Numerical simulation to evaluate the effect of the stepped chute on abrasion erosion of a stilling basin type III

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Abstract. Hundreds of concrete cubic meters may be ruined due to the abrasion erosion in several strategic hydraulic structures. Such unfavorable action can cause serious dangers, impose high maintenance costs, and reduce these structures' life span. The high-velocity water flow, which carries large amounts of sediments, is the main cause of this phenomenon. This study was directed to evaluate the possibility of minimizing the abrasion action by changing the hydraulic structure design criteria; a numerical simulation was conducted depending on the FLOW3D program. It aimed to evaluate the effect of using a stepped spillway chute on the applied water pressure and the flow velocity along the type III stilling basin. The numerical simulation results showed that using a stepped chute instead of the traditional smooth chute provided a better water pressure distribution and reduced the maximum applied pressure by approximately 28.8 to 68.2%. Moreover, it also reduced the flow velocity along the stilling basin. Thus, the stepped chute use can be considered a possible solution to reduce abrasion erosion hazards in hydraulic structures.

1. Introduction

Each type of structure is designed to carry some types of effective loads. Gravity loads are the typical loading of residential, commercial, office and other service buildings, which can also be accompanied by loads like wind, seismic and lateral loads. Occasionally, buildings may become under the influence of accidental loads like fires [1] or short period impacts [2,3]. Sudden impacts can be due to hits of car collisions or dropping masses from upper altitudes [4,5]. On the other hand, the impact forces are considered one of the main design loads, like airport runways from airplane wheels and offshore structures from water waves [6]. Hydraulic structures are one type where the impact of water and waterborne materials are continuous on horizontal or vertical surfaces, which causes the erosion of these surfaces reducing the live span [7].

Erosion of concrete in hydraulic structures can be defined as the gradual disintegration that mainly occurs by three major causes; abrasion, cavitation, and chemical attack. Briefly, the main cause of cavitation damage is the explosion of vapor bubbles created due to the pressure change through a very high-speed water flow. In contrast, the chemical attack is caused by the action of chemicals and their interaction with the concrete surfaces [8]. On the other hand, the main cause of the abrasion erosion is the action of the
water-borne solids such as sand, silt, gravel, ice and debris against the surface of concrete during the hydraulic structure operation [8-11].

In general, abrasion damage occurs in hydraulic concrete due to two mechanisms. The first one occurs in horizontal surfaces of hydraulic structures. It is caused by the rolling and sliding of solid particles conveyed by the water flowing on the concrete surface. This action depends on the water velocity and the transmitted bed load. The second mechanism can occur in the vertical components of these structures. It is created by the normal impact action of the transported particles. The inclined concrete surfaces may be subjected to the effect of both mechanisms [12-16].

As a rule, the stilling basin's performance is significantly related to the inlet flow properties, which are affected by the spillway's geometry [17-19]. The classic investigations focused on the inverted smooth chutes. The smooth surface of the chutes can provide little kinetic energy dissipation. Thus, significant abrasion damage would occur in the stilling basin accessories. Few recent studies were carried out to understand the effect of the stepped chute. They revealed that this type of chute acts as a continuous energy dissipater. Thus, the abrasion damage can be reduced; construction and maintenance costs can be minimized, and the hydraulic structure's life span can be prolonged as well [20].

Several previous numerical studies were conducted to evaluate the stepped chute's effect, it can be concluded that the increment of the number of steps significantly increases the energy dissipation [21-24]. Frizell and Svoboda [25] conducted experimental work to evaluate the effect of the stepped spillway on the flow characteristics for the type III stilling basin compared with that of the smooth spillway. An adjustable slope flume was used to provide three different slopes of 14.04, 26.57 and 51.34° with the horizon. Data were gathered for both the smooth and the stepped chute. The height of the used steps was 38.1 mm. different flow discharges were applied. Test results showed that the stepped chute's use seems more acceptable for the type III stilling basins. The incoming velocities were minimized, and the tailwater levels were also reduced. Valero et al. [20] directed a numerical work based on the experimental work of Frizell and Svoboda [25] with the aid of the FLOW3D program. Test results showed that the complicated behavior of the water flow through the hydraulic jump could be analyzed using Computational Fluid Dynamic (CFD).

