non-submerged outlets acting on an erodible bed is attempted. It was assumed that the Bernoulli equation was valid in the neighborhood of the stagnation point, depth of scour was small compared to the tailwater depth in integrating the continuity equation of mass sediment transport, that the rate of sediment transport depends only on shear velocity and size and specific gravity of the sediment, lateral diffusion along the bed after impingement of the jet on the bed is negligible, and that the bed is a hydraulically smooth boundary. The effect of the velocity distribution within the diffusing jet on the scour phenomena, is important. The shape of the scour hole depends on the velocity distribution transverse to the direction of flow, and the development of the scour hole with respect to time depends on the velocity distribution in the direction of flow. The angle of impingement of the jet on the boundary has a noticeable effect on the depth of scour.

248. Enger, P. E., 1960. Tractive force distribution around the perimeter of an open channel by point velocity measurements. Master's Thesis, Colorado University, Boulder, Colorado, 1960.

Velocity distributions were obtained in a straight trapezoidal channel constructed with a well-graded, sand-gravel boundary. The boundary shear distribution was calculated from the velocity distribution and the average was compared with the average obtained by the duBoys formula. General agreement of the two averages was achieved at all discharges, indicating that tractive force distributions can be obtained with reasonable accuracy from measured point velocities. Velocities were measured by Pitot cylinder banks. The average tractive force was calculated from $\tau_o = \gamma R S$ where S = slope of measured water surface. A small representative sample of the material settling in the tail box of the flume was collected and analyzed following each test. The tests indicated that the geometric mean size and the deviation about the mean both increase as the tractive force increases. The largest error in determining the tractive force from point velocities originates with the difficulty of establishing the slope of the velocity gradient.

249. Iwagaki, Y., Smith, G. L. and Albertson, M. L., 1960. Analytical study of the mechanics of scour for three-dimensional jet. Colorado State University Research Foundation, Report No. CER60GLS9.

A theoretical analysis is attempted for the mechanics of scour for three-dimensional jets issuing from submerged and non-submerged outlets. Both the theoretical and experimental investigations for vertical and inclined jets from non-submerged outlets indicate that the rate of scour by a jet is governed by the characteristics of jet diffusion. In the case of a submerged outlet, the variation of the scour depth follows the logarithmic law with respect to time. Three regimes of scour are identified as (1) maximum jet deflection, (2) minimum jet deflection, (3) final conditions. The regimes of maximum jet deflection disappears when the final angle of jet impingement on the tail water reaches approximately 61°. When the angle is less than 61°, the regime is minimum jet deflection only. Impingement of a three-dimensional jet on a normal boundary is analyzed by assuming that the Bernoulli equation is valid in the neighborhood of the stagnation point.

250. Johnston, J. P., 1960. On the three-dimensional turbulent boundary layer generated by secondary flow. Transactions Am. Soc. of Mech. Engrs., Series D, Journal of Basic Engineering 82, 1960, pp. 233-248.

A visual model of a three-dimensional turbulent boundary layer with secondary flow is established. The data from the laboratory study enabled establishment of four of the five auxiliary relations required to solve a boundary layer problem using the momentum-integral equations.

251. Johnston, J. P., 1960. The turbulent boundary layer at a plane of symmetry in a three-dimensional flow. Transactions Am. Soc. of Mech. Engrs. Series D, Journal of Basic Engineering 82, 1960, pp. 622-628.

Methods of computing the characteristics including separation of boundary layers symmetrical about a plane normal to the wall bounding the flow is presented. Adaptations of the two-dimensional momentum integral computing methods are shown to be successful in predicting the characteristics.

252. Knezevic, Bogic, 1960. Prilog proucavanju erozije oko mostovskih stubova (Serbian) (Contributions to research work of erosion around bridge piers.) Institut za vodoprivredu, Jaroslar Ceri Beograd, Yugoslavia, 1960. Translated by Markovic, filed at Colorado State University, Civil Engineering Department, Fort Collins, Colorado.

The investigations of scour around bridge piers are described. Three series of laboratory tests were made in a model with different sizes of sand for each series, ($d_{50}$ = 4.5 mm, 2.4 mm, and 0.285 mm). The equation for the depth of scour $d_s$ was derived as $d_s = \frac{C(q-q_c)^{3/2}}{D^{5/4}\ q^{3/4}}$ where for rectangular piers C = 9.80 and for semi-circular pier fronts C = 8.72. It was found that by aspiration, (aspirating the flow along the stagnation line in front of the pier) the depth of scour could be reduced to 46 percent and the volume of material scoured could be reduced to 23 percent from the corresponding values without aspiration. For "ship's beak" piers the values were 34.5 percent and 19.1 percent reduction for depth and volume respectively. Variation for determining the most advantageous form and magnitude of the aspiration slot was not investigated. It was also found that horizontal bands around the pier served to decrease the amount of scour but it was not as effective as aspiration. Flow lines were traced out around the piers by dye. It was observed that the pier caused the streamlines to deviate far upstream of the pier.

253. Leopold, L., Bagnold, R. A. Wolman, and Brush, L. M., 1960. Flow resistance in sinuous or irrigation channels. U.S. Geological Survey Professional Paper 282-D, U.S. Government Printing Office, Washington, D.C., 1960.

This paper concerns the resistance of natural channels. It is stated that a large part of the total flow resistance of an irregular channel is due to internal energy loss in eddies and vortices at local deflections in the stream. Those resistances are then evaluated.

254. Liu, H. K., and Skinner, M. M., 1960. Laboratory observations of scour at bridge abutments. Highway Research Board Bulletin, No. 242, 1960, pp. 69-77.

See reference 260.

255. Masch, F. D. and Moore, W. L., 1960. Drag forces in velocity gradient flow. Journal of the Hydraulic Division, Am. Soc. of Civil Engrs. No. HY7, pp. 1-11.

An exploratory investigation was made of the drag coefficient for a circular cylinder as influenced by a velocity gradient along its axis. The velocity gradient will induce flow components along the axis of the cylinder. Along the upstream element of the cylinder (the stagnation line), the stagnation pressure will be greater at the end of the cylinder, where the velocity is high, than at the end where the velocity is low. This will produce a pressure gradient along the axis of the cylinder and induce a flow along the stagnation line toward the low velocity end of the cylinder. In a similar way, the reduced pressure in the wake will be affected by the local approach velocity. At the high-velocity end of the cylinder, the pressure in the wake will be less than at the low-velocity end, thus, inducing a longitudinal flow toward the high-velocity end of the cylinder in the wake zone. It was found that the velocity gradient very definitely affects the local drag coefficient.

