EFFECT OF USING DENTATE SKI JUMP SPILLWAYS ON SCOURING PROFILE

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Flip buckets or ski jumps are known as the most economical design for energy dissipation at high dams. The dissipation of energy does not take place in the bucket itself (except at low flows) but in the air and in the river bed where severe erosion can be expected. Flip buckets have been designed in various shapes and forms. The main criterion in design of all types of flip buckets is: to discharge the flow from the spillway into the river as far as possible so as to achieve the greatest jet dispersion possible at all discharges. Experience shows that using dentate splitters on the ski jump spillways can effectively reduce scouring depth and its development in downstream plunge pool.

In this paper, effect of using dentate ski jump spillways was investigated in a 1/50 scale comprehensive model of a concrete gravity arch dam built in a narrow and deep gorge. The model test investigations carried out in hydraulic laboratory of Water Research Institute to optimize the best shape of ski jumps. The model studies was based on a comparison between conventional bucket type (CB) with continuous solid lip of angles 0^o and 20^o and a 5 teeth dentate (toothed) bucket (DB). The jet flow patterns were observed and the scouring profiles on the river bed along the bucket axis were measured. Results showed that dentate buckets can effectively reduce ultimate depth of scour hole and the potential of erosion which may be expressed by volume of eroded materials.

1 Introduction

Scouring process downstream of flip buckets or ski jumps, consist of several stages which can be simplified as follows: free trajectory jet behavior in the air and aerated jet impingement, plunging jet behavior and turbulent flow in the plunge pool and other processes which finally lead to displacement of the scoured materials by sediment transport.

One of the most important measures affect on limiting the scour hole extent and its deepening is forced aeration and splitting of jet leaving spillway structures. In order to increase turbulent intensity, split and aerate the jets leaving flip buckets and crest lips, they are often equipped with splitters and deflector teeth in the form of dentate buckets (Novak 1981, Schleiss 2002). A free trajectory jet in air is affected by both turbulence and shearing action. If the jet trajectory is long and the discharge small, the two effects may cause the jet to disintegrate almost completely before striking the water surface in the tail water. If a jet is only partially disintegrated, it causes a larger amount of scour in the impact area. The energy dissipating effect of dentate buckets is superior to conventional type (continuous lip) buckets, this fact has been proved by a great many experimental researches and engineering practices even though there should be a pay attention to prevent cavitation damage on the side surfaces of teeth (Vischer & Hager 1995).

The main idea in design of dentate buckets is to partition a single compacted solid jet to individual jets in order to enhance jet cross section and jet disintegration during throwing through the atmosphere. This leads to a weak impact of the falling jet on a larger area in plunge pool and reduces the ultimate depth of scour hole.

One of the more recent innovations in the design of energy dissipators for overflow spillways is the use of aerated nappe splitters. Splitters aerate and spread the jet so that forces on the basin slabs or the depth of erosion are considerably reduced. Although this principle was developed in 1939 by Roberts, the feasibility of such devices for large scale applications was only recently demonstrated (Locher & Hsu 1984).

A comparison of erosion in a model study using an erodable bed showed that the depth of erosion without the splitters was almost twice as great as the depth with the splitters and that the bottom of scour hole was much closer to the dam (Back et al 1973).

The dispersed and aerated jet stresses the downstream river bed (plunge pool) much less than a compact unaerated jet. This was used by Coyne in 1951 for the design of spillway surfaces of a number of dams in the shape of a ski jump placed on the roof of the downstream river power station. Coyne has mentioned that the disintegration and aeration of even very high overfall jets during their free fall through the air is considerably aided by baffles on the take-off edge of the ski jump. The junction of the spillway and baffles should be as smooth as possible to prevent cavitation. The baffles considerably increase the turbulence, the disintegration and the surface area of the overfall jet and spread it over a considerably greater area. By a suitable design one can attempt to achieve a situation where even a very high overfall jet falls on the downstream water surface as a mixture of air and water without a compact core (Novak & Cabelka 1981).