Moreover, the stepped chute significantly reduced the flow velocity along the stilling basin. Christodoulou [26] conducted experimental work to study the excess kinetic energy's dissipation over a stepped spillways. A stepped spillway model with an angle of 55° was prepared, and different discharges were applied. The results obtained from this work showed that the spillway steps considerably increased energy dissipation. The loss of energy largely relies on the $y_c/h$ ratio, where $h$ is the height of the step, and $y_c$ is the critical depth of the flow that passes over the spillway. Furthermore, they showed that it depends on the number of steps as well.

There are many types of stilling basins. In the present study, the type III stilling basin has been investigated. It is relatively short and contains chute blocks, baffle piers and a simple end sill [20, 27]. It is generally used in canal structures and comparatively small outlet works. For this type, flow velocity must range between 15.2 to 18.3 m/sec, while the discharge per the unit width must be less than 18.57 m$^2$/sec, and Froude number must be more than 4 [25, 27].

The abrasion damages can be minimized either by developing the mechanical properties of the concrete or, more importantly, by changing the hydraulic design criteria. To study the effect of the design criteria in controlling the abrasion phenomenon damages, a numerical work based on the experimental work of Frizell and Svoboda [25] was conducted in this work. A stepped spillway chute with an angle of 26.57° to the horizon, which is terminated by the type III stilling basin, was investigated. The flow velocity and water pressure, which are related directly to the abrasion damages [8], are investigated at the chute block's zones, baffle piers and end sill of this type of chutes, and the results are compared with that of the traditional smooth chute. Six different discharges of values ranged between 0.133 and 0.255 m$^3$/sec were applied in this work. The numerical simulation was carried out depending on FLOW3D v11.0.4 software.
2. Concept of utilizing CFD

CFD or Computational Fluid Dynamic can be defined as the part of fluid mechanics that depends on the numerical analysis using the computer to find the solution of the fluid flow dominant equations (the conservation of energy, mass and momentum) in 1, 2 and 3-dimensional models. In several ways, the use of CFD programs can compensate for the conducting of an experiment. Thus, it can considerably save time, cost and efforts as well. Like experimental work, the numerical work must represent the real-life conditions to obtain realistic results [28].

There are many CFD software programs such as FLOW3D, PHOENICS and FLUINT. In this study, to simulate water motion through the smooth and stepped chute, which is terminated by the stilling basin type III, the FLOW-3D program was used. FLOW-3D is a CFD program that employs numerical methods to find the solution of the fluid motion equations. It provides a series of numerical and physical options that give wide opportunities to simulate different flow cases [28].

The essential base of approximately each CFD problem is the equation of Navier-stokes. This equation simulates many fluid flows (only single-phase). During the previous century, various types of numerical approaches were developed to simulate the flow of fluids, using finite difference, element and volume methods. CDF codes usually depend on the Finite Volume Method (FVM). This method is commonly used because it requires smaller memory usage, and it provides a quick solution for bigger problems. Any numerical model should begin with a grid or computational mesh. It is made up of several interconnected cells or elements. These elements divide the physical space into tiny volumes with numerous nodes. The grid usually represents a numerical space that compensates for the real physical one [28]. The following equations represent the continuity and momentum equations that used to solve the partial differential equations in the FLOW3D program:

\[
\frac{V_f}{\rho} \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} (\rho A_x) + R \frac{\partial}{\partial y} (\rho A_y) + \frac{\partial}{\partial z} (\rho A_z) + \xi \frac{u A_x}{x} = \frac{R_{SOR}}{\rho}
\]

where \(V_f\) is the fractional volume open to flow, \(\rho\) is the fluid density, \(R_{SOR}\) is the mass source, \((u, v, \text{ and } w)\) are the velocity components in the coordinate directions \((x, y, \text{ and } z)\) or \((r, \theta, \text{ and } z)\). \(A_x, A_y, \text{ and } A_z\) are the fractional areas open to flow in \(x, y, \text{ and } z\) directions, respectively. \(R\) is a coordinates-dependent coefficient, \(c^2\) is the square of the sound, and \(p\) is the pressure [28].

\[
\frac{\partial w}{\partial t} + \frac{1}{V_f} \left( u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right) = - \frac{\partial P}{\rho \partial z} + G_x + f_x + b_z - \frac{R_{SOR}}{\rho V_f} (w - w_w - \delta w_z)
\]

where \(G_x, G_y, \text{ and } G_z\) are the body accelerations, \(f_x, f_y, \text{ and } f_z\) are the viscous accelerations, and \(b_x, b_y, \text{ and } b_z\) are the flow losses in porous media or across porous baffle plate [28].

