

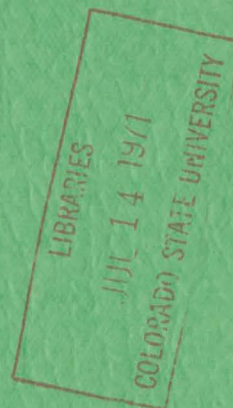
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TIME VARIATION OF BED DEFORMATION
NEAR BRIDGE PIERS

by
Hsieh Wen Shen
Yoshiaki Agawa
and
Susumu S. Karaki



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by HSIEH WEN SHEN

Associate Professor of Civil Engineering
Colorado State University, Fort Collins,
Colorado, U. S. A.

YOSHIAKI OGAWA

Graduate Assistant, Colorado State University,
on leave from Assistant Head, Hydraulic
Section, Civil Engineering Research Institute,
Hokkaido Development Bureau, Hiragishi,
Sappora, Japan.

SUSUMU S. KARAKI

Associate Professor of Civil Engineering
Colorado State University, Fort Collins,
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Bureau, Hiragishi, Sappora, Japan.

SUSUMU S. KARAKI

Associate Professor of Civil Engineering
Colorado State University, Fort Collins, Colorado, U.S.A.

SYNOPSIS

Time variation of scour depth at a circular pier is described in the paper. Adequate design of bridge pier foundation requires proper assessment of this phenomena. The deepest point of scour at any time occurred at the front of the pier, and thus analysis was made for flow in the stagnation plane upstream of the pier. Idealized experimental studies were performed to aid the analysis.

Experiments indicated that Froude number was the most important factor in determining scour depth. With known or assumed values of velocity and flow depth, scour depth can be determined for any time.

RESUME

L'affouillement autour d'une pile de pont circulaire en fonction du temps est décrite. Pour être adéquats les projets de fondations de piles de ponts réclament l'élucidation de ce phénomène. Le point le plus profond de l'affouillement se trouvait toujours a la face amont de la pile et par conséquent cette analyse fut faite pour l'écoulement dans le plan de stagnation en amont de la pile. Des études expérimentales idéalisées furent conduites pour aider l'analyse.

Les essais indiquent que le nombre de Froude est le paramètre le plus important pour la détermination de la profondeur d'affouillement, qui peut ainsi être estimée a un temps quelconque une fois données la vitesse et la profondeur du courant en amont.

1. Introduction:

Local scour problem near bridge piers has been investigated by O. V. Andreyer (1) of the U.S.S.R., C. C. Inglis (2) in India, E. M. Laursen (3) and W. L. Moore and F. D. Masch (4) of the U.S.A. Attempts were made to correlate maximum scour depth with various hydraulic conditions. Unfortunately no entirely satisfactory design guide was developed.

Since 1962, the Colorado State University under contract with the United States Bureau of Public Roads has undertaken a study of the local scour problem near bridge piers in the laboratory by measuring the flow distribution and observing the time variation of bed deformation.

Notations adopted for use in this paper are defined where they first appear and are listed alphabetically, for convenience of reference, in the Appendix.

2. Equipment:

a. Flume: A 6 feet wide by 4 feet deep and 60 feet long steel flume was used. Both sediment and water were made to recirculate through a 12-inch pipe by a propeller pump.

b. Sediment: Nearly uniform sand was used. 84%, 50%, and 16% of this sand were finer than 0.24 mm., 0.20 mm. and 0.15 mm. respectively.

c. Pier: A six-inch diameter plastic cylinder was used as the pier.

d. Measuring devices:

1. Discharge was measured by an orifice plate in the discharge pipe.

2. Velocity measurements were measured by a 1/16 inch outside diameter pitot tube connecting to a pressure transducer.

3. Experimental Procedures:

a. Variation of bed deformation near pier: A normal stream bed under given flow condition was established in the flume by recirculating over a long period. The six-inch cylindrical pier was then erected at about 35 feet downstream from the entrance of the flume and midway between the flume walls. After the alluvial bed around the pier was molded to its original undisturbed shape, desired flow was then re-established. The changing profile of the bed in the stagnation plane upstream from the pier was carefully measured with time until maximum scour depth was reached. This procedure was repeated for twenty-one different hydraulic flow conditions.

