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EROSION OF A UNIFORM SAND BED BY CONTINUOUS AND PULSATING JETS

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SYNOPSIS

An experimental investigation of erosion of a uniform sand bed by a vertical submerged jet shows that the momentum flux of the jet and the distance between nozzle and sediment determines the rate of scour. Under fully turbulent conditions, the relative dimensions of the scour hole depend only upon the time parameter and the ratio between the fictitious axial jet velocity at the bed and the fall velocity of the sediment particles. There exist two distinct values of this ratio, at which the eroding action of the jet becomes particularly effective.

At the same mean volume flux, the erosion rate can be more than doubled by pulsations of the jet velocity. For the relative distance between nozzle and bed investigated, the continuous jet has the least erosion capacity as compared to pulsating jets.

RÉSUMÉ

L'étude expérimentale de l'affouillement d'un lit de sable naturel par un jet submergé et vertical montre, que la quantité de mouvement et la distance entre la buse et le fond mobile détermine la loi de croissance de l'affouillement. On peut constater que les dimensions relatives de l'affouillement dependent seulement du paramètre de temps et de la vitesse fictive sur l'axe du jet au niveau du fond, par rapport à la vitesse de chute des grains. Pour deux différentes valeurs de la proportion de ces vitesses, il y a un affouillement extrème à cause du jet.

Un jet pulsant possède plus que la double capacité d'érosion qu'un jet permanent avec le même débit volume moyen. A la distance recherchée le jet permanent effectue le minimum de volume d'affouillement comparé aux jets pulsants.

1. INTRODUCTION

Erosion due to a vertical jet represents an extreme kind of sediment transport in several respects. The flow characteristics near the bed, which determine the scouring and transport rate, vary rapidly both in space and time. There exist strong pressure gradients and fluctuations of the flow in the stagnation region, and there is a strong interaction between the form of the scour hole and the flow field producing it. All of these factors preclude an analytical treatment of the problem, so that recourse has to be taken to experimental investigations.

Although the distance between jet origin and sediment bed appears to have a major influence on the rate of scour, there exist so far no systematic investigations of this effect. Rouse [1] has studied erosion due to a plane half-jet at two distances between nozzle and bed, and an investigation by Poreh [2] on round jets was limited to the initiation of motion. Therefore, this study is undertaken to investigate the influence of the relative nozzle distance and the momentum flux upon the rate of scour.

In practical applications, scouring jets are frequently subjected to flow pulsations due to disturbances produced by the jet generator (pumps, propellers, etc.). It can be expected that pulsations exert a strong influence upon the scouring action of the jet, since theoretical and experimental studies of pulsating flow fields have shown a considerable increase of the forces upon the sand particles, which causes a corresponding decrease of the effective particle settling velocity [5,6]. In order to investigate this effect, the present study has been extended to pulsating jets as well.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The experiments were conducted in a circular container with a diameter of 2 meters, which contained a 50 cm deep sand bed of uniform size (mean diameter d_s = 1.5 mm) covered by 50 cm of water (Fig. 1). Along the center line of the container, a round submerged jet was induced, at constant mean nozzle velocities u_0 between 0.7 and 3.7 m/s and at nozzle diameters D of 2, 3, and 4 cm. The distance l of the nozzle from the undisturbed sand bed was varied between 0 and 0.82 m. In the study of the pulsating jet, a harmonic variation of the momentum flux was produced by means of a rotating circular disc in the supply pipe, driven by a hydraulic motor (Fig. 1). The amplitude and frequency of the stagnation pressure was measured at a distance of 1 nozzle diameter downstream of the nozzle. The amplitude Δu_0, defined as the difference between the maximum and the minimum value of the jet velocity, could be varied between 1.7 and 2.5 m/s, and the frequency from 2Hz up to 24Hz. All pulsating-jet experiments were conducted at a constant relative distance of l/D = 14.5, i.e., in a range within which the influence of the mean momentum flux is relatively small. The pulsation frequency and amplitude were varied in a first test series, in which the mean jet velocity u_0 = 3.7 m/s and the nozzle diameter D = 4 cm were kept constant.

The profile of the scour hole was measured at several time intervals with an electronic profile indicator (Delft Hydraulics Laboratory) and recorded on an x-y plotter. From these profiles, which were taken in two orthogonal radial cuts, the depth at the center line, the radius of the scour hole and the scour form could be determined. The scouring volume was defined as the volume above the undisturbed bed level in the outer parts of the scour hole (Fig. 2).

