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PHYSICAL AND NUMERICAL MODEL STUDY INVESTIGATING PLUNGE POOL SCOUR AT KARIBA DAM[1]

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1. INTRODUCTION

Kariba Dam is a 128 m high arch dam located on the border between Zambia and Zimbabwe. The dam has been constructed in the late 1950s and formed at that time the largest man-made lake worldwide. The dam is equipped with 6 flood gates, each about 9 m high by 9 m wide, allowing for a total outflow of about 9000 m^3/s (Figure 1).

The plunge pool downstream of the dam consists of sound and relatively hard gneiss bedrock and is basically unlined. Nevertheless, frequent outflows

[1] *Étude physique et numérique de l'affouillement de la fosse d'érosion du barrage de Kariba.*

generated between 1962 and 1981 have formed an 80 m deep scour hole in the bedrock, which is unprecedented in dam history. As the flood gates are located in the upper part of the dam wall, they operate under relatively low velocities and thus generate plunging jets that impact quite close to the dam foundations. As such, potential regression during further scour formation might approach the dam foundations and should be avoided.

Fig. 1
General view of Kariba Dam
Vue générale du barrage de Kariba

This paper presents a combined physical-numerical study investigating scour potential at Kariba Dam, performed by a consortium consisting of the Laboratory of Hydraulic Constructions of the Swiss Federal Institute of Technology in Lausanne (EPFL) for the physical modelling and the consulting company AquaVision engineering Ltd. In Ecublens, Switzerland (AVE) for the numerical modelling and for future scour predictions.

The paper focuses on the hybrid methodology that has been proposed to assess past and future scour formation in the plunge pool.

2. SCOUR HISTORY AT KARIBA DAM

Scour history at Kariba Dam is strongly related to the detailed functioning of the 6 flood gates since 1962. In this sense, two main periods may be distinguished:

1. 1962 - 1981: Frequent and combined functioning of several flood gates, often for continuous periods of several weeks to months per year.
2. 1981 - 2010: Occasional functioning of one or more flood gates, together with very long periods of no gate functioning at all.

As such, it is obvious that most of the actually observable scour is related to the period between 1962 and 1981, subsequent scour formation being almost negligible.

3. HYBRID MODELLING APPROACH

To fully assess the major scour hole issues at Kariba, a hybrid modeling has been proposed, involving a sound and efficient combination of physical, analytical and numerical modeling (Fig. 2).

The physical model has a fixed bed and is only used to record the fully 3D turbulent pressure fluctuations and corresponding velocities along the fixed water-rock interface. This is done for several historic scour hole configurations (1972, 1981). The results are upgraded to prototype values and inserted into the numerical model. The latter then computes independently the scour hole evolution since 1962 until 1972 or 1981, based on 2D jet diffusion and calibrated by the physical model pressure recordings.

Once the numerical model calibrated, numerical scour predictions are made on the long term, with or without scour countermeasures. Potential enhancements to the actual plunge pool geometry are so defined by the numerical model, and then modeled by the physical model to check for the 3D pressure fluctuations. This go-and-back between the physical and the numerical model finally allows to determine a target pool geometry with all necessary countermeasures to solve the scour hole issue at Kariba Dam on the long term.

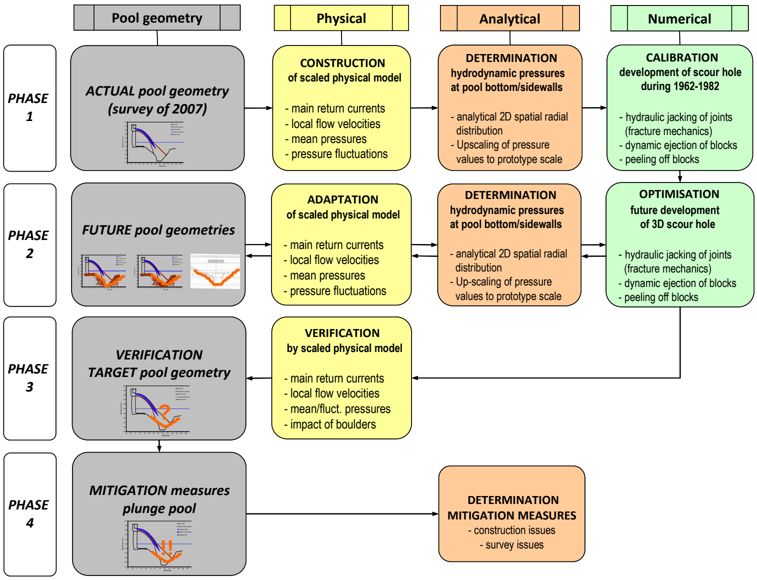

Fig. 2
Hybrid modeling technology of the Kariba Dam scour study
Technologie de modélisation hybride pour l'étude d'affouillement à Kariba