By systematic research on a number of models including Slapy dam & Orlik dam (Czech Republic), Cabelka & Horsky in 1961 concluded that take-offs with deflectors are always more effective than conventional type ski jumps (Cabelka & Horsky 1961). They used velocity coefficient ϕ, to express the energy loss at the point of jet entry into the downstream pool in different configurations of terminal structure of spillways. They prepared a graph which, compares ϕ, for different specific discharges q, in a relatively low spillway of a classical type, equipped with take-off edge (ski jump) without baffles and with baffles.

Auroy in 1965 reported that in order to obtain maximum energy dissipation and minimum scour simultaneously in Chastang dam (France), the perimeter of the jet was increased by positioning tooth-type elements at the take-off location. As a result, the rectangular approach jet becomes U-shaped shortly upstream of the impact area (Vischer & Hager 1995).

The bucket type splitter take-off was further developed by Luthra (1965). It consisted of a row of prismatic blocks with bucket-shaped top surfaces. The block spacing was uniform and was able to break up the underside of the compact approach flow and thus promote the jet diffusion. Their purpose was twofold: to improve the hydraulic performance of the ski jump and to enhance the spray action (Vischer & Hager 1995).

One of the most comprehensive researches on the optimization of slotted (dentate or toothed) buckets was performed by H.Chengyi (1988). According to several model tests on conventional (continuous lip) buckets, rectangular, expanding trapezoidal and contracting trapezoidal dentate bucket, he found that the contracted type of dentate bucket produce smaller erosions with lower values of depth of scour hole and the negative pressures occurred on side surfaces of teeth is rather slight. He also suggested some recommendations for design of dentate buckets in gravity arch dams including arrangements and dimensions of teeth on the contracting trapezoidal dentate buckets (Chengyi 1988).

S. L. Yang (1994), applied a dispersive type of energy dissipator for Shanzi dam in China, which combines features of slotted bucket and ski jump energy dissipators. Tests showed that downstream scouring depths can be reduced by 40% to 90%, compared with the conventional ski jump dissipators (Yang 1994).

Khatsuria (1994), has mentioned to successful using of dentate bucket in Magat dam in Philippines. Using a special design of dentate bucket (Serrated bucket) in this project gave two advantages: considerably larger cross sectional distribution of jet impact on the plunge pool and air entrainment to the point of separation from the solid boundary thus reducing possible cavitation problems (Khatsuria 1994).

Flip buckets or ski jumps in some of large dam projects constructed around the world are equipped successfully with deflector teeth such as: Karakaya dam and Keban dam (Turkey), Pishin dam and Agh-Chai dam (Iran), Picote dam (Portugal), Oroville dam and Celevland dam (USA), Slapy dam and Orlik dam (Czech), Chastang dam (France), Magat dam (Philippines), Stiegler's gorge dam (Norway) and Gutianxi dam (China). In all of the above projects, physical modeling was used to optimize the geometric design and configuration of dentate buckets.

For gravity arch dams with overflow sections terminating to ski jump built in narrow and deep gorges, there is not enough flat space for jet dispersion in plan view. This is the main reason of using converging walls in order to concentrate free jets in the middle part of the valley. According to the previous experiences, using dentate splitters on the ski jumps can reduce effectively scouring depths in such projects.

In this paper, the effect of using dentate buckets on the scour hole profile at downstream of a ski jump of an overflow spillway was investigated. The results are based on a comparison between measured scouring profiles in hydraulic model of plunge pool which was filled with uniformly graded non-cohesive erosive materials.

2 Specifications of Hydraulic Model

The experiments were carried out in a 1:50 scale comprehensive model of a height concrete gravity arch dam built in a narrow and deep george. The main body of dam includes an overflow section terminated to a ski jump structure. The convergent side walls of the spillway enforced the released flood to obey as a convergent free trajectory jet concentrating to the centerline of downstream deep valley. The power house is located below the ski jump structure and a tail pond dam is offered to increase tail water cushion.