256. Sanden, E. J., 1960. Scour at bridge piers and erosion of river banks. Proceeding of the Western Association of Canadaian Highway Officials. 1960.

The lack of a formula to use for the determination of scour depth by bridge engineers is emphasized. Experience, limited field data, or laboratory analysis seems to be the only methods to apply. The author then turns to the use of the regime formulae by Blench to arrive at a scour depth in terms of discharge, bed resistance and pier geometry.

Depth of scour, $D_s = 1.8\ q^{2/3}\ f_{bo}^{1/3}$ but for design, use a coefficient of 2 instead of 18. The value $f_{bo}$ is the zero bed factor (property of the bed material). From Inglis $\frac{D_s}{b} = 1.70 \left(\frac{q^{2/3}}{b}\right)^{0.78}$ where b = projected width of the pier. The author emphasizes that the equations should be checked by field data.

257. Schumm, S. A., 1960. The shape of alluvial channels in relation to sediment type. U.S. Geological Survey Professional Paper 352-B, U.S. Government Printing Office, Washington, D.C., 1960.

The fine fraction ($D_{10}$ less than 0.79 mm) sediment is effective in increasing the resistance of alluvium to erosion. The correlation of the width-depth ratio with the weighted mean percent silt-clay (M), shows that channels containing little silt-clay are relatively wide and shallow; whereas those composed predominantly of silt-clay are relatively narrow and deep. The author believes that the shape of channel seems to be independent of discharge. Comparisons of mean annual flood and mean discharge with the width/depth ratio showed no recognizable correlation. The absolute size of the channel, the width and depth in feet, is related to mean discharge, but the ratio of width to depth is apparently determined by the sediment type for the channels sampled (91 channels).

258. Toomre, A., 1960. The viscous secondary flow ahead of an infinite cylinder in uniform parallel shear flow. Journal of Fluid Mechanics, Vol. 7, No. 1, pp. 145-155.

A method is presented in this paper for calculating the secondary flow velocities and the lateral displacement of total pressure surfaces in the plane of symmetry ahead of an infinitely long cylinder situated normal to a steady, incompressible, slightly viscous shear flow. The cylinder is also normal to the vorticity, which is assumed uniform. The method is based on lateral gradients of pressure, these being calculated from the primary flow alone. Displacement effect is found to be virtually independent of the Reynolds number. "Displacement effect" is the distance which a particular curve of pressure measured at holes flush with the upstream face of a cylinder shifted (in the direction of decreasing total pressure) from the true total pressure profile of the undisturbed flow.

259. Varzeliotis, A. N., 1960. Model studies of scour around bridge piers. M. Sc. Thesis, University of Alberta, Edmonton, 1960.

The primary objective of the study was to determine the influence of pier geometry and flow angle on scour depth at bridge piers. The study was conducted in a 3 ft 8 in. wide flume 130 ft long using piers of different shapes and sizes. A uniform bed material of 1.7 mm size was used. The experiments shown that width, and shape of piers influence the scour depth, although test discharge and measured scour depths were small. Length of piers appear to have little influence on depth of scour. Skewed flow caused considerable increase in scour as compared to axial flow. Maximum depth of scour was observed to occur at the downstream end of the pier. Some tests were made to determine the scour retarding effect of a stone apron laid around the base of the pier.

260. Liu, H. K., Chang, F. M. and Skinner, M. M., 1961. Effect of bridge constriction of scour and backwater. Civil Engineering Section, Colorado State University, Fort Collins, Colorado, Report No. CER60HKL22. February 1961, pp. 1-118.

Two kinds of scour are discussed, general and local. The laboratory experiments indicate that the stream lines at some distance away from the abutment or pier is not affected by its presence in the flow. Scour is thus a local phenomena and is not significantly affected by the overall geometry of the flow. By their analysis the authors derive the equation

$$\int_a^c q_{sc}\, d\xi - \int_0^c q_{se}\, d\xi = d_s \cot\theta \frac{\Delta d_s}{\Delta t}, \text{ which}$$

cannot be solved mathematically. In the equation, $q_{sc}$ is the sediment discharge per foot of width at the contraction and $q_{se}$ is the sediment supply upstream of the contraction. The above equation was derived from observed geometry of the scour hole, scouring capacity, and the continuity equation. By dimensional analysis the following relationship is obtained:

$$\frac{d_s}{y_n} = \left( \frac{t_V}{\partial}, \frac{a}{y_n}, \theta, G, \frac{V^2}{y_n}, \frac{B}{a}, \frac{\partial}{y_n} \frac{w}{V} \right).$$

From the laboratory data, the equation for the equilibrium scour depth is

$$\frac{d_{se}}{y_n} = 215 \left( \frac{a}{y_n} \right)^{0.4} F^{1/3}, \text{ where } d_{se} \text{ is}$$

equilibrium scour depth, $y_n$ is the normal flow depth upstream, a is the length of obstruction perpendicular to the flow and F is the Froude number of the approach flow. The maximum depth of scour is

$$\frac{d_{sm}}{y_n} = 0.3 + 2.15 \left( \frac{a}{y_n} \right)^{0.4} F^{1/3}, \text{ where } d_{sm}$$

is the maximum scour depth.

261. Smith, G. L., 1961. Scour and scour-control below cantilevered culvert outlets. Colorado State University Research Foundation Report. CER61GLS14. May 14, 1961.

The theoretical approach is based on Iwagaki's analysis of a three-dimensional inclined jet (see reference 249). The equation is

$$\frac{d_s}{\sqrt{A \sin\theta}} = r \left\{ \log \left( \frac{\partial}{\sqrt{A \sin\theta}} \frac{V t}{h} \right) + \log D \right\},$$

where $Y + z = f(\sin\theta)$, $d_s$ = scour depth, A = cross sectional area of the jet, V = velocity of the jet, h = tailwater depth, t is time and $\theta$ = angle of the jet with the horizontal. From dimensional analysis

$$\frac{d_z^*}{H} = \phi \quad C_{m_{F_n}}, \frac{w_m t}{H}, \frac{h}{H}, \frac{\partial\, Vt}{\sqrt{A \sin\theta}\, h}$$

where H is height of fall, $\partial$ is mean sediment size and w is mean fall velocity of the sediment. The experiments were conducted in a rectangular alluvial channel with a preshaped scour basin. The tests confirmed Rouse's concept of maximum jet and minimum jet deflection. The maximum size of gravel needed to resist the prevalent shear forces was also studied.