3. Meshing and geometry

The three-dimensional models of the smooth and stepped spillways, which were modeled for the type III stilling basin, were plotted by the aid of AutoCAD 2010-3D environment. They were plotted depending on Frizell and Svoboda [25] and the numerical investigation of Valero et al. [20]. They represent a model with a scale of 1:26 as compared with the real Folsom spillway. The AutoCAD drawings were exported to the FLOW3D software in the format of lithography (*.stl). Figures 1 shows the investigated model's dimensions for the smooth and stepped chutes. On the other hand, Figure 2 presents the FLOW3D model of the smooth chute.

To achieve more accurate results, a suitable cell number must be chosen. Basically, as cell number increases, the accuracy of the analysis process results considerably increases. However, using a huge cell number can significantly increase the required time for the analysis process. Thus, an optimum cell number must be selected. FAVOR option may be helpful to choose the suitable cell number, and to achieve a good model shape as well. Figure 3 shows the stepped spillway model by FAVOR.
Figure 1. Dimensions (cm) of (a) the smooth chute; (b) the stepped chute [21].

Figure 2. FLOW3D model of the smooth spillway chute and its type III stilling basin.

Figure 3. FLOW3D model of the stepped spillway chute and its type III stilling basin by FAVOR.
4. Initial and boundary conditions
The solution of any problem conducted by FLOW3D depends on the fluid flow solution governing partial
differential equations at the initial and boundary conditions. Thus, precise results require an adequate
representation of these boundaries. In this study, six boundaries, as shown in Figure 4, were required for a
good simulation process. These boundary conditions are:
X-minimum (model upstream): Volumetric flow rate (Q).
X-maximum (model downstream): Outflow (O).
Y-minimum and Y-maximum (model sides): Wall (W).
Z-minimum (model bottom surface): Wall (W).
Z-maximum (model top surface): Specified pressure (P).

5. Fluid characteristics and physics
In this simulation, the used fluid was water with a dynamic viscosity of 0.01 gm/cm.sec and bulk density
of 1 gm/cm³. On the other hand, the water temperature was taken as 20 °C.
To provide an adequate simulation for the examined models, three main physics were stimulated. The
gravity was activated with a negative value of 980 cm/sec² in the Z-direction, density elevation was also
activated as a function of the other variables. Finally, the viscous flow was ticked.

6. Verification of the numerical model
As aforementioned, the present numerical work was verified depending on Frizell and Svoboda [25]. The
verification process was carried out based on the incoming flow depth ($D1$) and Froude number ($Fr$) at the
end of the chute. To provide a clear understanding of the verification process, the obtained results are
presented in the form of bar charts that relate the Verification Difference (VD) with the flow discharges
for both used chutes. VD for Froude number can be determined for each flow discharge by the following
equation.

$$ VD = \frac{Fr_e - Fr_n}{Fr_e} $$

where $Fr_e$ and $Fr_n$ are the Froude number values of the experimental and the numerical works for specific
chute type, respectively.
On the other hand, the VD of the flow depth can be determined by the following equation.
where $D_{1e}$ and $D_{1n}$ are the experimental and numerical incoming depth, respectively. Figure 5 shows the verification difference of Froude number and its variation with the applied discharges for the smooth and stepped spillway chutes. It can be noticed that good Froude number results could be achieved by using FLOW3D software. The VD of the smooth and stepped chutes were in the range of 7.74 to 9.8% and 5.82 to 9.7%, respectively.

Figure 5. Froude number verification difference.

Figure 6 presents the VD of the flow depth ($D_1$) with the applied discharges for both of the used chutes. Similarly, good depth results could be achieved, showing relatively small differences with their corresponding experimental results. The VD for the smooth chute was approximately in the range of 2.8 to 9.9%, while it was in the range of -1.9 to 8.8% for the stepped chute. Generally, it can be observed that the numerical Froude number and flow depth were close enough to the correspondent values of the experimental work with a maximum difference not exceeding 10%. Table 1 shows the results of the verification process.