The main components of this comprehensive model were: dam overflow section, ski jump structure and downstream valley. A 7 meters length of downstream river channel was built from rigid masonry materials and river bed media was filled with uniformly distributed coarse sand with d_{50}=1.2 cm. Tail water level was regulated by a control gate located at downstream end of river channel which simulated the downstream tail pond dam. Fig. 1, presents a schematic view of the longitudinal section of hydraulic model.

Each test consisted of operating spillway with known discharges and releasing jet flows on regulated tail water level and measuring the longitudinal profile of scouring pit developed due to impact of trajectory jets. As the river canyon is narrow and deep with an approximately constant width through the channel, just longitudinal profiles of scouring pit were used to compare the bucket variants. Time duration for each test was fixed to be 4 hours which was experimentally obtained as time required to stabilize the scour hole profile. The discharges per unit width of bucket lip used in the present study were: 30.2, 50.4 and 73.1 m^2/s and the tail water levels used in the tests were: 143, 145 and 148 masl which are prototype values and are compared with initial river bed which is 130 masl.

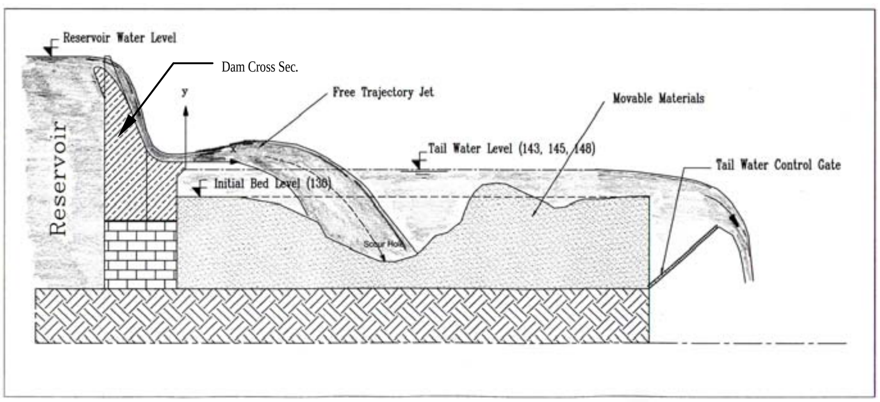

Figure 1. A schematic longitudinal section of hydraulic model

3 Characteristics of Used Deflector Teeth

During the hydraulic model tests, the operation of two types of ski jumps was compared :

- conventional type ski jump with continuous lip (CB) with lip angle = 0^o, 20^o
- dentate (toothed) bucket with lip angle of 0^o (for slotted part) and 20^o (for toothed part).

Selection of geometric design of deflector teeth used in dentate buckets was based on the previous experiences including:

- A review to some of the design standards available for energy dissipators

- A review to similar constructed dams previously equipped with dentate splitters
- Previous comprehensive researches on dentate buckets (Chengyi, 1988)

A specific type of contracting trapezoidal toothed bucket was selected and used in present study. Fig. 2, compares the geometric shape of deflector teeth used by author (type: a), with a conventional type of deflector teeth used in roller buckets (type: b). Fig. 3 shows the details of geometric design of deflector teeth used in the present model and the their configuration installed on the ski jump.

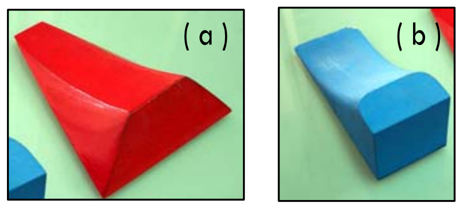

Figure 2. (a) deflector teeth used in the present study (b) conventional deflector teeth used in roller buckets