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- (1) Andreyer, O. V., "Planning of Stream Crossings," Second Edition. Engineering and Scientific Publishing House of Ministry of Automobile Transport and Highways of RSFSR, Moscow 1960.
 - (2) Inglis, C. C., "The Behavior and Control of Rivers and Canals," Research Publication 13, Part II, Central Water Power Irrigation and Navigation Report. Poona Research Sta., India 1949.
 - (3) Laursen, E. M., "Scour at Bridge Crossings," Trans. American Society of Civil Engineers, Vol. 127, Part I, 1962.
 - (4) Moore, W.L. and Masch, F.D., "The Influence of Secondary Flows in Local Scour at Obstruction in a Channel." Presented at the Federal-Inter-Agency Sedimentation Conference, Jackson, Mississippi, Jan. 28, 1963.

b. Velocity distribution near pier at maximum scour condition: Because instantaneous velocity measurements could not be made around the pier, and to avoid changing bed conditions during measurement, the entire alluvial bed of the flume was stabilized with a solution of calcium chloride and sodium silicate (waterglass). A small pitot tube was used to measure point velocities, with a length of yarn to establish the direction.

4. Theoretical Analysis:

The approaching velocity has a variation with depth. The bed of the stream at the base of the pier was assumed to have small irregularities and was essentially level initially. Around the upstream half of the pier, the stream pattern is altered by converging stream lines. A rise in water surface occurs at the stagnation plane in front of the pier, as the kinetic energy of flow is converted into potential energy. The magnitude of rise in water surface is dependent upon the change of velocity head. Vertical stagnation pressure gradient occurs because the velocity of the approaching flow is not uniform, and vertical flow results from the stagnation pressure gradient. As will be shown in the analysis, the maximum downward velocity which occurs just upstream from the pier has a magnitude smaller than the maximum velocity U_{max} of the approaching flow. The vertical velocity component impinges on the stream bed at the base of the pier and the bed material begins to be removed at a faster rate than the supply from upstream and scour starts.

As the process of scour continues the material adjacent to the scoured area is left without sufficient lateral support and slides into the scour zone. Then with time, the scour hole extends downward and outward through the simultaneous process of sliding and removal. The slope of the scour hole is approximately equal to the angle of repose of the material, during the entire scour process. Scour eventually ceases when the velocity components at the bed is no longer large enough to cause sufficient shear at the bed to move the particles. Since sediment movement is present in most streams, the scour process is said to reach equilibrium when the time averaged rate of sediment removal equals the time averaged rate of sediment supply.

Due to the lack of a universally agreed sediment transport rate equation, it is rather difficult to calculate the variation of bed deformation with time. One has to rely mainly on experimental investigation.

The significant hydraulic elements to govern the scour process are the velocity of the approach flow, the depth of the approach flow, and the sediment size. Since the sediment size has equal influences on the transport capability of the approach flow and removal rate by the impinging vertical jet in front of the pier, its only significant effect is on the side slope of the scour hole.

The potential flow theory is used to estimate the maximum vertical velocity near the pier. The stagnation pressure at any point is taken to be the difference of pressure at that location in the flow with and without the pier. It can be proved that for large Reynolds numbers, the viscous effect can be neglected in flow adjacent to the boundaries.

Set the origin of our cylindrical coordinate system (r, θ, y) at the center of the pier and let the O^0 line be the upstream stagnation plane. The stream function, ψ at y distance from the water surface can be shown to be

$$\psi = U_y \left(r \sin \theta - \frac{a^2}{r} \sin \theta \right)$$

where a is the radius of the pier and U, V are the velocities in $\theta=0, y$ directions respectively.

Therefore
$$U_r = \frac{1}{r} \frac{\partial \psi}{\partial \theta} = -U_y \left[\cos \theta - \frac{a^2}{r^2} \cos \theta \right] \text{-----} (1)$$

and
$$U_\theta = \frac{\partial \psi}{\partial r} = U_y \left[\sin \theta + \frac{a^2}{r^2} \sin \theta \right] \text{-----} (2)$$

The Euler equation in y-direction written in cylindrical coordinates is

$$U_r \frac{\partial V_y}{\partial r} + \frac{U_\theta}{r} \frac{\partial V_y}{\partial \theta} + V_y \frac{\partial V_y}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial y} \text{-----} (3)$$

where P is the stagnation pressure and ρ is the density of the fluid. At a point the total velocity squared,

$$U^2 = U_r^2 + U_\theta^2 = U_y^2 \left\{ 1 + \frac{a^4}{r^4} - 2 \frac{a^2}{r^2} \cos 2\theta \right\}$$

