Emergency Spillway for the Mt Coffee Hydropower Plant in Liberia

M. Stangl & A. Trifkovic
Fichtner GmbH & Co. KG
P.O. Box 101454
70013 Stuttgart
Germany

W. Hakin
Manitoba Hydro International
211 Commerce Drive
Winnipeg, Manitoba
Canada

Introduction

"It's a damn good idea to have an emergency spillway," said Ron Stork, policy director with Friends of the River, a Sacramento environmental group. A failure of the concrete slab in the spillway chute of Oroville dam, (the highest earthfill dam in the USA) in February 2017 caused the auxiliary/emergency spillway to operate for the first time since the dam was commissioned in 1968.[1] This incident puts the spotlight again on the importance of redundant spillway systems especially for dams with non overflow crests such as embankment dams. In the case of Oroville dam, the dam safety incident was not caused by non operation of the radial gates but rather a structural failure of the civil components which almost resulted in a "single cause total spillway unavailability" scenario.

For the Mt Coffee Hydropower Plant the result and the circumstances of its "single cause total spillway unavailability" scenario were much more severe. In August 1990, during the first of two civil wars, rebel forces seized the Mount Coffee facility and prevented power generation. Furthermore, the operators were prevented from gaining access to utilize an emergency generator to open spillway gates and provide for river flow control. In a month with the highest river flow of the year, this lead to overtopping of the dam, which finally breached over a length of approximately 180 m. The powerhouse was flooded and later stripped of all mechanical and electrical equipment during and after the civil unrest.[2]

Figure 1 - Breached dam section with Intake and Mt Coffee Powerhouse in May 2014 (source: Airmed Liberia)

Since the risk assessment for scenarios like a plant occupation by rebel forces as at Mt Coffee or a structural failure like at the Oroville dam is by its nature rather subjective and prone to uncertainty, the actual design philosophy for an auxiliary/emergency spillway requires a distinct amount of engineering judgment. This paper provides insight into the selection of the most applicable design criteria in terms of flood return period and the most appropriate design and construction methodology for implementation of a new auxiliary/emergency spillway for the Mt Coffee Hydro

Power Plant. It is focused on measures taken to increase the scheme safety by reducing the probability of dam failure even for cases similar to the one that occurred in 1990. The paper also provides reasoning behind the choice of the most suitable construction methodology for the emergency spillway sill, namely Rubble Masonry Concrete (RMC).

1. Project Background

The Mt Coffee Hydropower plant is located approximately 25 km north of the Liberian capital, Monrovia. The scheme comprises a main earthfill dam either side of the main spillway section (which is equipped with 10 radial gates) and three saddle dams, so called Forebay Dams. Water is diverted from the St Paul River through a Forebay Channel into an intake and four short penstocks to the turbines before returning to the main river course via an 820 m long tailrace.[2]

After commissioning in 1967 and the expansion in 1973 with two additional Francis turbines, Mt Coffee had an installed capacity of 64 MW. The scheme generated approximately 20% of Liberia's electricity requirements until the Liberian Civil war. The operating staff was ordered to leave the facility even though this was during the rainy season and only two gates were left partially open. Consequently the water level increased and after several days of overtopping of the dams, a large section of Forebay Dam 1 breached on August 12, 1990.
The power station was flooded and the facility has remained inoperable for over twenty six years. During the time of the civil unrest until 2003 and even thereafter looting of the facility occurred and all mechanical and electrical equipment was sold as scrap. During this period floods passed through the area of the breached dam, before it was decided to rehabilitate this integral national asset critical to Liberia's future electricity supply.

The rehabilitation is financed by the European Investment Bank (EIB) under a concessional loan and grants from the German Government through KfW, the Norwegian Government through the Norwegian Ministry of Foreign Affairs, the Millennium Challenge Corporation (MCC) of the USA, and the Government of Liberia.
The national power utility, Liberia Electricity Corporation (LEC), engaged Manitoba Hydro International (MHI) to manage (through a Project Implementation Unit (PIU)) all aspects of the Mount Coffee rehabilitation project on behalf of the stakeholders. In spring 2013, the Norplan-Fichtner Joint Venture (NFJV) was assigned the role as the Engineer for the project.

Finally in May 2015, the main rehabilitation activities commenced, after the region of Sierra Leon, Guinea and Liberia succeeded in overcoming the devastating Ebola outbreak of 2014. The first hydropower unit started producing power in December 2016 and the main construction activities, apart from the Emergency Spillway, are expected to be completed by October 2017. The powerhouse has been equipped with four Francis turbines of 22 MW installed capacity each. Having in mind the history of Mount Coffee and due to the fact that the facility is the largest generating system in Liberia and probably the country's most valuable single asset, special attention was focused on how to make the scheme as safe and sustainable as reasonably possible.

Figure 2 - Power House before (2013) and after rehabilitation (2017)

2. Increasing Scheme Safety

Particularly in the light of the Mt Coffee dam failure, the rehabilitation is defined not only as a reinstatement of the breached dam and rehabilitation of the scheme to the pre-civil war condition, but it has also focused on all aspects for increasing performance capacity and safety of the electrical, mechanical and hydro-mechanical equipment as well as the civil structures.

The first approach taken was to provide a high degree of redundancy for the power supply system to the spillway radial gates. Operation of the gates can be undertaken by various systems namely: power supply to the gate electric winches through a 22kV grid connection; an emergency diesel generator located adjacent to the spillway and finally manual gate operation. A battery room is also provided in the south spillway control room for powering the control systems if required.

