Plunge pool scour in prototype and laboratory

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ABSTRACT: Scour is a major concern with flip buckets in hydraulic engineering, given the several serious incidents over the past 50 years. The present research is based on previous laboratory observations conducted at VAW, ETH-Zurich, Switzerland, to explore the effect of cross-sectional jet shape, the effect of tailwater jet submergence and the jet impact angle on the plunge pool scour features. It was observed that the maximum scour depth may be significantly larger for so-called dynamic flow conditions than for static conditions when the jet action has seized. This was attributed to large dynamic forces with a twofold effect: (1) Suspension of sediment by the highly turbulent flow, and (2) Steeper scour hole slopes as compared with the natural angle of repose. The following thus intends to relate the static end scour depth to the maximum dynamic scour depth in order to allow prediction of the effective scour maximum for prototype conditions.

1 INTRODUCTION

Plunge pools are economic means to dissipate hydraulic energy for high-speed flows, provided the geological site conditions are favorable and the upstream jet velocity is larger than typically 20 m/s. For smaller velocities, stilling basins are often used, but these are highly unreliable for larger velocities because of concerns with cavitation damage, large spray production, unstable flow and tailwater wave generation (Vischer and Hager 1998). The limitations of plunge pools are dictated by large scour depth, its sufficient distance from other hydraulic structures to inhibit structural damages and control of spray action.

Plunge pools are usually at the end of either surface spillways or bottom outlets as applied in dam engineering. The flood discharge for surface spillways is first conveyed over a gated or ungated spillway crest that is followed by a chute. Once the discharge has reached an elevation close to the dam foot, it is directed onto a flip bucket to be ejected into the air. Accordingly, an air-water jet travels through the atmosphere and eventually strikes the plunge pool, in which the hydraulic energy is dissipated, and a stilled tailwater may be conveyed to the downstream receiving water course.

Plunge pools are currently a standard design in hydraulic engineering, although its scour patterns are not yet fully understood. Therefore, a fundamental research project was initiated at Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie VAW, at ETH Zurich, Switzerland. Its purposes was: (1) Set-up of a laboratory installation to experimentally investigate such flows, (2) Define the main parameters of plunge pool scour and (3) Present design relations that may be applied in dam engineering. An exploratory study was provided by Canepa and Hager (2003), in which the complicated laboratory set-up was simplified in an air-water high-speed flow generated with a circular pipe, thereby profiting from well-defined upstream boundary conditions. Also, a three-phase Froude number was introduce that accounts for the effects of water, air and sediment involved in the flow. Minor, et al. (2002) presented implications of this research and applied results to hydraulic practice. Recently, Pagliara, et al (2004) presented a
large experimental study in which various points were further clarified. The main findings may be summarized as follows: (1) The effect of jet shape on plunge pool scour is small provided the cross-sectional average mixture velocity is considered, (2) the impinging jet angle has a relatively small effect provided it is included between 30° and 90° measured from the horizontal, and (3) there are distinct effects of both submergence of jet by the tailwater level and pre-aerated flow characteristics. The research is accompanied with generalized scour hole profiles and the effect of temporal scour depth development was also investigated. The present paper would like to add to previous research by relating maximum scour depths measured during scour progress, and as observed after jet flow was stopped. The motivation is simple: The prototype scour hole may exclusively be observed when floods have ended, and the true extent of prototype scour thus normally remains unknown. Using laboratory observations, this unknown may be determined. The present laboratory data are then compared with prototype observations to check the fit. A typical computational example is also added to explain the design procedure.

2 DESCRIPTION OF LABORATORY OBSERVATIONS

The experiments were conducted in a laboratory channel of 0.500 m width, 0.70 m height and 7 m length. The jet was generated with pipes of different diameters ranging up to 0.100 m, in which also nozzle elements were placed to vary the cross-sectional jet geometry. Sands and gravels of almost uniform grain size of up to $d=0.007\, \text{m}$ were used to replace a completely disintegrated rock surface, of which the height was up to almost 0.35 m. Air was added to the pipe flow to simulate an air-water high-speed jet. Standard observations resulted in discharges for water $Q_w$ and air $Q_a$. The water surface was recorded with a point gage, whereas the sediment surface was read with a special gage having a 0.04 m circular plate at its end to measure the sediment surface to approximately $d/2$ (Canepa and Hager 2003).