The stagnation pressure $\frac{P}{\gamma}$, where γ is the specific weight of the fluid, is approximately equal to

$$\begin{aligned} \frac{U_y^2}{2g} - \frac{U^2}{2g} &= \frac{U_y^2}{2g} - \frac{U_y^2}{2g} \left\{ 1 + \frac{a^4}{r^4} - 2 \frac{a^2}{r^2} \cos 2\theta \right\} \\ &= \frac{U_y^2}{2g} \left(2 \frac{a^2}{r^2} \cos 2\theta - \frac{a^4}{r^4} \right) \text{-----} (4) \end{aligned}$$

Substitute the values of U_r from Eq. (1), U_θ from Eq. (2) and $-\frac{1}{\rho} \frac{\partial P}{\partial y}$ from Eq. (4) into Eq. (3), one obtains

$$\begin{aligned} \cos \theta \left(\frac{a^2}{r^2} - 1 \right) \frac{\partial V_y}{\partial r} + \frac{\sin \theta}{r} \left(1 + \frac{a^2}{r^2} \right) \frac{\partial V_y}{\partial \theta} + \frac{V_y}{U_y} \frac{\partial V_y}{\partial y} \\ = \left(\frac{a^4}{r^4} - 2 \frac{a^2}{r^2} \cos 2\theta \right) \frac{\partial U_y}{\partial y} \end{aligned}$$

When $\theta = 0$, and $r = a$,
$$\frac{V_y}{U_y} \frac{\partial V_y}{\partial y} = \frac{\partial U_y}{\partial y}$$

or
$$V_y^2 = U_y^2 + C \text{-----} (5)$$

When $y = 0$, $V_y = 0$, $U_y = U_s$ where U_s is the surface velocity of the undisturbed approach flow. $C = U_s^2$

Therefore Eq. (5) becomes
$$V_y^2 = U_s^2 - U_y^2 \text{-----} (6)$$

Since at $r = a$, potential flow theory can not be applied, the value of V_y obtained from Eq. (6) can only give upper limit of the actual vertical velocity.

In the stagnation plane the maximum upstream jet velocity near the boundary of the scour hole probably is slightly less than the maximum actual vertical velocity by Bernoulli equation.

There is no universally agreed transport equation for bedload, but the parameter of u_*^2/gk_s , where u_* is the shear velocity and k_s is the representative sand size, is probably the most significant variable to govern transport rate.

u_*^2/gk_s , the ratio between the force exerted on the sediment grain by the flow and the resistance force of the grain, has been used as an indication of bedload transport by A. Shield (5) and by H. A. Einstein (6).

(5) Shields, A., "Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung." Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau. Berlin, Heft 26, 1936.

(6) Einstein, H.A., "The Bed Load Function for Sediment Transportation in Open Channel Flows," United States Department of Agriculture, Soil Conservation Service Technical Bulletin No. 1026. September 1950.

To calculate the value of u_* , one must know the velocity distribution at the boundary. For turbulent flow, the velocity near the boundary of scour is assumed to follow the one-seventh law and

$$\frac{u}{u_0} = \left(1 - \frac{y}{\delta}\right) \left(\frac{y}{\delta}\right)^{\frac{1}{7}} \quad \text{----- (7)}$$

In Eq. (7), u_0 is a characteristic velocity and the thickness of the boundary layer is δ where $u = 0$. Theoretically the maximum velocity in the boundary layer is equal to $0.65 u_0$.

Since the thickness of boundary layer is small comparing with the total depth of flow, the gradient of static pressure in y -direction can be neglected. Therefore the flow in the boundary layer could be treated as a part of the conduit flow and the expression for the shear stress, τ_0 , at the boundary is

$$\frac{\tau_0}{\rho} = \frac{\lambda}{8} u_m^2 \quad \text{----- (8)}$$

where λ is a resistance coefficient which equals to $0.3164/R^{1/4}$ for turbulent flow over smooth bed, R is equal to $u_m D/\nu$, D is the distance between $u = 0$ and maximum u , and u_m is the average velocity between $y = 0$ and $y = D$.

The value of u_m/u_0 is 0.635. Substitute the expression of u_m and λ into Eq. (8), one obtains

$$\frac{\tau_0}{\rho} = 0.0252 \left(\frac{\nu}{\delta}\right)^{\frac{1}{4}} u_0^{\frac{7}{4}}$$

or

$$u_* = 0.16 \left(\frac{\nu}{\delta}\right)^{\frac{1}{8}} u_0^{\frac{7}{8}} \quad \text{----- (9)}$$

For small suspended transport rate load, u_* as calculated from (9) should equal to u_* of the approach flow when maximum scour condition occurs.