262. Garde, R. J., Subramanyan, K., and Nambudripad, K. D., 1961. Scour around obstructions. Journal of the Central Board of Irrigation and Power, July 1961, pp. 651-659.

As the water flows around an obstruction, there is a change in the flow pattern, and hence a change in the shear distribution on the bed around the obstruction. As a result of the changed shear distribution the material around the obstruction is scoured. As the scour progresses, the shear distribution also changes. The process continues until the various forces acting on the sediment particles are in equilibrium. This changing shear distribution cannot be solved analytically. Therefore, dimensional analysis is used and experimental data are collected to establish a relationship for scour depth. Flow is assumed to be two-dimensional.

263. Hattersley, R. T., and Cornish, B. A., 1961. Hydraulic model investigation of gabion protection of culvert outlets. The University of New South Wales, Water Research Laboratory, Research Laboratory, Report No. 48, October 1961.

This investigation concerns the use of loosely bound aprons of broken rock ("gabion" mat) for controlling the outflow from pipe culverts. The prime feature of the non-rigid apron is that it acts as a cushion for jet impingement. The control of scour downstream of the apron depends to a great extent upon whether the water can be spread uniformly on the apron before reaching the erodible bed. An equation is derived for computing the total volume of stone required to construct various sizes of gabions.

An articulated hanging type deflector was used to direct the outflowing jet from the culvert downwards onto the "gabion" and spread it fan-wise. The tests showed this type of structure to be suitable for controlling scour and it promises to be cheaper than other types used previously.

264. Garde, R. J., 1961. Scour at bridge piers in alluvial channels. Mimeographed paper filed at Civil Engineering Department, Colorado State University, Fort Collins, Colorado.

Scour at bridge piers in alluvial channels is analyzed from the conditions of similarity. A generalized expression for determining maximum scour depth is proposed. The equation is

$\frac{D_1}{D} = A \eta_1 \eta_2 \eta_3 \frac{1}{oc} F_r^{\,n}$ where $A$ = constant,

$\eta_1 = f(C_D)$, $\eta_2 = f(F_r, \frac{1}{b})$, $\eta_3 = f(F_r, C_D)$

Fair agreement with existing selected data is indicated. The approach is inherently restricted to laboratory data. No application to field measurements is cited. See also reference 292.

265. Garde, R. J., 1961. Local bed variation at bridge piers in alluvial channels. University of Roorkee Research Journal, Vol. IV, No. 1, November 1961.

See reference 292.

266. Garde, R. J., Subramanyan, K., and Nambudripad, K. D., 1961. Study of scour around spur dikes. Proceedings, Am. Soc. of Civil Engrs. Journal of the Hydraulics Division, Vol. 8, No. HY 6, Paper No. 2978, November 1961.

The maximum depth of scour at a spur dike was investigated in the laboratory. The influence of the flow, spur dike and sediment characteristics on the maximum scour depth are said to be adequately represented by the Froude number of the normal channel, the opening ratio, the angle of inclination of the spur dike, and the average drag coefficient of the sediment particle. It was concluded that the maximum scour depth is affected by the size of the sediment, that $F_r = \frac{V}{\sqrt{gD}}$ is adequate to represent the flow characteristics, the opening ratio, and is the significant characteristic of geometry and $C_D = \frac{4}{3} \frac{\Delta s}{w^2} d$ represents sediment size, and $\frac{D+d_s}{D} = k \frac{1}{\alpha} F^n$ where $k, n = f(C_D)$

Other writers (Lacey ref. 27, Khosla ref. 51, Blench ref. 204, Izzard ref. 219, Ahmad ref. 157) have found relationships between $D + d_s$ and $q$. Garde et. al. contend that other factors are involved, and to determine these factors a dimensional analysis of the problem was used with the experimental data.

267. Anonymous, 1961. Restoring scoured bridge foundations under water. Civil Engineering and Public Works Review (Great Britain), Vol. 56, No. 664, November 1961, p. 1435.

The Wychnor bridge over the river Trent has velocities as high as 7 feet per second and has created substantial scour around bridge piers. When the foundation of the bridge was examined it was found that the river had undermined the faces of the piers to a depth varying from 6 inches to 5 feet 6 inches. Divers were engaged to drill holes through the bases of the bridge piers through which new concrete was pumped to spread under the existing invert slabs extending across the width of the river between the piers of the bridge.

268. Kain, D. H., 1961. Scour effects at the Chirna bridge. Public Works Department, Zomba, Nyasaland.

This investigation concerns the model of a submersible bridge over the Chirna river. The bridge is to be used to replace an old bridge which was destroyed by a flood in February, 1957.

The causes of scour are considered in two general categories, those characteristics of the stream itself, and those due to the modifications of the flow by the bridge crossing.

Many different schemes were tested in a model to eliminate excessive scour. From the tests it was concluded that the major scour under peak flood conditions occurs mainly on the upstream side of the bridge, and is due to the constriction of the flow caused by the approach embankments. A sheet pile spur dike appeared to give the best protection to the embankments.

The debris collection on the nose of piers had considerable influence on scour depth. Whenever practical, a debris deflector is recommended. Spur dikes should be constructed at the bridge abutments in a direction parallel to the normal flow of the river. Gabion protection to the toe of the spur dike and the upstream apron would be a valuable and inexpensive means of reducing scour at these points. Downstream protection is required.

269. Karaki, S., 1961. Laboratory study of spur dikes for highway bridge protection. Drainage structures - design and performance 1960, Highway Research Board Bulletin 286, Washington, D.C., 1961.

An empirical study was conducted to determine the shape, length and location of spur dikes to be established at bridge abutments. The laboratory model was not scaled to any specific structure. In determining spur dike geometry, the depth and extent of scour holes formed were used as criteria. There was no sediment inflow into the flume and certain restrictive applications are noted. The article shows some photographs of scour at abutments due to concentration of the flow there. No attempt is made to approach the scour problem analytically.

270. Kresser, W., 1961. Influence d'injection de liquides sur le courant d'eau autour d'une pile. (French) (Influence of injection of fluid into the water current at the front edge of a pier). Proceedings. Intern. Assoc. for Hydraulic Research, 9th Convention Proceedings, Dubrovnik, 1961, pp. 1055-1060.

Studies were undertaken at the Hydraulic Institute of the Technical University of Vienna to study the surface disturbances around piers, and methods of eliminating them. Proper forming of the pier was investigated. The boundary layer was siphoned out and the front part of the backwater at the pier was aspirated. It was found necessary to draw off about 3 percent of the total flow of the stream for this method to be effective in reducing scour. Introduction of flow at the front of the pier caused the surface pattern around the pier to be hydraulically smooth. It changed the pressure distribution around the pier and although not determined experimentally, should undoubtedly affect the scour pattern. Details on scour changes are not given, only surmised.