The investigation determines the relation between the scour hole, described by the center-line depth y_0, the radius R, and the scouring volume V, and the independent variables: distance l between nozzle and sand bed, nozzle diameter D, jet exit velocity u_0, and sediment properties ρ_s, d_s, σ_s, as well as time T. The dimensions of the container have been chosen such that the influence of the container walls is negligible and the water and sediment bodies can be treated as infinite. Since the jet flow is fully turbulent and the flow around the sediment particles is also considered not to be influenced by viscosity because of the negligibly small thickness of the viscous sublayer as compared to the grain diameter, the influence of the sediment characteristics can be described by the mean fall velocity w_m of single particles in a fluid at rest. With regard to flow characteristics of submerged continuous jets, the erosion rate depends only upon the constant kinematic momentum flux M_0/ρ_w. Description of the jet pulsation requires two additional parameters, the Strouhal number for the pulsation frequency $S = f\,D/\bar{u}_0$ and the amplitude ratio $\alpha = \Delta u_0/\bar{u}_0$ at the nozzle. This yields the following functional relation:

$$\frac{y_0}{l},\ \frac{R}{l},\ \frac{V}{l^3},\ \text{scour form} = \varphi\left(\frac{M_0/\rho_w}{w_m^2 l^2},\ \frac{w_m T}{l},\ \frac{fD}{\bar{u}_0},\ \frac{\Delta u_0}{\bar{u}_0}\right) \equiv \varphi\left(M^*, T^*, S, \alpha\right)$$

The experiments show that there is a certain correspondence between the momentum-flux parameter M^* and the time parameter T^* insofar as small momentum-flux parameters and large time parameters yield the same volume as correspondingly large momentum flux parameters and small time parameters.

3. DESCRIPTION OF THE SCOURING PROCESS

The block diagram in Fig. 3 gives a physical interpretation of the scouring process as an interaction between the flow parameters near the bed and the scour hole parameters. The magnitude of the relevant flow parameters near the bed together with the sediment properties give an indication of the state of movement of the bed. Movement of the particles begins, when the momentum-flux parameter M^* exceeds a certain critical value. For momentum-flux parameters slightly above the critical value, the sediment is transported primarily along the bed as bed load (scour hole form I). For momentum-flux parameters much larger than the critical value, there forms a marked zone of erosion in the stagnation region and, at larger radial distances, a marked region of transport and settling (scour hole form II). For continuity reasons, the transport capacity of the deflected jet decreases in the radial direction. This leads to deposition along the inner flanks of the scour hole, causing sliding of these flanks towards the erosion zone in the center and thereby renewed erosion. However, only the transport rate across the highest elevation of the scour profile (control section) contributes to the actual increase of the scour volume. After very long times, when the variation of the scour volume with time is zero, the erosion process has reached a dynamically stable cycle, which is symbolized by the feedback-lines A and B; for jet deflections of nearly 180°, the direct feedback C is very pronounced.

4. RESULTS FOR THE CONTINUOUS JET

For a constant kinematic momentum flux M_0/ϱ_w, the erosion capacity of continuous jets shows a strong dependence upon the nozzle distance l . Fig. 4 gives experimental values of the final scour-hole volume after very long times, from which it can be seen that the given jet produces an absolute and a relative maximum of eroded volume. The first maximum is given at very large distances, when the deflected jet barely induces sediment motion and still is not separated from the sediment bed. When the distance between nozzle and sand bed is decreased, the deflected jet separates from the boundary which causes a corresponding decrease of the eroded volume due to the smaller transport velocity near the bed. The second maximum is given by the distance at which, for the separated deflected jet, there exists an optimal relation between erosion in the center and transport along the inner flanks of the scour hole. At still smaller distances, the flow configuration changes considerably in a sense which leads to a decrease of the transport capacity of the deflected jet, therefore the final scour volume decreases. In the region of larger nozzle distances, the kinematic momentum flux obviously has a much greater influence upon the final scour volume than for small distances.