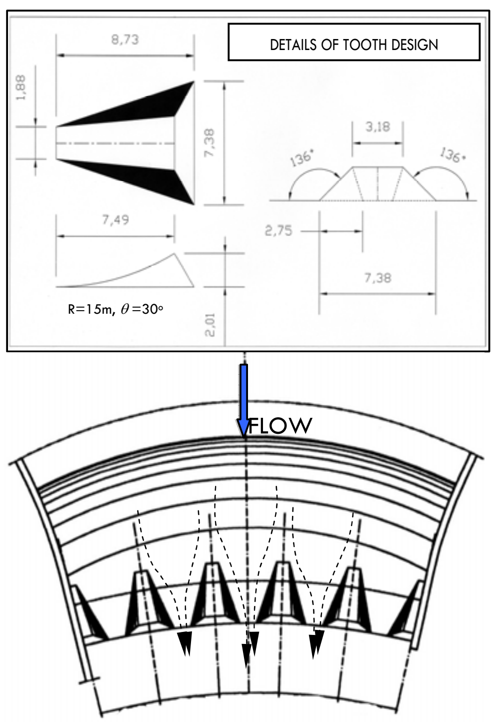

Figure 3. Specifications of deflector teeth used in present paper (Contracting trapezoidal toothed bucket)

4 Analysis and Discussions of Experimental Results

After measuring scouring profiles, they were compared with each other based on the following criteria:

- Distance from dam toe (bucket lip) to the position of maximum depth of scouring pit (X_{max})
- Distance from dam toe (bucket lip) to the position of maximum depth of scouring pit (X_{Beg})
- Maximum depth of scour hole (d_{sc})
- Unit width volume of scouring pit (V_{sc})
- Delay in the beginning of scour hole profile (L'= $X_{Beg,DB}$- $X_{Beg,CB}$)
- Delay in the location of maximum depth of scour hole (L"= $X_{max,DB}$- $X_{max,CB}$)

Typical measured profiles are shown in Fig. 4, in which scour hole profiles issued from DB (5 teeth) is compared with scour hole profiles created by CB(θ_{lip}=0^o) and CB(θ_{lip}=20^o).

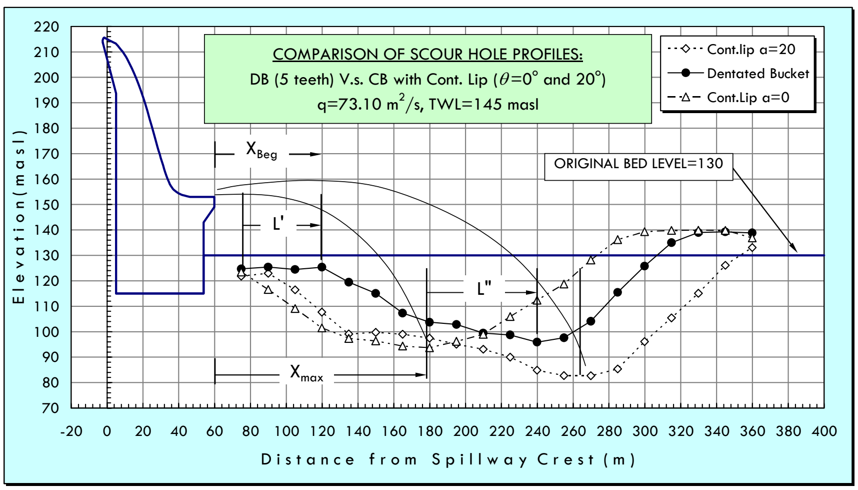

Figure 4. Comparison of Scour Hole Profiles issued from DB and CB

The experimental results showed that value of X_{max} for DB is given by the following inequality:

$$X_{\max}(CB,\theta=0^o) \le X_{\max}(DB,5teeth) \le X_{\max}(CB,\theta=20^o) \quad (1)$$

More accurately it can be expressed by the following equation:

$$X_{\max}(DB,5teeth) \approx \frac{1}{2}\left[X_{\max}(CB,\theta=0^o)+X_{\max}(CB,\theta=20^o)\right] \quad (2)$$

Fig.5 shows the above relationship in a non-dimensional form. Generally such a relationship depends on the configuration of slots and teeth partitions on the ski jump. In this figure, H_v, is the velocity head at the lip of the ski jump and q, is discharge per unit width of bucket lip.