271. Enzo Levi, and Humberto, Luna, 1961. Dispositifs pour reduire l'affouillement au pied des piles de ponts. (French) (Dispositions for decreasing scour at base of bridge piers). Proceedings, Intern. Assoc. for Hydraulic Research, 9th General Assembly, 1961, pp. 1061-1069.

The authors refer briefly to investigations made at the Institute for Engineering, University of Mexico to try to reduce scour at bridge piers. They advocate placing a pile (angular or rectangular) upstream of the pier so that scour will occur at the pile and the material thus scoured will deposit at the base of the downstream pier to compensate for material which would normally be scoured. Various dimensions and positions of the pile relative to the piers were studied. Pier noses with various included angles were also studied. Various design curves are given for determining the size of pile, height, and location relative to the pier to achieve minimum scour. The tests show that a reduction of up to 1/2 the normal scour can be achieved. It was concluded that a pile of the same width as the pier should be placed vertically in the stream bed at a distance of 2.2 times the pier width upstream of the pier. The pile is to be placed 1.3 times the maximum water depth below the bed level and should extend into the bed a depth of 0.35 times the maximum water depth above the stream bed.

272. Posey, C. J., and Sybert, J. H., 1961. Erosion protection of production structures. Production structures. Proceedings, Intern. Assoc. for Hydraulic Research, 9th General Assembly, Dubrovnick, 1961, pp. 1157-1162.

Platforms for drilling oil wells, founded on tabular piles driven into sand 15 meters or more, were built off shore of Padre Island, Texas. Observations made 30 months after the first platform was installed showed that the sand was being scoured away to such a depth that the stability of the platform was endangered. The scour depth ranged from 1-4 meters. Scour was, however, saucer shaped and general under the platform, not a distinct scour hole around each pier. Model efforts to duplicate the scour formation showed that the use of a lightweight material (gilsonite) with low velocities and surface waves induced scour similar to the prototype. The general velocity in the test flume was not large enough to cause much local scour. Each time a wave passed, material was thrown into suspension and the turbulence created was strong enough to keep material in suspension until it was removed from the general area. Riprap mat protection of steel mill slag with a T-V gradation was found to be successful in preventing scour. No equations are given describing the scour phenomenon or the transport mechanics.

273. Schlichting, H., 1961. Three-dimensional boundary layer flow. Proceedings, Intern. Assoc. for Hydraulic Research, 9th General Assembly, Dubrovnik, 1961, pp. 1262-1290.

This paper gives a review of some classic methods and describes some recent research work on three-dimensional boundary layer flow. Contrary to two-dimensional boundary layers, three-dimensional boundary layers in many cases have a secondary flow normal to the direction of the main flow. This secondary flow is responsible for many peculiar flow phenomena of three-dimensional boundary layers.

The following subjects are discussed to some extent: (1) flow on rotating bodies, as for instance a rotating disk revolving in axial flow, and rotating propeller blades, (2) curved pipes, (3) straight and curved diffusers and, (4) corner flow. Experimental results are presented for the secondary flow in cascades resulting from a blade attached to a wall.

274. Smith, George L., and Hallmark, D. E., 1961. New developments for erosion controls at culvert outlets. Drainage structures - design and performances, 1960. Highway Research Board Bulletin 286, Washington, 1961.

The need for erosion control structures at outlets from culverts is emphasized with pictures of some actual field conditions. A laboratory study to determine an economical method of protection is described. Although not all ranges of flow and geometry were investigated in the laboratory study, it was concluded that a certain amount of dumped gravel of specified sizes in a preformed scour hole at the outlet would form an armour plate within the scour hole and in its neighborhood. The extent of scour protection would then depend upon the thickness of armour plate formed and the effectiveness of the sorting action of the various sizes of gravel.

275. Streeter, V. L., (Editor-in-Chief) 1961. Handbook of fluid dynamics. Section 18, Sedimentation by Anderson, A. G., McGraw-Hill Book Co., Inc. First Ed., 1961, pp. 18-32.

Channel contractions and obstructions cause changes in channel regimen from normal conditions. General dimensionless forms for the functional relationships between hydraulic, fluid, sediment and geometric parameters are shown and scour due to horizontal submerged jet, (by Laursen, Scour around bridge piers and abutments, see reference 162) is discussed.

276. Choudhury, A., 1962. Hardinge bridge on the lower ganges at Paksey. The Pakistan Engineer, Vol. 2, No. 5, January 1962, pp. 51-56, 44.

This paper presents a brief account of the background history of the Hardinge bridge at Paksey. The problems experienced and the corrective measures taken are described.

277. Razzak, A., 1962. Protection against erosion by Ganges river at Rajshaki. The Pakistan Engineer, Vol. 2, No. 5, January 1962, pp. 30-31, 38.

A temporary measure of bank stabilization of the Ganges River was undertaken to protect a town. Brick mattresses six inches thick, enclosed in hexagonal wire netting were used.

278. Baumann, P., 1962. Back scour during floods above pits and basins. Proceedings, Am. Soc. of Civil Engrs., Journal of the Hydraulics Division, March, 1962, pp. 139-151.

The author believes that drag as a criterion for bed-load movement during floods should be limited to mountain streams, that is, to streams where slopes are on the order of one percent or more. For valley streams with very small slopes and, therefore, fine-grained bed material, the drag criterion is no longer applicable. The method of duBoys is used for determining the rate of bed-load movement, expressed in terms of weight. An equation for bed-load movement is given as

$$q_1 = \frac{8.60\ B}{(1-V_p)(V_s-\gamma)}\ \bar{D}\,(\bar{D}-\bar{D}_o)$$ where $q_1$ = volume of bed load moved, B = width of stream bed, $v_p$ = pore volume of bed load, $\gamma_s$ = unit dry weight of stream-bed materials, $\gamma$ = unit weight of water, $\bar{D}$ = drag, $\bar{D}_o$ = lower limit drag, no bed-load movement. It was found that maximum scour occurs in the early part of the rising flood stage and back scour extends progressively upstream as the depth of scour tends to decrease at the pit.

279. Chaplin, T. K., 1962. Discussion of study of scour around spur dikes (by Garde, R. J., Subramanya, K., and Nambudripad, K. D., Am. Soc. of Civil Engineers, Journal of the Hydraulics Division, Vol. 87, No. HY 6, Part I, November 1961, pp. 23-37), Journal of the Hydraulic Division, Am. Soc. of Civil Engrs., Vol. 88, No. HY 2, Part I, March 1962, p. 192.