During the main phase of the scouring process, the center-line depth y_0 and the scour-hole radius R as well as the scour volume V show a logarithmic time dependence. Fig. 5 shows the development of the scour volume with time for various momentum-flux parameters. For constant time parameters, the relative scouring volume V increases with the momentum-flux parameter M^* . The final values for the relative scouring volume V are given in Fig. 6 as a function of the momentum-flux parameter. Fig.7 gives the final values of the relative center-line depth y_0 / l and the relative scour-hole radius R/l as a function of the momentum-flux parameter. Since the fictitious center-line velocity of the jet at a distance l from the nozzle depends linearly upon $\sqrt{M_0/\varrho_w}/l$, the beginning of motion can be characterized by a certain ratio of this fictitious center-line velocity $u_{\not{c},l}$ to the fall velocity w_m of the particles, which is in accordance with the experimental results of Poreh and Hefez [2] . Because of the dependence of the axis of this figure upon l^2 and l^3, respectively, the maximum values of the final scour-hole volumes with respect to the variation of distance l are given by the points on the curve with a slope of 3/2. All erosion conditions are determined by the value of the velocity ratio $u_{\not{c},l}/w_m$. This shows that final scour-hole profiles are geometrically similar for given values of the velocity ratio $u_{\not{c},l}/w_m$. This implies that under fully turbulent conditions for the jet flow and the flow around the particles, the velocity- and shear-stress distribution at a flat bed (beginning of scouring) are similar at any distance l and depend only upon the axial velocity. In jet erosion, the relative profile of the scour hole depends on momentum flux, time, and pulsation parameter.

The values of the final center-line depth and the final scour-hole radius in Fig.7 give an indication of the scour-hole dimensions in dependence of the momentum-flux parameter. For very small momentum-flux parameters, only the variation in depth contributes to the scouring volume. In a certain range of momentum-flux parameters, the radius and the depth show a marked change, which corresponds to the transition from one flow configuration to the other. This transition region is also characterized by a strong decrease of the erosion capacity. The same phenomenon has been observed by Rouse in a comparable two-dimensional investigation [1] .

5. RESULTS FOR THE PULSATING JET

Fig.8 shows the variation of the erosion volume with time both for the continuous jet and the pulsating jet at various Strouhal numbers and amplitude ratios. Again the results show a logarithmic time dependence of the scour volume. For the particular set of parameters kept constant in these experiments, the results show a marked increase of the erosion rate due to the influence of the jet pulsation, both with increasing amplitude and frequency. Whereas the influence of the amplitude can be explained by the corresponding increase of the mean momentum flux, it is interesting that the influence of the frequency on the erosion is even more pronounced. It is surprising, that a low-frequency jet (2 Hz) with a high velocity amplitude (Δu_0 = 1.4 m/s) yields the same erosion rates as the continuous jet: this shows clearly, that in accordance with the results in Ref. [4] , the continuous jet can be considered as a limiting case of the pulsating jet with the frequency tending towards zero. The relative increase of the scour-hole volume for the extreme case f = 24 Hz, Δu_0 = 2.5 m/s, and the continuous jet (u_0 = 3.7 m/s) after about 1000 minutes of scouring action is about 110%.

The experiments conducted so far did not yet lead to maxima of the erosion-rate increase and therefore give no clue as to which values of the pulsation parameters correspond to optimal erosion and transport rates. Whether the pulsation influences the rate of erosion by changing the characteristics of the jet or rather by influencing the transport capacity can only be concluded from further investigations, which include variations of the distance l and the mean velocity $\bar{u}_0$.

6. CONCLUSIONS

The investigations show that the erosion of a coarse sand bed by a continuous jet depends primarily upon the ratio of the fictitious jet velocity at the level of the undisturbed sand bed to the fall velocity of the sediment particles. For a given momentum flux, there exist two distances from the bed with very different flow configurations for which the scouring action of the jet becomes most effective. It can be expected, that similar statements can be made at least qualitatively for jets with an inclined axis, as long as there result considerable pressure and velocity gradients near the bed.

Harmonic pulsations of the jets cause a marked increase of the erosion rate as compared to the continuous jet of same mass and momentum flux, which depends upon the pulsation frequency and amplitude and probably upon the distance l between the nozzle and the amplitude and the sand bed. Since the pulsating flow field is most effective in the region of the quadratic relationship between mean-flow velocity and resistance force, further investigations promise to become particularly interesting for coarse grains and small nozzle distances.