4. PHYSICAL MODEL STUDY

The physical model of Kariba Dam included all relevant components of the prototype needed to thoroughly reproduce the jet and turbulent flow features generated within the plunge pool. It is constructed with a scaling factor of 1:65 and reproduces an upstream section of the Kariba reservoir, the Kariba Dam itself with its crest and spillway sluices, the free falling jet, the detailed downstream plunge pool and a section of the adjacent valley topography, including the powerhouse outlet structures on both river banks (Fig. 3).

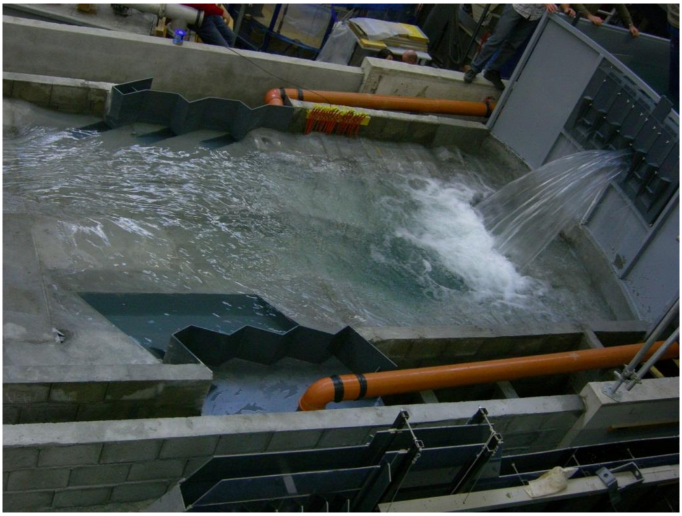

Fig. 3
General view of physical model
Vue générale du modèle physique

The maximum spillage capacity of 9000 m^3/s on prototype corresponds to 264 l/s on the model. Also, the powerhouse discharges add two times 700 m^3/s on prototype, equivalent to two times 21 l/s on the model. Upstream of the dam, a supply basin reproduced a section of the reservoir in the vicinity of the sluice spillway on an area of approximately 42 000 m^2 (220 m laterally and 190 m longitudinally) with a depth of approximately 100 m. Downstream of the dam, the topography was soundly reproduced on a surface of approximately 100 000 m^2 (280 m laterally and 370 m longitudinally), including the actual plunge pool scour hole with a rigid surface. The tailwater level was regulated by a flap gate weir mounted in front of the restitution basin.

The measurement equipment included devices to control the input discharge (by MID) and the water level (by point gauges). Furthermore, measurements focused on dynamic pressure fluctuations at the plunge pool bottom and the corresponding flow velocities along the slopes near the bottom. As such, the pressures were measured simultaneously at 16 relevant points using piezo-resistive flash diaphragm transmitters with an acquisition frequency of 1 kHz. The flow velocities indicating the general flow field within the pool were derived from ADV measurements. The data were statistically and hydraulically analysed before their transfer to the numerical model.

Several gate opening configurations were tested, starting with individual gates and ending with scenarios of maximal discharge with all gates opened, and various combinations.

5. NUMERICAL MODEL STUDY

The numerical modelling was performed by using the Comprehensive Scour Model (CSM, [1]). This physics based model allows expressing detailed scour hole formation as a function of time of flood duration and is based on the following rock break-up processes:

1. hydrodynamic fracturing of closed-end rock joints (= joints that are not completely formed yet);
2. dynamic uplift / peeling off of so formed rock blocks (= once the joint network is completely formed).