The writer believes that in any study concerning alluvial channels that the shape of the sand particles should be included among the sediment properties, since shape affects both the mechanical and physical behavior of the sand. A method of placing sand in the flume should be standardized so that the porosity of the bed at the beginning and end of each test could be obtained.

280. Neill, C. R., 1962. Discussion of scour around spur dikes. Proceedings Am. Soc. of Civil Engrs. Journal of the Hydraulics Division, March 1962.

The writer contends that Garde's formual

$$\frac{D + d_s}{D} = \frac{4.0}{\alpha}\ F^{2/3}$$ can be transformed to

$$D + d_s = \frac{4.0}{\alpha}\ \frac{V^{2/3}\ D}{g^{1/3}D^{1/3}} = \frac{1.26}{\alpha}\ q^{2/3}$$ which is

similar to equations of Blench and Izzard. Mr. Neill cannot agree with the use of the drag coefficient $C_D$ as a measure of the sediment properties since $w_,$ the setting velocity is proportional to $\sqrt{d_m}$, $C_D$ is nearly a constant for gravel. Therefore, $d_s$ is independent of size above say 1.5 mm. Hence riprap would be ineffective to reduce scour. It is suggested that Laursen's conclusion that scour depth is independent of all flow characteristics except flow depth can be interpreted to mean that scour depth is regime depth, and since regime depth is a function of velocity and sediment size, velocity and sediment size are also implicit in Laursen's equations.

281. Brush, Lucien M., Jr., 1962. Exploratory study of sediment diffusion. Journal of Geophysical Research, Vol. 67, No. 4, April 1962, p. 1427.

A study was made of the diffusion of glass beads in a submerged axisymmetric jet in order to compare the characteristics of the diffusion of sediment with those of the diffusion of momentum in free turbulence shear flow. A vertical 1/4-inch jet of sediment-laden water was directed downward into relatively large cylindrical tank of still water. Small concentrations of nearly spherical glass beads, both within and above the Stokes range in size were introduced into the recirculating system. The efflux velocity of the jet was maintained at 20 feet per second or more to decrease the relative importance of the fall velocity of the individual particles. Concentration profiles of the sediment were measured at various downstream sections in the zone of established flow and were compared with the velocity profiles at the same sections. The diffusion characteristics of the sediment laden water were analyzed by the use of approximate theories derived for clear water jets. The results are applied to a suspended-load equation presently used for two-dimensional flow in open channels. Certain conclusions are drawn as to the propriety of the assumptions pertaining to the fall velocity and sediment diffusers used in deriving this equation.

282. Moore, Walter L., and Masch, Frank D., Jr., 1962. Experiments on the scour resistance of cohesive sediments. Journal of Geophysical Research, Vol. 67, No. 4, April 1962, pp. 1437-1449.

Previous studies of the scour of cohesive materials as presented in engineering literature and as obtained directly by personal contact with some investigators are briefly reviewed. Exploratory tests for measuring scour resistance are described, and some correlated results are presented for a test involving scour by a vertical submerged jet impinging on the horizontal surface of a soil sample. The characteristics of the scour surface were observed for remolded and natural sediment samples, and the rate of scour was measured by the weight loss of the sample. The results are presented in terms of dimensional parameters. A new apparatus is described, which is designed to permit direct measurement of uniform shear stress developed at the surface of a cylindrical sample of a cohesive sediment. Comments are made regarding the direction of future research of this problem.

283. Tinney, E. R., 1962. The process of channel degradation. Journal of Geophysical Research, Vol. 67, No. 4, April 1962, pp. 1475-1483.

A section of an alluvial stream begins to degrade whenever the rate of sediment supply continues to be less than the rate at which the sediment is being transported away. An analysis of this process is presented for uniform sands in laboratory flumes. The theory is then applied to a set of experiments previously conducted by C. T. Newton. Finally it is pointed out that many features such as sorting, meandering, changing roughness and vegetative growth complicate direct application of the theory to natural streams. The partial differential equations for the continuity of sediment motion and degradation are given and an equation for degradation is developed.

284. Tsuchiya, Y., 1962. Criterion for scour at the downstream end of a smooth bed. (Japanese) Transactions of Japan Society of Civil Engineers, No. 80, April 1, 1962.

In this paper the criterion for scour from flows at the downstream end of a smooth bed is considered theoretically on the basis of Iwagaki's study on critical tractive forces. Experiments on the criterion for scour are described to verify the theoretical considerations. The influence of the shape factor of sand grains on the criterion for sand movement is also considred. A new definition for the criterion for sand movement is also considered. A new definition for the criterion for sand movement and scour is presented.

The criterion is

$$\frac{V_{*c}^2}{(\frac{\rho_s}{\rho} - 1)\, g\, \partial \tan \phi_f} = \frac{4}{3}\, \phi_i \quad i = 1, 2, 3, \ldots$$

where $V_{*c}$ = critical shear velocity, $\rho_s$ = density of sand grains, $\rho$ = density of fluid, $g$ = acceleration due to gravity, $\partial$ = size of sand grains, $\phi_f$ = friction angle of the sand grains and $\phi_i = f(\frac{V_{*c}\,\partial}{\nu})$ . The scour analysis is based on the critical shear velocity. Presumably if the shear velocity is less than $u_c^*$ , no scour will occur. Hence, the limiting depth can be calculated from this consideration.

285. Tsuchiya, Y., 1962. Basic studies on the criterion for scour from flows downstream of an outlet. (Japanese) Transactions of Japan Society of Civil Engineers, No. 82, June 1962.

In the region of flow establishment and established flow the criterion for scour is expressed as

$$\frac{V_{*c}^2}{(\frac{\rho_s}{\rho} - 1)\, g\, \partial \tan \phi_f} = \frac{4}{3\ \phi_i}\ , \quad i = (1, 2, 3, ..8)$$

in which $_i = {}_i\, (\frac{V_{*c}\,\partial}{\nu}\ ,\ \frac{V_{*c}}{V}\ \text{or}\ \frac{V_{*c}}{V_o})$

and the remaining symbols are defined as in reference 284 except for $\xi$ which is the sheltering coefficient, $\xi = 0.4$; $i = 1, 2, 3, 4$, for the zone of flow establishment and $i = 5, 6, 7, 8$, for the zone of established flow.

The theory is based on boundary layer growth in wall jets issuing from a submerged outlet and the momentum equation for a boundary layer of a two-dimensional free turbulent jet. Iwagaki's formula for critical tractive force is used.