5. Experimental Results:

a. The Froude number in the experimental study ranged from 0.105 to 0.935, which covered practically all subcritical flow cases. The values of maximum scour depth, d_s , for different flow conditions are given in Table 1.

b. Each scour hole had the shape of a symmetrical circular cone and the side slope of the cone during the entire scour process was approximately equal to the angle of repose of the bed material.

c. Figure 1 gives the ratio of d_s/d versus U/\sqrt{gd} where d and U are the depth and average velocity of the approach flow respectively. Our result agreed rather well with Poona experiments obtained by C. C. Inglis (2) and C.V. Chitale (7). Sediment sizes of 0.16 mm., 0.24 mm., 0.68 mm., and 1.51 mm. were used in Poona to form a single curve.

d. Figure 2 gives the relationship between d_s/d and t_0 for different Froude number, U/\sqrt{gd} . t_0 is the time when d_s has just been reached.

e. Figure 3 gives the relationship between d_s^*/d_s and t/t_0 for different Froude number. d_s^* is the scour depth at time t . This is the major result of this study. With a given flow condition of U and d of the approach, one can obtain the values of d_s from Figure 1 and t_0 from Figure 2. With the known values of U , d , d_s and t_0 , one may find the scour depth at any time from Figure 3.

(7) Chitale, S. V., "Discussion of Scour at Bridge Crossings." Trans. American Society of Civil Engineers, Vol. 127, Part I, 1962, pp. 191-196.

f. Flow distribution at the stagnation plane upstream from the pier is given in Figure 4. For this particular run, the average and maximum velocities of the approach flow were 1.0 feet per second and 1.27 feet per second respectively. d was 0.8 foot, the slope of the approach flow was 0.0006. the average bed material size was 0.57 mm., the measured maximum vertical velocity V_{max} upstream from the pier was 0.85 foot per second, and the maximum velocity, U_{max} in the boundary layer was 0.80 foot per second.

i. The velocity profiles with different distances upstream from the pier in the boundary layer were similar. The assumption of $u/u_0 = (1-y/\delta) (y/\delta)^{1/7}$ was verified as shown in Figure 5.

ii. The rise of water surface at any location was equal to the difference of velocity heads of the uniform approach flow and of the flow at that section. Maximum velocity was used to calculate the velocity head. Theoretically the average velocity above the point of maximum velocity should be used to calculate the velocity head. (Maximum velocity did not always occur at the water surface)

iii. As shown on Figure 5, the separation line of AB made an angle of 7° with the horizontal. This agreed with the usual concept of making divergent flow not greater than 7° to avoid separation.

iv. The vertical velocity just upstream from the pier increased sharply from $y = 1/2 d$ to $y = d$ and then remained constant for $y > d$. This agreed well with Eq. (6).

v. Figure 6 gives the vertical velocity distributions upstream from the pier. If these curves are extended to the pier, a maximum velocity of 1.2 feet per second would have occurred. This agreed with Eq. (6); that the maximum vertical velocity was equal to the maximum velocity of the approach flow.

vi. With the measured values of δ and max. u in the boundary layer u_* was found to be 0.052 feet per second from Eq. (9). From the procedure proposed by H. A. Einstein (6) the u_*' pertaining to the grain roughness was found to be 0.055 feet per second for the approach flow.

6. Conclusion:

Our experimental study indicates that the Froude number of the flow is the most significant parameter in the scour process. With known values of U and d , one may obtain not only the maximum scour depth from Figure 2 but also the scour depth at any time from Figures 3 and 4.

From flow measurements in the scour hole near the pier, it has been shown that the potential flow theory can be used away from the boundary and the velocity distribution in the jet above the scour hole is $u/u_0 = (1-y/\delta) (y/\delta)^{1/7}$. At maximum scour condition the shear stress at the bottom of the scour hole is approximately equal to the shear stress of the approach flow.