![a)](image1)
![b)](image2)
![c)](image3)
![d)](image4)

Figure 1. Photographs of plunge pool scour (45° jet angle) development (a) close to scour initiation, (b) close to scour end; view of a test with jet angle of 60°; (c) dynamic condition; (d) ‘dry’ conditions.
Prior to experimentation, the sediment was horizontally inserted into the test channel, and air discharge was added by the in-house pressurized air supply system. Then, water discharge was started, with the temporal start of a run set at the initiation of scour. It should be noted that scour initiated immediately once the air-water mixture flow impinged on the plunge pool. Readings of the sediment surface were made after 1, 5 and 20 minutes, and sometimes after longer time. At the end of an experiment, the water flow was stopped, the jet at the same time deflected to inhibit further scour action and the resulting sediment surface measured after water had been drained from the test reach. This condition was referred to as the ‘dry’ scour measurement. Figure 1 shows typical photographs close to scour initiation, and scour end.

It was at once obvious that the scour profile close to end scour conditions, thus under a dynamic load, was significantly different from the ‘dry’ scour profile. Evidently, this difference results due to two reasons: (1) During jet flow, a considerable amount of sediment is in suspension that deposits as soon as the jet flow stops, and (2) much steeper slopes of sediment surface may result due to dynamic jet forces, in addition to gravity. Figure 2 shows typical scour hole profiles for four jet impact angles $\alpha$ and three subsequent observational times, in addition to the ‘dry’ condition. It may be observed that both the maximum scour depth increases with time, as the maximum aggradation height increases to reach the final scour profile. Temporal changes for $\alpha=30^\circ$ appear to be larger than for $\alpha=90^\circ$. Also, the ‘dry’ scour profile reaches never the scour depth under dynamic conditions, although the maximum aggradation is normally larger, due to the deposition of suspended sediment after the jet being stopped. Note that differences between the ‘dry’ or static condition and the dynamic condition are relatively small for small jet angle, and increase as the jet angle $\alpha$ increases.

Figure 3 shows the cross-sectional shape of the scour hole under maximum scour depth. The tests involved a jet angle of 45$^\circ$ and 90$^\circ$. As for the longitudinal scour hole profiles, this plot demonstrates the significant differences between the final dynamic and the dry scour hole geometries. In certain case, the dry scour surface was practically horizontal, and one might have thought that there was absolutely no scour action. Such a presumption may be dangerous because the real extent of scour may be largely underestimated. Means to detect the maximum scour depth during dynamic scour action are thus an important basis for adequate hydraulic design.

3 EFFECT OF JET SHAPE

The effect of jet shape was further tested with a pipe nozzle 29 mm wide and 99 mm long in both the horizontal and vertical positions, for a jet angle of $\alpha=30^\circ$. Figure 4 compares the maximum scour depths for dynamic $Z_m$ and static $Z_s$ conditions, where $Z=z/D$ and $D=$equivalent pipe diameter. Note that the full symbols represent unsubmerged (U), and the open symbols submerged (S) impact conditions into the tailwater. These tests were made for blackwater (BW) flow conditions, i.e. there was no air addition to the water flow.

Figure 4 shows absolutely no shape effect because all respective data for submerged and unsubmerged conditions lie on well defined, yet different curves. Also included is the line $Z_s=Z_m$, from where it follows that all static scour depths are smaller than those under dynamic condition. In the following these differences are determined, based on a large data series that involved four jet impact angles, submerged and unsubmerged tailwater conditions and white water (WW) and black water (BW) approach flow conditions. The ‘dry’ scour data are related to the dynamic scour data here, because the effects of the previous parameters on the dynamic scour depth have been determined previously by Pagliara et al. (2004).
Figure 2. Scour profiles for dynamic and static conditions for (a) α=30°, Run BW30UB183, (b) α=45°, Run WW45UB21, (c) α=60° Run WW60SC67, and (d) α=90° Run BW90UC89 at times (---) 1, (...) 5, (-----) 20 minutes and (---) ‘dry’ condition. Circles in (a) to (c) show the impact region of the falling suspended material when flow is stopped.

Figure 3. Cross-sectional scour profiles for (---) dynamic and (-----)static conditions, (a) α=45° (test BW45SA14) and (b) α=90° (test WW90SC77).
4 STATIC VERSUS DYNAMIC SCOUR DEPTHS

The data relative to the static and dynamic conditions were further considered to propose a generalized correlation. Figure 5 shows all the data available for the four jet angles $\alpha$, blackwater and whitewater conditions, and submerged and unsubmerged impact conditions. It may be noted that the angle $\alpha=30^\circ$ involves the smallest deviation, whereas $\alpha=90^\circ$ results in significant deviations between $Z_s$ and $Z_m$, under otherwise identical conditions.