286. Grund, Ivan, 1962. Mekhanichka podobnost pri modelovom vyskume vmolov za hydrotechnickymi stavbami. (Czechoslovakian) (Dynamical similarity in model investiagtions of scour downstream of hydraulic structures) Vyskumny ustav Vodohospodarsky Bratislava, Práce a studie 15 July 1962.

This article states that a quantitative model investigation of scour downstream of hydraulic structures requires undistorted geometrically similar model of the structure and of the downstream river bed. The gradation must be similar to the prototype and the size and specific weight must satisfy the dimensionless number $\frac{\partial \, \gamma_s}{V^2 \, \gamma}$ for both prototype and model where $\partial$ = grain diameter, $g$ = acceleration of gravity, $\gamma_s$ = specific weight of solids in water, $V$ = average velocity of the water, and $v$ = average velocity of the water, and $\gamma$ = specific weight of water.

287. Anonymous, 1962. Sediment transportation mechanics: Erosion of sediment, (Progress report) Proceedings, Am. Soc. of Civil Engrs., Vol. 88, No. HY 4, Paper 3195, July 1962, pp. 109-127.

The rate of scour can be described by the equation $\frac{d\, f(\Phi)}{dt} = g(\Phi) - g(S)$ where $f(\Phi)$ is a mathematical description of the boundary, sediment transport rate out of the scour zone as a function of the boundary shape and position, and $g(S)$ refers to the rate of supply to the scour zone, or, $f(\Phi) = \left| g(\Phi),\, g(S),\, t \right|$. The influence of grain size on the depth of scour and the effect of discharge on the depth of scour is shown. The results of experiments on local scour indicate that when the rate of supply into the scoured region is zero, scour depends on the sediment size as well as the energy contained in the flow and the flow pattern. If the supply is not zero, the extent and pattern of scour is independent of the sediment size and depends only on the flow pattern as governed by the boundary geometry.

288. Bruk, Stevan, 1962. Properties of flowing sediment. International Association of Scientific Hydrology. Comm. of Land Erosion, Symposium of Bari, October 1962. Publication No. 59, pp. 283-292.

Shear flow of sediment in the form of bedload on the bottom of alluvial rivers is one of the important aspects of sediment transportation. The flowing sediment grains show peculiar properties not present in homogeneous fluids. These peculiar properties are listed as cross-stresses. and volumetric dilation, non linear stress-strain relationship, structural anisotropy and inertial effects.

The flow in an alluvial channel is divided into three quasi-distinct zones; zone of turbulent flow (suspended load), contact zone (transition zone), and zone of flowing sediment (bed load). Preliminary treatment is given to each zone, using largely data by Bagnold, but the study fails to solidify a unified treatment of the total flow. Rather, it is intended to emphasize the importance of treating properties of granular materials in any treatise involving flow of sediment.

289. Chang, F. M. and Yevdjevich, V. M., 1962. Analytical study of local scour. Colorado State University, Fort Collins, Colorado, Report No. CER62FMC26.

This report is an addendum to a parent report published earlier (See reference 260). It includes review of additional pertinent literature not included in the parent report, discusses further the results presented in the earlier report, and describes in words the mechanism of local scour around obstructions in a river channel. An outline intended as a guide for future research in the local scour problem is proposed.

290. Laursen, E. M., 1962. Scour at bridge crossings. Transactions, Am. Soc. of Civil Engrs., Part 1, 1962.

Relationships are proposed for the prediction of scour at piers and abutments for the case when sediment is supplied to the scour hole. The relationships are developed from approximate analysis and laboratory experiments and depends upon knowledge of the flow conditions at the site.

In the analysis, a bridge crossing is considered as a long contraction foreshortened to such an extreme that it has only a beginning and an ending. An approximate form of a total sediment load equation proposed by the author is used.

The assumptions made are: (1) Manning's equation describes the flow, (2) Laursen's sediment transport equation is valid, (3) the Manning's roughness coefficient, $n$, is the same in the contracted and uncontracted regions, (4) $\frac{\tau'_o}{\tau_c}$ is large in comparison to 1, and (5) shear velocity in all reaches of the stream is the same. The equations are:

for scour at bridges on the overbank, $\frac{ds}{D} = \left(\frac{Q_t}{Q_c}\right)^{6/7} - 1.$

for scour at bridges in the contracted channel,

$$\frac{d_s}{D} = \left(\frac{B_1}{B_2}\right) 0.59 - 1 \quad \text{for} \quad \sqrt{\frac{gys}{w}} < 1/2$$

$$\frac{d_s}{D} = \left(\frac{B_1}{B_2}\right) 0.64 - 1 \quad \text{for} \quad \sqrt{\frac{gys}{w}} = 1$$

$$\frac{d_s}{D} = \left(\frac{B_1}{B_2}\right) 0.69 - 1 \quad \text{for} \quad \sqrt{\frac{gys}{w}} < 2$$

where $D$ = upstream depth, $B_1$ = upstream channel width, $B_2$ = contracted channel width, $Q_t$ = total flow, $Q_c$ = channel flow upstream and $w$ = fall velocity.

See also reference 231.

291. Chitale, S. V., 1962. Discussion of scour at bridge crossings. Transactions, Am. Soc. of Civil Engrs., Vol. 127, Part 1, 1962, pp. 191-196.

The results of the Hardinge Bridge model (1938-42) is discussed. Model data and graphical results are given. With axial flow, maximum scour depth is at the nose of the pier. The scour at the sides of the piers is less by 5 to 15 percent. The rate of scour at the nose of the pier depends on the depth of flow and the velocity. The depth of the approach flow influences the final scour depth, and the depth of scour has a direct relationship with the upstream Froude number.

292. Garde, R. J., 1962. Local bed variation at bridge piers in alluvial channels. Presented at the Annual Research Station meeting of Central Board of Irrigation, Poona, India, 1962.

The analysis of local bed variation at bridge piers in alluvial channels is made from laboratory models of prototype bridges. As a result of this investigation, a generalized equation for the maximum scour depth is proposed. The equation is a prediction for scour depth as bridge piers, spur-dikes, and for any other obstruction in the channel. It is shown that the proposed equation is applicable to the flume data as well as to field data. The proposed equation is:

$\frac{D_s}{D} = 4.0\ \eta_1\ \eta_2\ \eta_3\ \frac{1}{\alpha}\ F^n$ where $D_1$ = scour depth measured from the water surface, $D$ = water depth, 4.0 is an experimental coefficient, $\eta_1 = f(C_D)$, average drag coefficient of a sediment particle, $\eta_2 = f(\frac{l}{b}, C_D)$ where $l$ = pier length and $b$ = pier width, $\eta_3 = f(C_D, F)$ and $n = f(C_D)$.