7. Appendix:

a. Notation:

- d = average approach flow depth
- d_s = maximum scour depth for a given flow condition
- d_s^* = scour depth at time t
- D = vertical distance in the boundary layer when $y = D$, $u =$ maximum
- k_s = the mean diameter of sediment size
- R = Reynolds number of the flow

- t = time
- t₀ = time when maximum scour depth has just been reached
- u = velocity in the boundary layer, see Figure 4.
- u_m = average velocity in the boundary layer from y = 0 to y = D
- u₀ = a characteristic velocity in the boundary layer, see Figure 5
- u* = shear velocity
- U = velocity of the approach flow upstream from the pier
- V = vertical velocity in front of the pier
- γ = specific weight of the fluid
- δ = thickness of boundary layer
- θ = angle with the stagnation plane
- λ = resistance coefficient
- ν = kinematic viscosity of fluid
- ρ = density of the fluid
- τ₀ = shear stress at the boundary
- ψ = stream function

b. Table 1.

EXPERIMENT RESULTS (FLUME WIDTH 6 ft)

Run No.	Discharge Q cfs	Depth d ft	Velocity V ft/sec	Max Scour d _s ft	Water Temp °F	Slope x 10 ⁻²	Froude No.	d _s /d
1	3.23	0.373	1.44	0.476	61	2.52	0.415	1.28
2	5.65	0.719	1.31	0.515	59	0.95	0.273	0.717
3	1.73	0.385	0.75	0.317	60	1.17	0.213	0.823
4	2.39	0.380	1.05	0.402	60	1.80	0.300	1.06
5	4.17	0.391	1.78	0.550	60	1.60	0.502	1.41
6	6.64	0.377	2.94	0.574	61	1.30	0.840	1.52
7	7.52	0.385	3.34	0.557	64	2.20	0.935	1.45
8	7.53	0.507	2.47	0.656	59	2.17	0.612	1.29
9	6.02	0.520	1.93	0.593	68	1.36	0.472	1.14
10	4.79	0.497	1.61	0.534	68	1.57	0.401	1.07
11	3.61	0.513	1.18	0.521	68	1.125	0.289	1.02
12	2.80	0.493	0.95	0.363	67	0.65	0.239	0.737
13	3.38	0.720	0.78	0.303	66	0.35	0.162	0.420
14	2.08	0.701	0.496	0.084	70	0.175	0.105	0.120
15	4.06	0.711	0.952	0.444	68	0.40	0.199	0.624
16	5.00	0.675	1.24	0.557	62	0.961	0.265	0.825
17	5.97	0.690	1.44	0.571	60	1.20	0.305	0.827
18	6.96	0.680	1.71	0.600	66	1.08	0.365	0.882
19	7.83	0.699	1.87	0.674	62	0.90	0.395	0.965
20	7.07	0.864	1.36	0.610	66	1.07	0.262	0.706
21	6.01	0.880	1.138	0.596	67	0.75	0.214	0.677

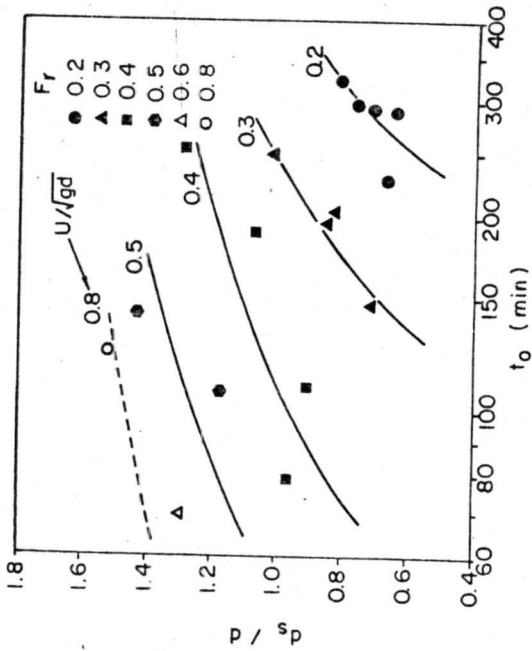


Fig. 2. Variation of t_0 with d_g/d (t_0 is the time when d_g just been reached).

Variation de t_0 avec d_g/d (t_0 est le temps au moment d_g vient juste d'être atteint).