7. REFERENCES

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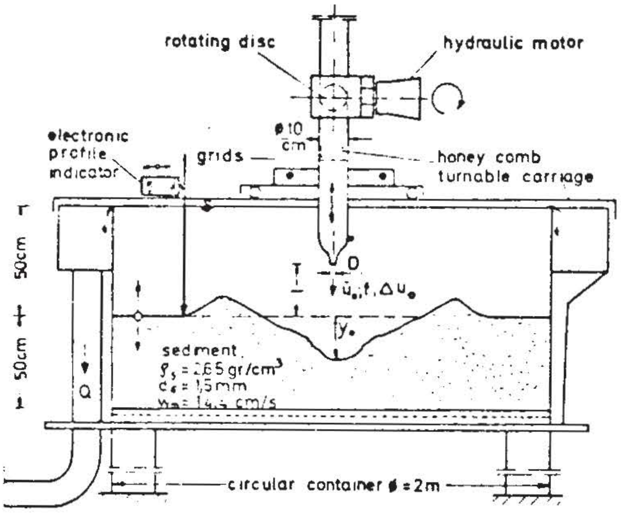

Fig.1: Experimental Setup

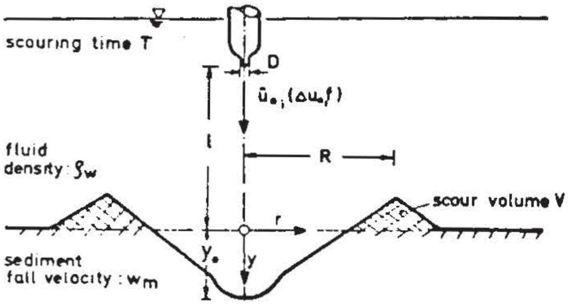

Fig.2 Definition Sketch

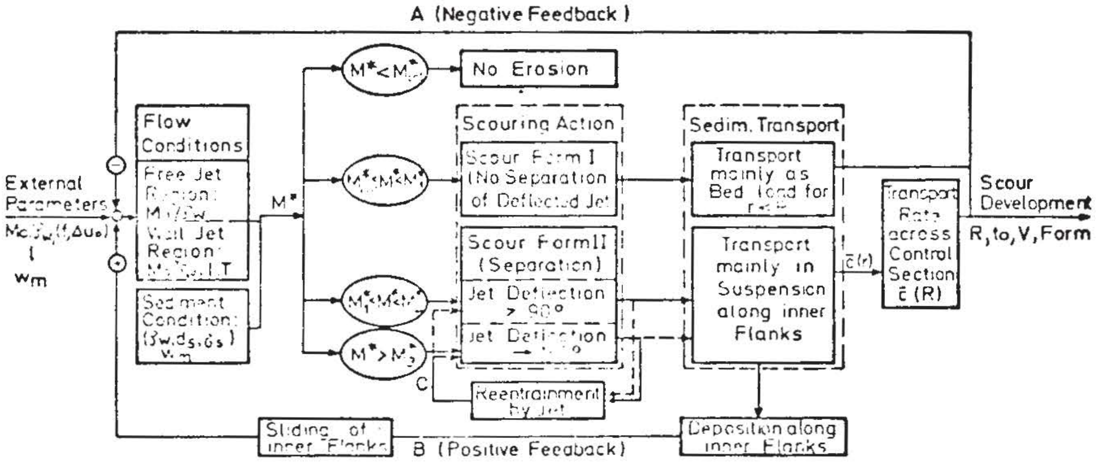

Fig. 3 Block - Diagram of Jet Erosion Process

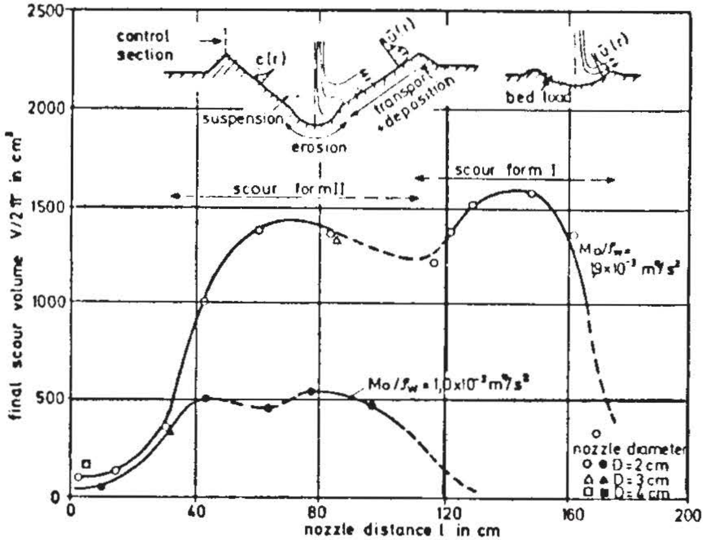

Fig.4: Effect of Nozzle Distance on Final Scour Volume (Continuous Jet)