Figure 6. Water depth verification difference.
Table 1. Results of the verification process.

| Discharge (m³/sec) | Smooth Chute | Stepped Chute |
|-------------------|--------------|---------------|
|                   | Froude No. | D₁(cm)       | Froude No. | D₁(cm) |
|                   | Exp.       | Num.         | Exp.      | Num.       | Exp.      | Num.         |
| 0.113             | 10.43      | 9.623        | 3.19      | 3.041      | 5.34      | 5.343        | 4.98      | 5.074       |
| 0.142             | 9.83       | 8.867        | 3.85      | 3.54       | 5.67      | 6            | 5.55      | 5.578       |
| 0.17              | 10.62      | 9.596        | 4.13      | 4.015      | 6.05      | 6.0574       | 6.01      | 5.609       |
| 0.198             | 10.63      | 9.602        | 4.57      | 4.261      | 6.38      | 6.132        | 6.42      | 6.28        |
| 0.227             | 10.46      | 9.487        | 5.05      | 4.55       | 6.36      | 6.153        | 7.03      | 6.411       |
| 0.255             | 10.05      | 9.142        | 5.61      | 5.06       | 7.56      | 6.827        | 6.78      | 6.21        |

* Experimental work results
b Numerical work results

7. Result and discussion
The current numerical study results are displayed in bar charts that relate the effect of using the stepped chute with the various applied flow discharges.

7.1 Steps impact on the water pressure
Results obtained from the numerical analysis are presented in the form of bar charts. These charts relate the Steps Effect on the water pressure (SEₚ) with the applied flow discharges at different stilling basin zones. SEₚ was determined according to the following equation.

\[ SEₚ(\%) = 100(P_{sm} - P_{st})/P_{sm} \]  

where \(P_{sm}\) and \(P_{st}\) are the water pressure for a specific zone and certain discharge due to the smooth chute and stepped chute, respectively.

As it is known, if a stepped spillway chute is used, the chute block of the stilling basin will be needless [20]. Accordingly, the area just next to the last step was chosen to represent the chute block zone of the stepped chute because it can be seen that the maximum water pressure and velocity took place there. This critical zone must not be neglected, and it should be taken into account for comparison and, more importantly, for design purposes. Figure 7 displays the intended zone.
Figure 8 reveals that the water pressure was significantly increased at the chute block zone when the stepped chute was used. This effect decreases as the flow discharge increases. This can be attributed to the fact that as the discharge reduces, the energy dissipation lowers [26, 29]. For flow discharges of 0.113 and 0.255 m³/sec, the SEPs were -1759 and -397%, respectively.

Figure 9 shows that the use of the stepped chute minimized the applied pressure on the baffle piers. For flow discharges of 0.113, 0.142, 0.17, 0.198, 0.227, and 0.255 m³/sec, the effect of the steps were 67.7, 41.2, 36.7, 49.8, 47.1, and 44.1%, respectively. It can be noticed that the presence of the steps reduced the applied pressure that acts on the end sill as well. This effect was lowered as the flow discharge was increased. The SEPs were 68.2 and 28.8% for the flow discharges of 0.133 and 0.255 m³/sec.

Generally, the use of the stepped chute exceedingly reduced the applied pressure on the stilling basin accessories. Despite the noticeable pressure increment that occurred at the chute block zone, the stepped chute provided a better and safer pressure distribution throughout the length of the stilling basin. In the smooth chute and for the discharge of 0.113 m³/sec, the pressures were 412, 37027, and 14552 gm/cm² at the chute block, baffle piers, and end sill zone, respectively. When the stepped chute was used, the pressures for the same zones sequence were 7660, 11965, and 4628 gm/cm², respectively.
7.2 Steps impact on the flow velocity

To provide a clear understanding of the effect of the steps on the flow velocity at the various accessories of the type III stilling basin, results obtained from the current numerical investigation were presented in the form of bar charts. These bar charts relate the Steps Effect on the flow velocity (SEV) with the applied flow discharges for the selected zones. To calculate the SEV, the following equation must be applied.

\[ SEV(\%) = 100\left(\frac{V_{sm} - V_{st}}{V_{sm}}\right) \]  

where \( V_{sm} \) and \( V_{st} \) are the flow velocity in a specific zone and discharge due to the smooth and stepped chute, respectively.