Curves are given for exponent $n$ vs $C_D$, $\frac{D_s}{D}$ vs Fr and $C_D$, $\eta_1$ vs $C_D$, $\eta_2$ vs $F_r$ for $\frac{l}{b} \leq 1$, $\eta_3 = 0.9$ for rectangular pier nose. See also reference 262.

293. Marin, J. N. M., 1962. An investigation of local scour around bridge piers. M. Tech. Thesis. Univ. of New South Wales. Water Resources Lab. Manley Vale, N.S.W. Australia.

Scour of a stream bed of sand at the vicinity of bridge piers was studied for the simple case of flow between lateral construction plots in a laboratory channel, with no bed load in the approaching sub-critical flow. Contraction ratios, and velocities and depths of the approaching flow were varied. The depth of scour in each case appeared to approach a limiting value. The rate of the maximum scour depth to the approach flow depth was found to be a function of the Froude Number of the approaching flow and the degree of lateral contraction.

294. Neill, C. R., 1962. Use of echo sounders to measure scour at bridges. Research Council of Alberta - Highways Division, Edmonton, Alberta, unpublished report, preliminary, November 1962.

This report describes various types of echo sounders, and field and laboratory experiments to investigate their suitability for measuring field scour at bridge piers under flood conditions. Some of the field data obtained is presented. It is concluded that a high-frequency recording survey type sounder is a suitable instrument to be used in a field survey. A program for a systematic collection of scour data is proposed.

Some echo sounder models studied were:

(1) White Model D-51-12-Vacuum tube circuit,
(2) Marconi Ferrograph "Inshore" (transistorized),
(3) Bloodworth ES 130 (tubes and transistors),
(4) Raytheon DE-119,
(5) Bendix DR-17.

295. Tarapore, Z. S., 1962. A theoretical and experimental determination of the erosion pattern around obstructions placed in an alluvial channel with particular reference to vertical circular cylindrical piers. Ph.D. Dissertation, University of Minnesota, 1962.

A theoretical method is established for computing the approximate depth of scour near an obstruction in an alluvial channel, based on the potential flow around the body and the diffusion of the velocity of flow and grain size of the sediment are not important parameters so long as the rate of bed-load transport is advanced. For circular cylinders, if the depth of flow is large, the depth of scour is 2.7 times the radius of the cylinder. For low depths of flow, a dimensionless ratio of the depth of scour to the radius of the cylinder is a function of the ratio of the depth of flow to the radius of the cylinder. Suspended load has no effect on depth of scour. Also, it was found that an equilibrium depth of scour exists for case of zero sediment supply, contrary to results of some previous investigations did not reach equilibrium was because the length of time for a test run was too short.

296. Toomey, J. J., 1962. Scour in two-dimensional flow from a lined channel. M.S. Thesis, University of New South Wales, Water Resources Laboratory, Manley Vale, N.S.W., Australia.

A two-dimensional model investigation of the bed scour produced at the outlet from a lined channel into an unlined one showed that the ultimate scour hole profile to the point of maximum depth is very nearly a sine curve. The ratio varied logarithmically with time, at least for a considerable portion of the scour operation. However, the logarithmic plot changes slope at several points of discontinuity. These are related to the removal, after scour has proceeded for some time, of the material heaped downstream of the scour hole in the early stages. Eventually, the whole of the downstream bed is lowered to approach an ultimate scour level.

297. Znamenskaja, N. S., 1962. BLEJANEE SREDNEK RUSLOBblK FORM NA TESTNblE RAZMblBbl u MOSTOBblK OPOR (Russian) (Influence of average river bed configuration on local scour around bridge piers). Trudy Gosudarstvenny Gidrologicheskii Institut, Lenningrad, Vol. 97, 1962.

The local scour problem around bridge piers was considered in connection with moving sand bars on the bed of rivers. Any study concerning local scour around bridge piers should consider the influence of the moving sand bars in the river. The author analyzed different types of river bed configurations and proposed several classifications according to the influence on stability of bridge piers. He proposed an equation for moving bars but little detail is given on the mechanics of scour.

298. Vallentine, H. R. and Cornish, B. A., 1962. Notes on the design of culverts with outlet scour control. Report No. 62. Water Research Lab., University of New South Wales, Manley Vale, N.S.W., Australia.

Essentially same contents as reference 263.

299. Emmett, W. W., and Leopold, L. B., 1963. Downstream pattern of river-bed scour and fill. Presented at the Federal Inter-Agency Sedimentation Conference, Jackson, Mississippi, January 28 to February 1, 1963.

Observations on channel scour and fill over relatively long reaches of three streams in the Western United States is presented. Separate sections are devoted to observations on ephemeral streams and those on perennial streams. Depth of scour was measured by embedding chains in a vertical position in the river bed. When scour occurred the chain would collapse to the depth of scour and this depth could be measured later. It was observed that the mean scour depth in a channel appears to be proportional to the square root of the discharge per unit width of the channel. It was also found that the magnitude of scour is apparently independent of the channel width and slope. Although it might be expected that scour should be greatest at sections of smallest flow area which, for constant discharge, have the highest mean velocities, no systematic correlation between the flow area and magnitude of scour was apparent. The authors do not agree with the hypothesis of Love and Borland that scour occurs in narrow sections of a channel and deposits the sediment in wide sections downstream. On the contrary, the authors found the magnitude of scour to be of the same order in all types of sections. They interpret this to mean that although the volume of material scoured and moved may be large, because of its low mean velocity the whole volume does not move entirely out of a long reach but, in effect, is shifted downstream only a limited distance.

300. Laursen, E. M., 1963. Some aspects of the problem of scour at bridge crossings. Presented at the Federal-Inter-Agency Sedimentation Conference, Jackson, Mississippi, January 28 to February 1, 1963.

Clear water scour and scour with sediment supply are concerned. In clear water scour, the velocity, sediment size, and the geometry of the situation are important factors in determining the depth of scour. The experiments performed at the University of Iowa are discussed. Some equations for the scour in a long contraction previously published, see reference 290, are given and these equations are adapted for scour at piers and abutments. Unless the scour is so deep that the scour holes overlap, the scour at piers will not be affected by the overall contraction of the flow. Scour in a long contraction is generally much less than local scour around the piers and abutments. If a long contraction can be obtained by proper design of guide dikes upstream of the bridge, the cost of such dikes may be less than the cost of deeper foundations. By this means much shorter bridges are a possibility.