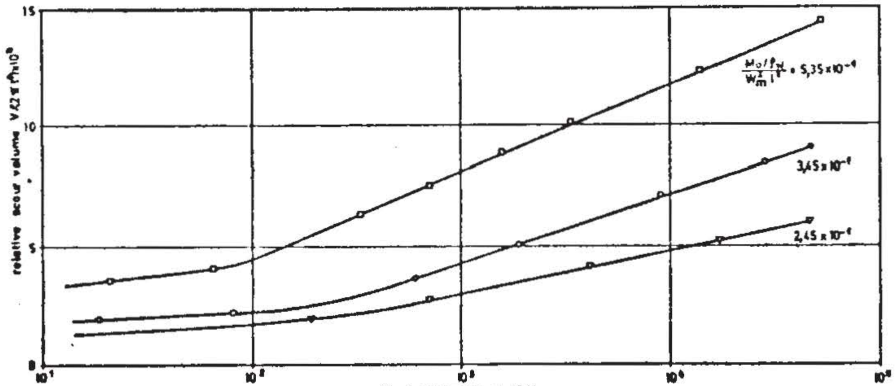

Fig.5: Time Development of Scour Volume for Continuous Jet

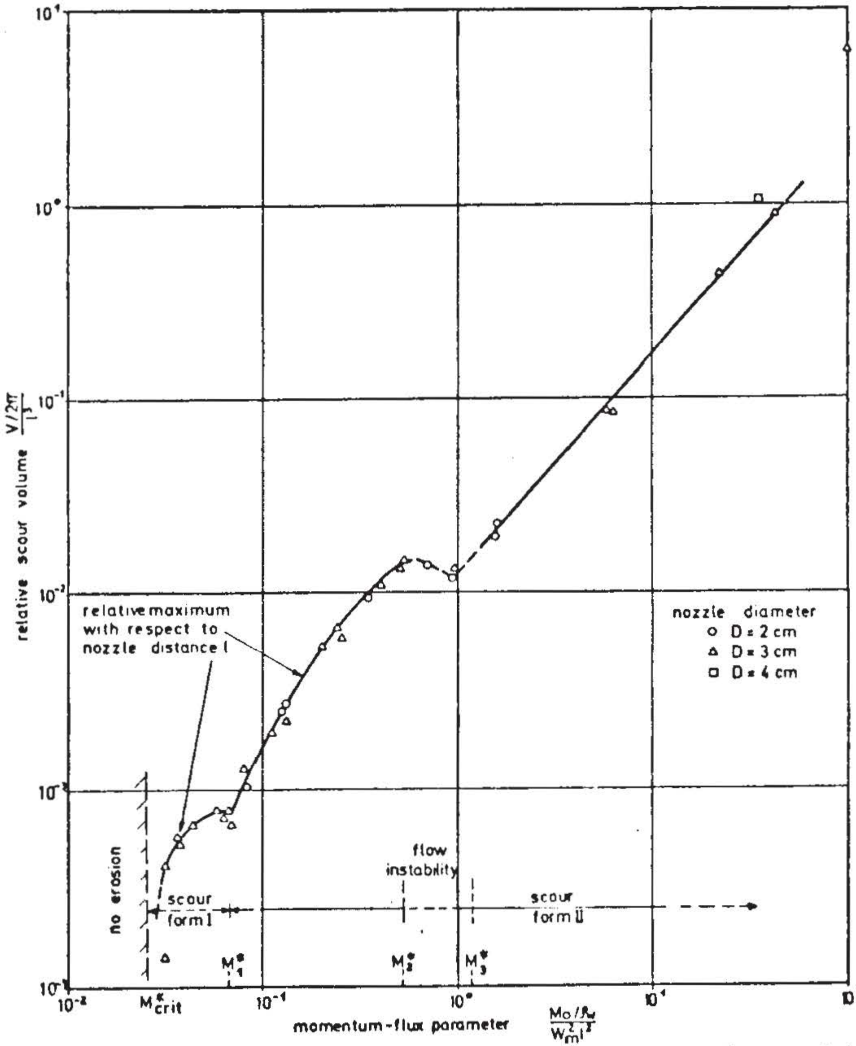

Fig.6: Relation between Momentum-Flux Parameter and Final Scour Volume (Continuous Jet)