Application of the detailed history of gate functioning and lake levels since 1962 allowed to reconstitute the time-dependent scour hole formation in the plunge pool.

Starting from an idealized flat pool bottom (initial situation at time of dam construction), and using an automatically adapted 2D jet diffusion model that generates pressure fluctuations along the scouring bottom, the CSM was perfectly able to reproduce not only the ultimate scour depths at different time periods in history, but also the general shape of both the up-and downstream slopes of the scour hole. Fig. 4 compares the numerically computed scour hole with the bathymetric recordings made in 1972 and 1981. It can be seen that a striking similar shape of scour hole is obtained for both time periods. While the 1972 scour hole was rather oriented towards downstream, the 1981 scour hole is much more directed towards the toe of the dam.

This aspect is of particular importance because of the risk of regressive erosion towards the dam toe. Hence, the CSM was perfectly able to reproduce the necessary details of scour development of the scour hole, making it suitable for future scour predictions.

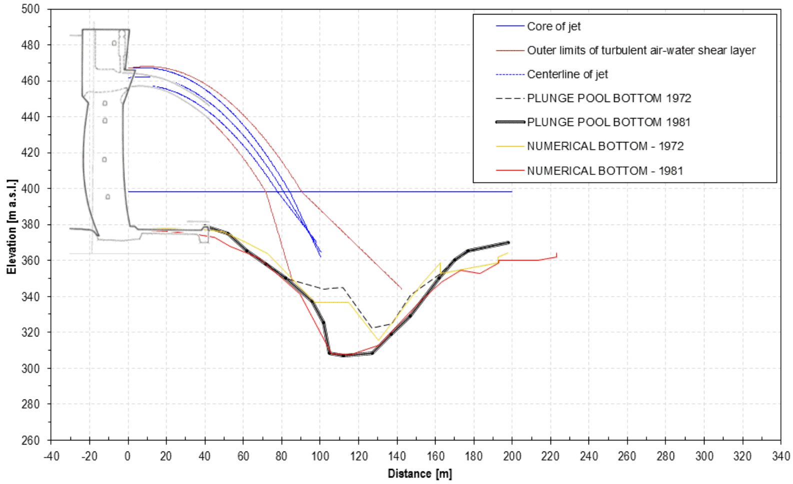

Fig. 4

Numerical scour hole versus real scour hole

Comparaison de la fosse d'érosion numérique - réelle

REFERENCES

[1] BOLLAERT E.F.R., A comprehensive model to evaluate scour formation in plunge pools. *Int. Journal of Hydropower & Dams*, 2004, 2004(1), pp. 94-101.

SUMMARY

Hybrid modelling techniques allowed sound combination of physical and numerical modelling to successfully reproduce more than 40 years of successive scour hole formation at Kariba Dam (Zambia-Zimbabwe). While the physical model allowed recording of 3D turbulent pressure fluctuations at the pool bottom, the numerical model successfully related these pressures to the major rock break-up processes as a function of space and time. This not only allowed to reproduce the ultimate scour depth with time, but also the detailed shape of both the up-and downstream slopes of the complex scour hole at Kariba Dam, since 1962 until now.

In a second step, scour predictions made by the numerical model will allow to define enhancements to the current state of the plunge pool, with the aim to minimize any future scour formation for the remaining lifetime of the dam.

RÉSUMÉ

Des techniques de modélisation hybride ont permis de combiner un modèle physique avec un modèle numérique de manière à reproduire avec succès plus de 40 ans d'évolution de la fosse d'affouillement du barrage de Kariba (Zambia-Zimbabwe). Tandis que le modèle physique permet de mesurer les fluctuations de pression 3D au fond de la fosse, le modèle numérique a appliqué ces pressions aux différents modules d'affouillement du massif rocheux, dans le temps et dans l'espace. Ceci n'a pas seulement permis de reproduire la profondeur ultime de la fosse en fonction du temps, mais également la forme détaillée des faces amont et aval de la fosse complexe de Kariba depuis 1962 jusque maintenant.

Deuxièmement, les prévisions d'affouillement basées sur le modèle numérique serviront pour déterminer les mesures nécessaires à prévoir sur la fosse dans son état actuel, de manière à minimiser toute formation future d'affouillement pour la durée de vie restante du barrage.