301. Moore, W. L., and Masch, F. D., 1963. The influence of secondary flows on local scour at obstructions in a channel. Presented at the Federal-Inter-Agency Sedimentation Conference, Jackson, Mississippi, January 28 to February 1, 1963.

An attempt is made to develop the characteristics of the three-dimensional flow patterns occurring at obstructions in a stream channel from the viewpoint of secondary flows.

With a uniform approach velocity, $V_o$, pressure along the stagnation line on the upstream face of the pier is $\frac{\rho V^2}{2}$, the tangential velocity, $V_t = V \; 2 \sin\theta \; (0 < \theta < \frac{\pi}{2})$ where $\theta$ is measured from the direction of the approaching flow. The variation in piezometric head around a circular pier is given by
$\Delta h = h - h_o = \frac{V^2}{2g}(1 - 4 \sin^2\theta), \; (0 < \theta < \frac{\pi}{2}),$
where piezometric head $h = \frac{P}{\gamma} + y$.

For a non-uniform approach velocity, the secondary flow velocity, $V_y$, is calculated to be

$\frac{V_y^2}{2g} = \frac{U_{o_{max}}^2}{2g} - \frac{U_o^2}{2g}$, and since at $y = 0$ (bottom), $U_o = 0$, $V_y = U_{o_{max}}$ (surface velocity)

This accounts for the strong secondary current which is developed at the noses of piers and results in maximum scour occurring at the upstream point of piers rather than occurring at the maximum breadth points as indicated by two-dimensional flow analysis. The secondary flow also creates spiral vortices along the sides of the piers in the scour hole. This concept of local scour is supported by observations of flume scour patterns around a circular pier. Scour at abutments of bridges is similarly presented. Some methods of controlling scour are presented.

302. Posey, C. J., 1963. Scour at bridge piers. Civil Engineering, May 1963. pp. 48, 49.

Increase of velocities and flow depths in a river during floods create spiral rollers at the bases of bridge piers which in turn create large conical scour holes upstream of a pier. If the material is cohesive, the action is different since the turbulence downstream of the piers produces scour faster than the spiral roller upstream. The flow around a pier also causes underflows in the porous bed. Removal of bed material is especially rapid than when flow is upwards. Thus, by covering the bed with an inverted filter, removal of the bed material can be prevented. It is recommended that a T-V gradation filter be used to retard scour.

Also, locating a pile in front of the pier is advocated.

303. Stabilini, L., 1963. Scour at bridge piers, cause and effect. Civil Engineering, May 1963, pp. 46-47.

The amount of scour is proportional to the magnitude of the rise in the water surface even though the river bed is not visible. It was found that a concrete floor on the bed of a river beneath a bridge is of doubtful value while riprap was found to be helpful. The author cautions against changes being made in a river in the vicinity of an existing bridge. It is recommended that if scour is noted, the hole should be filled with graded stone, the smallest on the bottom and largest on top and underpin the piers if necessary. Other methods recommended are reduction of velocity by flood measures, use of wider bridge spans, use of pile foundations extending to great depths and above all, good maintenance practice.

304. Kadib, Abdel-Latif, 1963. Beach profile as affected by vertical walls. Beach Erosion Board, Office of the Chief of Engineers, Corps of Engineers, Technical Memo, No. 134, June 1963.

The investigation reported was concerned with a laboratory investigation of the equilibrium profiles of protected beaches, promoted by observed failures of protective works, almost always because of scour behind the structures. The study was limited to vertical walls with varied top elevation subjected to wave action. Under all conditions of waves and relative wall heights studied, an equilibrium profile of approximately the same shape was obtained behind the wall. It was found that the equilibrium profile behind the wall depended upon the top elevation of the wall with respect to the still water level. The least amount of wave attack behind the wall was observed to occur when the top elevation of the wall was one wave height above the still water level. This condition gave the largest scour in front of the wall. The smallest scour in front of the wall occurred when the erosion behind the wall was largest and occurred when the wall was a half wave length below the still water level. Increasing the mean diameter of the bed material decreased the scour depth both in front of and behind the wall. The mechanism of sediment motion in the vicinity of the wall was believed to be affected by the interaction of the wave action, and a vortex created by the backflow of the water over the wall. Top elevations of the wall from a half wave length below still water to one wave length above still water were studied.

305. Tsuchiya, Y., 1963. Basic studies on the criterion for scour resulting from flows downstream of an outlet. (Japanese) Disaster prevention research institute, Bulletin No. 63, Kyoto University, Kyoto, Japan, June 1963.

Problems in the design of the length of apron downstream from an outlet to prevent local scour are briefly discussed. Boundary layer growth in wall jets emerging from a submerged outlet in connection with the criterion for scour from wall jets is analyzed and considered on the basis of the momentum equation of a boundary layer, and compared with experimental results. The empirical formulas for the criterion for scour from wall jets and for determining the necessary length of an apron for complete protection against scour are proposed.

306. Sanden, E. J. and C. R. Neill, 1963. Measuring scour around bridge foundations in floods. Public Works in Canada, September 1963. (Reprint)

Essentially the same subject matter discussed in reference 295 is republished in this article. The reader is alerted to the fact that while a quantity of literature is available on the subject of local scour very little information is in a form directly useable by the bridge designer. The need for better understanding of the local scour process is emphasized.

Field studies of scour around bridge piers with the use of echo sounders are described with particular emphasis on the equipment used. The Bludworth ES-130, a battery operated unit is recommended. Because of the infrequency of large floods in any one river, in order to collect sensible quantities of field scour data, a nationwide program is recommended. (Canada)

307. Neill, C. R., 1963. Introduction to the problem of scour at bridges. Unpublished informal paper presented to the sub-committee on Bridge Scour of the Committee on Bridges and Structures, Canadian Good Roads Association. Winnipeg, Manitoba, October 1963.

The problem of scour at bridge foundations is seen to be related to more general problems of bridge location and design of alluvial streams. Considering the present state of knowledge on sediment-water behaviour, it is suggested that satisfactory development of design criteria from theoretical methods is a remote possibility in the foreseeable future. A physical description of the scour process is visualized to consist of two parts: (1) permanent bed scour due to river degradation and (2) temporary scour due to floods. Because of the general lack of reliable model-prototype scale ratios for alluvial streams, it is emphasized that field measurements must be relied upon to develop suitable design criteria. A short list of references is included.

AUTHOR INDEX

SUBJECT INDEX