The data shown in figure 5 may be approximated with $\alpha$ [in deg.] as

$$Z_s = 0.75 Z_m^\varepsilon, \quad \varepsilon = E_\alpha^{-0.75}, \quad 30^\circ \leq \alpha \leq 90^\circ$$

(1)

where the coefficient $E=14$ for unsubmerged, and $E=10$ for submerged jet flow. Figure 6 is a summary plot in which the previous blackwater tests are shown again, together with the respective curves from (1). Accordingly, the impact angle has a significant effect on the reduction of the static, as compared with the dynamic scour depth. The effect of tailwater submergence is relatively small for angles $\alpha \geq 45^\circ$, but considerable for small impact angles $\alpha$ of the order of $30^\circ$. Once the maximum dynamic scour depth $Z_d$ is known from previous research (Pagliara et al. 2004), equation (1) may be applied to find the reduction of the static scour depth, in terms of all other hydraulic parameters involved in the plunge pool scour features. Also, a measured static scour depth recorded after a flood may be used to predict the effective dynamic scour depth that had occurred.

Figure 7 shows the data in a more concise arrangement, by using the abscissa proposed in (1). It is seen that the present data cover a wide range of the combined parameter $Z_m^\varepsilon$, namely from 0.5 up to about 4. Both submerged and unsubmerged data lie evenly spaced along the straight of perfect agreement, indicating a small bias of (1). Figure 7 may be considered a condensed plot of a large number of data to determine the ratio of static to dynamic plunge pool scour depths. The application of (1) to cases of practice is straightforward, once the basic scour parameters such as impact angle $\alpha$, impact jet velocity $V$, determining median sediment size $d_{90}$, jet air content $\beta$ and equivalent jet diameter $D$ are known. The following intends to compare prototype data with (1).
Figure 5. Maximum scour depths $Z_s$ versus $Z_m$ for $\alpha = (a) 30^\circ$, (b) 45°, (c) 60°, and (d) 90° and both blackwater BW and whitewater WW conditions, and submerged, and unsubmerged jets.

Figure 6. Regression of data for unsubmerged U and submerged S conditions for different angles $\alpha$ (eq.1).
5 COMPARISON WITH PROTOTYPE DATA

The previous results were applied to typical cases reported in the literature, to check whether agreement with the analysis may be obtained. Figure 8 compares data relative to Picote dam (Portugal), Ukai dam (India), Kilickkaya dam (Turkey) and Cabora Bassa dam (Mozambique). In all evaluations, an unsubmerged air-water jet was assumed to occur, as is typical for hydraulic structures. The various parameters needed for the analysis according to Pagliara et al (2004) were estimated based on Yildiz and Üzücek (1994) and Whittaker and Schleiss (1984), with the jet air content $\beta$ calculated according to Ervine and Elsawy (1987) and a determining sediment size $d_{90}$ of 0.30 to 2 m. It should be noted that this effect is relatively small and does not lead to a significant modification of the results. The $z_m$ values were calculated by means of Eq. (4) (Pagliara et al 2004), while the corresponding $z_s$ values originate from (1).

Figure 8 indicates reasonable agreement between prototype observations and prediction according to laboratory measurements. The $z_s$ values calculated are close to the measurements (black squares), while the $z_m$ values calculated (white squares) indicate a deeper scour during flow as compared with the static condition.

It should be noted that the effects of jet impact velocity $V$ and effective jet diameter $D$ on both the static and the dynamic scour depths are significant, because both are linearly related to the maximum scour depth. Both of these parameters may be difficult to estimate, given that the exact development of cross-sectional average blackwater velocity and the air entrainment characteristics along the chute and over the flip bucket involve some degree of uncertainty, typically of the order of some 20%. Also, the jet development across the atmosphere, from the bucket to the tailwater impact is actually not simple to predict, given a serious lack of research in this field. The present project may be considered a step forward in this direction.

6 CONCLUSIONS

Prototype scour may only be determined under static conditions, i.e. after a flood wave has passed and the scour hole is accessible again. This research was concerned with the maximum scour depth under dynamic conditions, based on an extended laboratory program. It was found that the ratio between static and dynamic scour depths depends particularly on the jet impact angle, whereas the effect of jet submersion is relatively small except for small impact angles. The present results were verified with literature data of prototype static scour holes, of which reasonable agreement resulted. The present results may thus be a basis of future scour hole
assessments, and can also be a design basis for plunge pools.

Figure 8. Comparison between prototype and calculated values of maximum scour depth $z_m$ and $z_s$.

REFERENCES