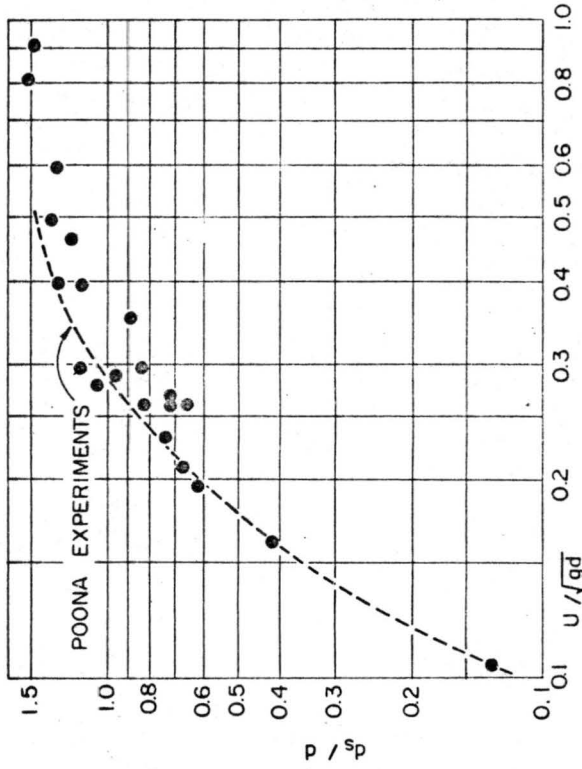


Fig. 1. Ratio of maximum scour depth d_g to flow depth d versus Froude number.

Rapport de la profondeur d'affoulement maximum d_g à la profondeur de l'écoulement.

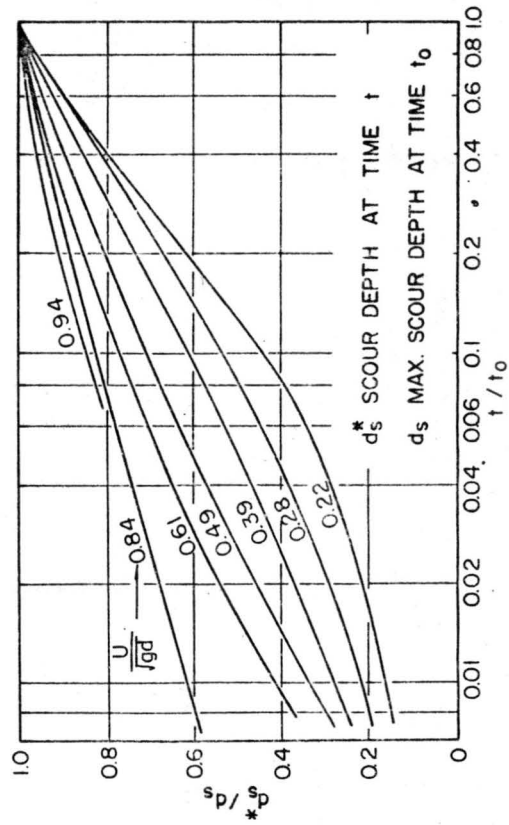


Fig. 3. Variation of scour depth, d_g , with time.

Variation de la profondeur d'affoulement d_g en fonction du temps.