Figure 10 shows the velocity reduction due to the stepped chute's use in the chute block, baffle piers and end sill zones. First of all, in the chute block zone, the minimum velocity reduction can be observed. On average, the velocity was reduced approximately by 18% when the stepped chute was used. It can also be noticed that the steps' effect was not significantly affected by the change of the flow discharge. On the other hand, a great effect can be observed clearly in the baffle piers zone. Furthermore, it can be noticed that the effect of the step reduced slightly as the flow discharge increased. For the flow discharges of 0.113, 0.142, 0.17, 0.198, 0.227 and 0.255 m³/sec, the SEV values were 37.2, 31.3, 31, 28.7, 25.9 and 25.2%, respectively. Finally, the greatest velocity reduction took place in the zone of the end sill. Like the baffle piers zone, the steps' effect decreased noticeably as the flow discharge increased. The SEV was 42.7, 35.9, 33.5, 32.9, 22.9 and 22.8% for the flow discharges of 0.113, 0.142, 0.17, 0.198, 0.227 and 0.255 m³/sec, respectively.

As it is already known, the stepped chute's use provides a higher air concentration [25]. Thus, the cavitation damage must be reduced due to the higher air-water ratio [8]. Moreover, the discussed results showed that this type of chute provides a better pressure distribution throughout the stilling basin length and significantly reduces the water pressure and flow velocity. This effect would considerably minimize abrasion damage [8 and 30, 31]. Thus, it can reduce the construction and maintenance costs and increase the hydraulic structure's life span.

8. Conclusions

Hydraulic structures that are subjected to a supercritical water flow that drags large amounts of particles are susceptible to severe abrasion erosion damages. This will increase the maintenance costs and reduce
the life span of these strategic structures. Many previous studies were conducted to reduce this danger. In this work, numerical work was directed to investigate the hydraulic design criteria’ effect on reducing the abrasion wear. The aid of FLOW3D software studied the impact of using stepped spillway chute on the flow velocity and the applied water pressure throughout the length of type III stilling basin. According to the results obtained from the current numerical work, the followings can be considered as the main conclusions:

- Although the use of the stepped chute increased the applied water pressure at the chute block zone, it provided a preferable pressure distribution along the stilling basin. Also, it reduced the maximum pressure that took place, for both cases, at the baffle piers by approximately 28.8 to 68.2%.
- In the chute block zone, the flow velocity was reduced on average by approximately 18%. On the other hand, the reduction was between 25.2 to 37.2% in the baffle piers zone. The maximum flow velocity reduction occurred at the end sill zone; it ranged between 22.9 to 42.7%.
- The steps that were mentioned in the previous points were generally reduced as the flow discharge increased.
- Thus, it can be said that the use of the stepped spillway chute significantly reduces the abrasion erosion damages and provides a more economical stilling basin.

9. References

[1] Al-Gasham T S, Mhalhal J M and Jabir H A 2019 Influence of post-heating on the behavior of reinforced self-compacting concrete hollow columns Structures 22 266–277.
[2] Salaimanimagudam M P, Suribabu C R, Murali G and Abid S R 2020 Impact response of hammerhead pier fibrous concrete beams designed with topology optimization Periodica Polytechnica Civil Engineering.
[3] Abid S R, Abdul-Hussein M L, Ayoob N S, Ali S H and Kadhum A K 2020 Repeated drop-weight impact tests on self-compacting concrete reinforced with micro-steel fiber Heliton 6 1–11.
[4] Abid S R, Abdul-Hussein M L, Ali S H and Kazem A F 2020 Suggested modified testing techniques to the ACI 544-R repeated drop-weight impact test Construction and Building Materials 244 118321.
[5] Murali G, Abid S R, Amran Y H M, Abdelgader H S, Fediuk R, Susrutha R and Poonguzhali K 2018 Impact performance of novel multi-layered prepacked aggregate fibrous composites under compression and bending Structures 28 1502–1515.
[6] Haridharan M K, Matheswaran S, Murali G, Abid S R, Fediuk R, Amran Y H and Abdelgader H S 2020 Impact response of two-layered grouted aggregate fibrous concrete composite under falling mass impact Construction and Building Materials 28 1502–1515.
[7] Hilo A N, Abid S R and Daek Y H 2018 Numerical model for flow of stilling basin type III International Conference on Advance of Sustainable Engineering and its Application (ICASEA), Wasit University, Kut, Iraq 126–130.
[8] ACI Committee 210 2003 Erosion of concrete in hydraulic structure (ACI 210R-03) American Concrete Institute, USA, 1–24.
[9] Abid S R, Hilo A N, Ayoob N S and Daek Y H 2019 Underwater abrasion of steel fiber-reinforced self-compacting concrete Case Study in Construction Materials 11 1–17.
[10] Abid S R, Hilo A and Daek Y H 2018 Experimental tests on the underwater abrasion of engineered cementitious composites Construction and Building Materials 171 779–792.
[11] Ayoob N S and Abid S R 2020 Analysis of abrasion rates in concrete surfaces of hydraulic structures IOP Conference Series: Material Science and Engineering 888 1–9.
[12] Kryżanowski A, Mikoś M, Śušteršič J, Ukrainczyk V and Planinc I 2012 Testing of concrete abrasion resistance in hydraulic structures on the Lower Sava River Journal of Mechanical Engineering 58 245–254.
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[13] Abdul-Hussein M L, Abid S R, Ali S H and Kadhum A L 2020 Abrasion of reactive powder concrete under direct water impact Applied Mechanics and Materials 897 41–48.