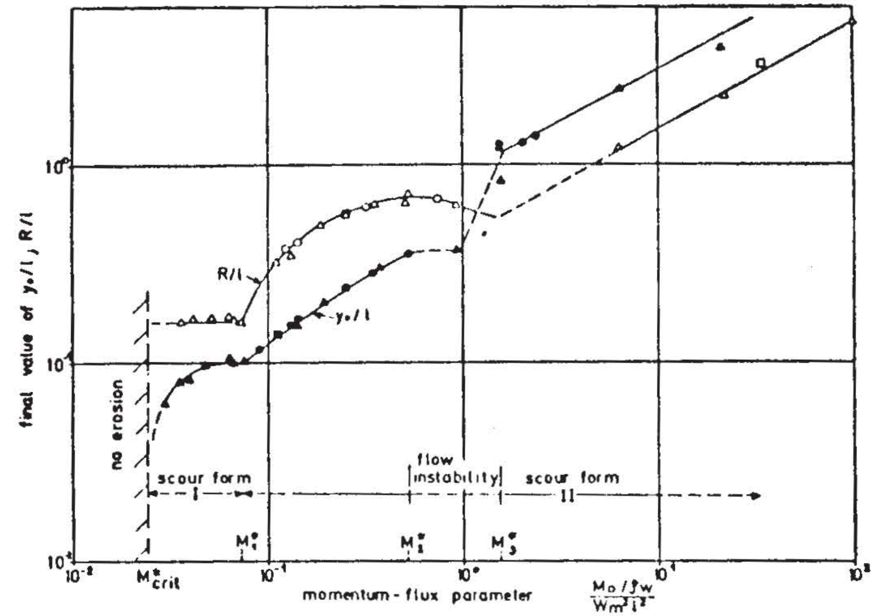

Fig 7: Effect of Momentum-Flux Parameter on Final Depth and Radius (Continuous Jet)

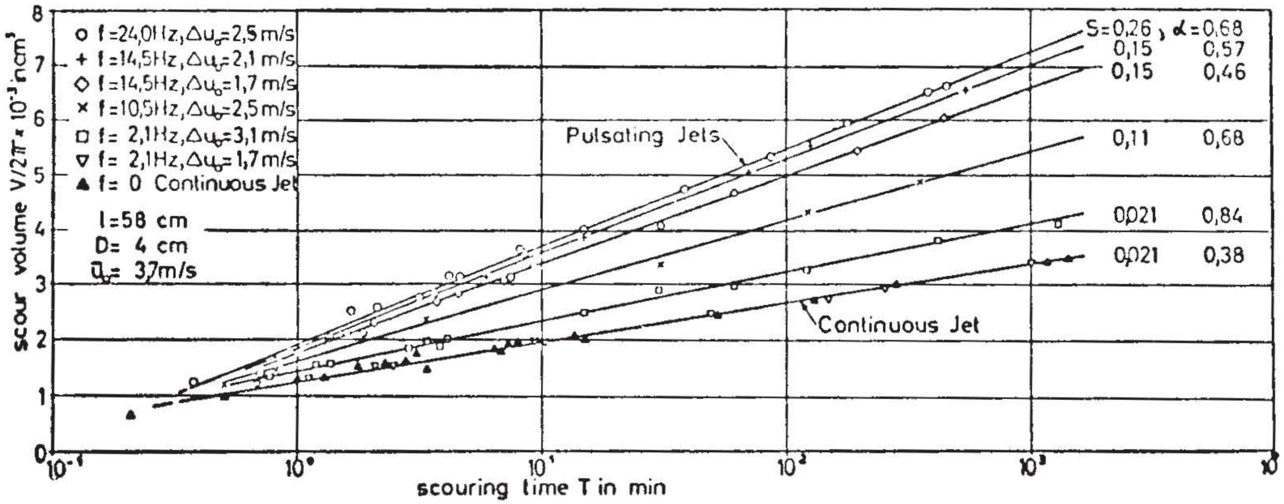

Fig.8: Increase of Scouring Rate due to Pulsation of the Jet Velocity