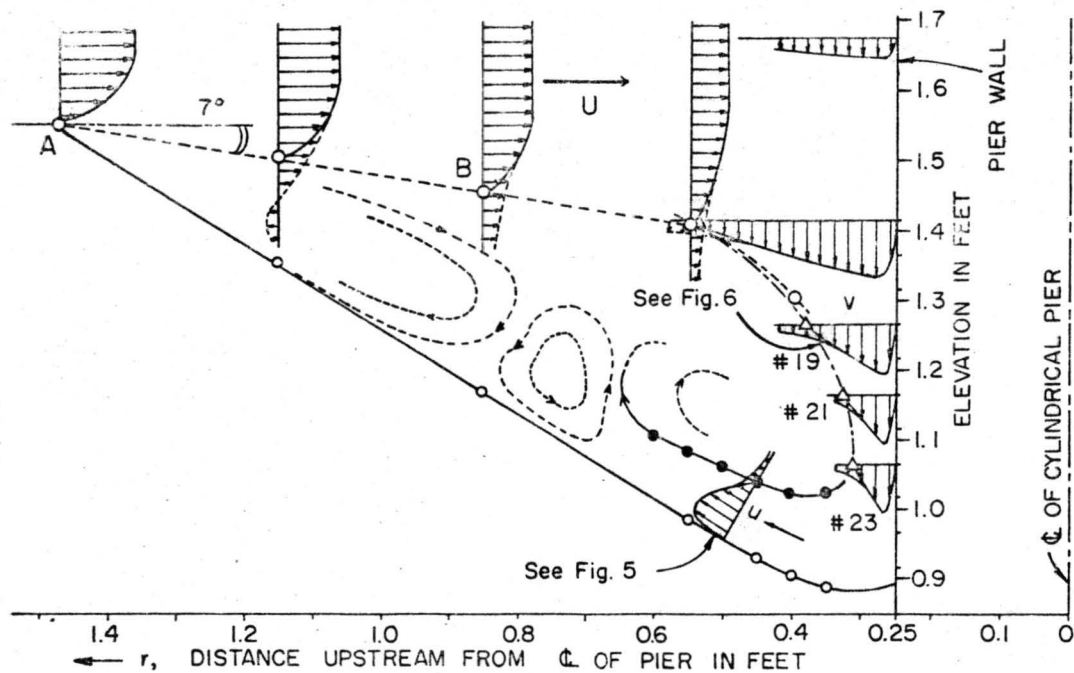


Fig. 4. Schematic flow pattern.
Schéma de l'écoulement.

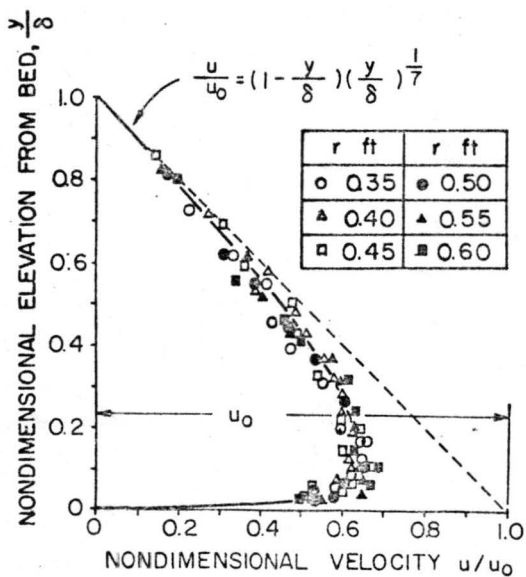


Fig. 5. Velocity distribution in the boundary layer.
Répartition des vitesses dans la couche limite.

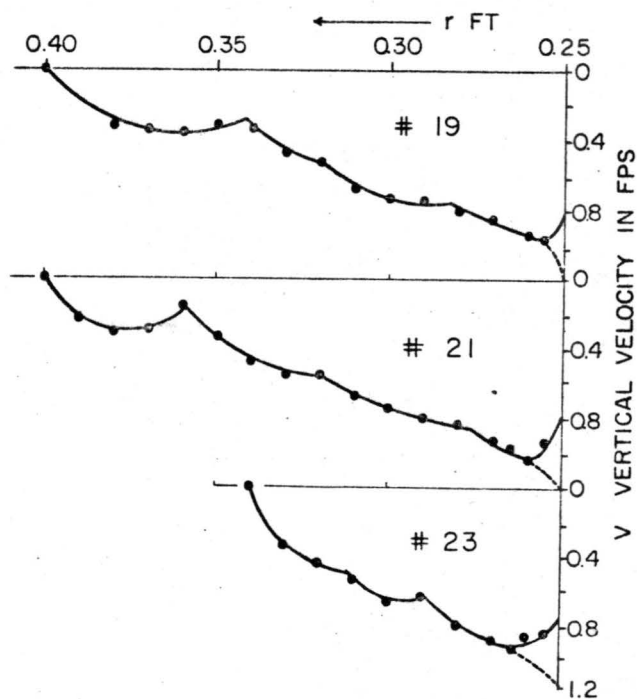


Fig. 6. Vertical velocity distribution at the stagnation plane of pier.
Répartition des vitesses verticales dans le plan de stagnation de la pile.

ИЗМЕНЕНИЕ ВО ВРЕМЕНИ РАЗМЫВА РУСЕЛ ВБЛИЗИ МОСТОВЫХ ОПОР

Аннотация

В данной статье рассматривается изменение во времени глубины размыва около цилиндрической опоры моста. Правильный расчет основания мостовой опоры требует надлежащего изучения этого явления. Точка наибольшей глубины размыва в любой момент наблюдается перед опорой, поэтому исследовался поток вверх по течению от опоры. Экспериментальные исследования проводились на идеализированных моделях. Эксперименты показали, что самым существенным фактором при определении глубины размыва является число Фруда. При известных скоростях и глубинах потока глубина размыва может быть определена в функции времени.