Experimental results showed that by using DB (5 teeth), maximum depth of scour hole diminishes up to 40% and unit width volume of scouring pit diminishes up to 49%, lower than CB(θ_{lip}=20^o). Moreover using DB (5 teeth), shifts downstream wards the location of maximum depth of scour hole up to 1.5 times more than CB(θ_{lip}=0^o). As a final result using DB (5 teeth), shifts downstream wards the beginning point of scouring pit up to 4 times more than CB(θ_{lip}=0^o) which is important from the stability point of view (Table.1,2).

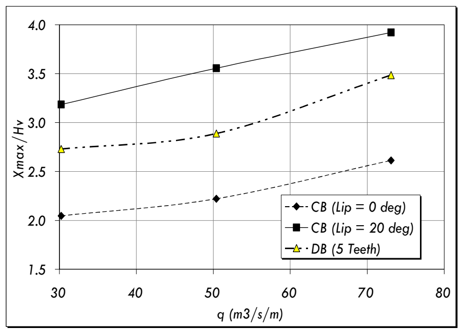

Figure 5. Comparing the location of maximum depth of scour hole in DB and CB

Table 1. Comparing scouring properties of DB(5 teeth), CB (θ_{lip} =20^o) and CB (θ_{lip} =0^o) for 13m tail water depth

Items (%)	q_1=30.24	q_2=50.40	q_3=73.10
Percent of reducing maximum depth of scour hole (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	39.0	30.0	32.3
Percent of reducing unit width volume of scouring pit (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	39.9	34.0	49.3
Shifting D/S wards of the location of maximum depth of scour hole , L"/Xmax (DB, 5 teeth v.s. CB, θ_{lip} =0^o)	22.2	50.0	33.3
Shifting D/S wards of the beginning point of scouring pit, L'/XBeg (DB, 5 teeth v.s. CB, θ_{lip} =0^o)	100.0	153.3	200.0
Shifting D/S wards of the beginning point of scouring pit, L'/XBeg (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	33.3	68.9	50.0

Table 2. Comparing scouring properties of DB(5 teeth), CB (θ_{lip} =20^o) and CB (θ_{lip} =0^o) for 15m tail water depth

Items (%)	q_1=30.24	q_2=50.40	q_3=73.10
Percent of reducing maximum depth of scour hole (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	37.3	39.7	27.9
Percent of reducing unit width volume of scouring pit (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	44.7	46.9	46.6
Shifting D/S wards of the location of maximum depth of scour hole , L"/Xmax (DB, 5 teeth v.s. CB, θ_{lip} =0^o)	33.3	30.0	33.4
Shifting D/S wards of the beginning point of scouring pit, L'/XBeg (DB, 5 teeth v.s. CB, θ_{lip} =0^o)	34.4	145.0	300.0
Shifting D/S wards of the beginning point of scouring pit, L'/XBeg (DB, 5 teeth v.s. CB, θ_{lip} =20^o)	34.4	63.3	100.0

Conclusions

Scour hole due to free jets released from dentate (toothed) buckets was modeled using non-cohesive materials in a 1/50 scale hydraulic models of real shaped spillways. On the basis of measurements of scour hole profiles along the center line of the bucket in both dentate and conventional type bucket with continuous lip, it was concluded that:

- Using the dentate (toothed) buckets can effectively reduce the ultimate depth of scour hole. This confirm with previous researches.
- Using the dentate (toothed) buckets can effectively reduce the potential of erosion which may be expressed by volume of eroded materials.
- The jet throw distance estimated from the deepest point of the scour hole profile shows that the impact point of jet for dentate buckets could be far enough as the conventional type and its value can be estimated from a simple mathematical combination of trajectory equations of CB.
- Upstream development of scour hole issued from DB, may be far enough from dam toe which is important from stability point of view
- The configuration and number of teeth and slots are important factors in design of dentate buckets. Physical modeling is a powerful tool for optimizing the configuration of deflector teeth and slots.

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