[14] Ayoob N S, Abid S R and Hilo A N 2020 Water-impact abrasion of self-compacting concrete Magazine of Civil Engineering 96 60–69.

[15] Abid S R, Shamkhi M S, Mahdi N S and Daek Y H 2018 Hydro-abrasive resistance of engineered cementitious composites with PP and PVA fibers Construction and Building Materials 187 168–177.

[16] Y W, Cho S W and Hsu T H 2012 Impact abrasion of hydraulic structures concrete Journal of Marine Science and Technology 20 253–258.

[17] Chinnarasri C and Wongwisess S 2004 Flow regimes and energy loss on chutes with upward inclined steps Canadian Journal of Civil Engineering 31 870–879.

[18] Dong Z, Wang J, Vetsch D F, Boes R M and Tan G 2019 Numerical simulation of air–water two-phase flow on stepped spillways behind x-shaped flaring gate piers under very high unit discharge Water 11 1956.

[19] Tassinari L C, Sanagiotto D G, Marques M G, Lauffer L L and Neto E F T 2020 Combination of experimental and numerical approaches to determine the main characteristics of skimming flow in stepped spillways Brazilian Journal of Water Resources 25(3) 1-17.

[20] Valero D, Bung D, Crookston B and Matos J 2016 Numerical investigation of USBR type III stilling basin performance downstream of smooth and stepped spillway 6th International Symposium on Hydraulic Structures 652–663.

[21] Tabbora M, Chatila J and Awwad R 2005 Computational simulation of flow over stepped spillways Computers and Structures 83 2215–2224.

[22] Rad I N and Teimouri M 2010 An investigation of flow energy dissipation in simple stepped spillways by numerical model European Journal for Scientific Research 47(4) 544–553.

[23] Tabari M M R and Tavakoli S 2016 Effects of stepped spillway geometry on flow pattern and energy dissipation Arabian Journal for Science and Engineering 41 1215–1224

[24] Irzooki R H, Mohammed J R and Ameen A S 2016 Computational fluid dynamics modelling of flow over stepped spillway Tikrit Journal of Engineering Sciences 23(3) (2016) 1–11

[25] Frizell K W and Svoboda C D 2012 Performance of type III stilling basins–stepped spillway studies Bureau of Reclamation 1–21.

[26] Christodoulou G C 1993 Energy dissipation on stepped spillways Journal of Hydraulic Engineering 119 644–650.

[27] Peterka A J 1978 Hydraulic design of stilling basins and energy dissipaters Department of the Interior, Bureau of Reclamation, Engineering Monograph No. 25, USA, Denver, 8th edition.

[28] Flow Science 2014 FLOW 3D version 11 user manual.

[29] Peyras L, Royet P and Degoutte G 1992 Flow and energy dissipation over stepped gabion weirs Journal of Hydraulic Engineering 118(5) 707–717.

[30] Liu Y W, Yen T and Hsu T 2006 Abrasion erosion of concrete by water-borne sand Cement and Concrete Research 36 1814–1820.

[31] Horszaiczrak E 2008 Mathematical model of abrasive wear of high performance concrete Wear 264 113–118.