This is in line with the development over recent years in international dam engineering standards and in particular the International Commission on Large Dams (ICOLD) guidelines. Such recommendations consider the fact that the probability of a dam failure is more likely through an "operational failure" than through a rare flood event such as the Probable Maximum Flood (PMF). Mechanical spillway control systems should have a level of redundancy and safety built in which is appropriate to the environmental, social and political characteristics of the country/region in which the facility exists. In case of Mt. Coffee, these systems were brought to the very high level of redundancy.

The above mentioned systems are still dependent on the correct and timely actions of the operations staff. Their absence would still cause a similar "single cause total spillway unavailability" as occurred in 1990. The original design of 1967 provided only 2m between the top of the radial gates and the non overspill crest level (NOSC). This is just enough capacity over the spillway gates to discharge the 400 m^3/s which corresponds to the turbine discharge of all four units in an event where all units are suddenly shut down. In the event that none of the spillway gates are available, a flood with an Annual Exceedance Probability (AEP) of only 1:1 years would still cause overtopping of the dam which could lead to breaching.

Analyses done during the inception phase of the project in 2013, showed that the most simple and cost effective way of increasing spillway discharge capacity is to increase the level of the water retaining structures. The existing dam geometry allows a maximum raising of the crest level from 31.1 masl to 33.4 masl. The heightening of the bridge invert from 30.4 masl to 32.6 masl increases discharge capacity over the closed spillway gates to an approximate Annual Exceedance Probability (AEP) of 1:1 year. This also increases the spilling capacity by regular operation during a flood event. The level for the increase was based on the ICOLD recommendations given in Bulletin 125 and considering malfunction of part of the spillway for the design flood (with a 1: 10 000 Annual Exceedance Probability (AEP) flood event) and assuming one gate is unavailable (i.e. with an (n-1 criteria)).

Such an increase of the reservoir level requires not only an heightening of the existing water retaining structures but also an analysis of the environmental, socio and other impacts within the reservoir area. Still it was decided to undertake these structural and non-structural measures since these significantly add upon the overall safety of the project.

Still, the fact that the design of increased water retaining structures only provided safety for an AEP of 1:1 years for an event of "total non spillway gate unavailability" was considered to be inadequate especially considering the economic consequences of losing such an integral national asset critical to Liberia's future electricity supply. Therefore, the only way to increase the overall safety of Mt. Coffee HPP was by adding a structure that will increase the overall spilling capacities of the scheme. The fact that the water retaining structures were increased from 31.4 masl to 33.4 masl, provided for the possibility to use this newly created freeboard for in an additional free overflowing spillway. This auxiliary spillway is herein referred to as the Emergency Spillway (ES). Only such a structure will allow for a project safety of more than AEP of 1:1 years in an event of "total non spillway gate unavailability".

Considering the latest ICOLD's publications which recommend the implementation of non-gated spilling structures in regions with unreliable and insufficient hydrological records, possibly low levels of maintenance and areas which maybe susceptible to political and social unrest, it was obvious that the design efforts shall focused on a fixed crest, uncontrolled, free overflow spillway to be located above the current Full Supply Level of 29.0 masl (FSL). In addition the following design criteria were considered for the ES design:

- almost maintenance free structure;
- no requirement for major repairs after operation;
- no freeboard on dam structures required for the extreme load case of “single cause total spillway unavailability”;
- not to impede an ongoing rehabilitation and no delay in the key milestone for reservoir impounding in August/September 2016 and commissioning of the first hydropower unit in December 2016;

It is evident that the first three design criteria are very general and could be considered in many similar rehabilitation works. These go in line with the ICOLD’s recommendations on the overall measures to increase the safety of the project in low income countries by adding additional non-gated auxiliary spillways. The last, was very project specific, since the decision to implement such a safety structure was taken during an ongoing rehabilitation works on the existing structures. Still it also shows that in a rehabilitation project the possibilities for increase of the project safety need to be sought all the way through implementation of the works.

3. Emergency Spillway Design

3.1 Location

The general arrangement of the Mt Coffee hydropower scheme consists of rolling hills in a relatively flat landscape. This provided various alternatives and different locations for an additional spillway. The possible solutions investigated included an overflowable dam or a concrete dam with spillway at the previously breached dam section, a new spillway section within the Main Dam north of the existing spillway and a fixed spillway sill or fuse gates at the northern and southern abutment of the Main Dam.

Balancing the following decisive criteria the location just south of the Main Dam was decided to be the most favorable position for an additional spillway because:

- it minimized the risk for existing structures (e.g. the Power House);
- allowed implementation without any delay to the key milestone of commencing reservoir impoundment in August/September 2016;
- minimized the excavation and construction costs by reusing the excavated rock in the reinstatement of the breached dam;
- it provided sound geological conditions allowing a minimum of structural spillway elements.

Just south of the Main Dam the natural terrain is relatively flat at an elevation of around 34 masl and rises slowly up to 38 masl between 200 m and 300 m south of the Main Dam. Further to the south the natural terrain reaches an elevation of around 42 masl before the ground elevation reduces again at the start of Forebay Dam 1. Therefore, the northern extremity of the ES being located close to the Main Dam, where the elevation of the natural terrain is at a minimum, is the optimal location. Downstream and west of the proposed spillway axis a natural, small valley forms the spillway chute and connects the ES to the natural river bed.

To reduce geological risk for the construction and to determine possible shears below the weir, field investigations by test pits and core drilling confirmed a competent rock quality at the selected location. The geology is characterized by gneiss-type rock overlain with lateritic overburden. Based on the results of this investigation the final spillway axis was optimized by avoiding massive excavation in rock but also providing a solid foundation for the spillway chute reasonably resistant to erosion. This allows reducing the concreting works for the spillway, since due to good rock quality concrete is only required at the flow control section.

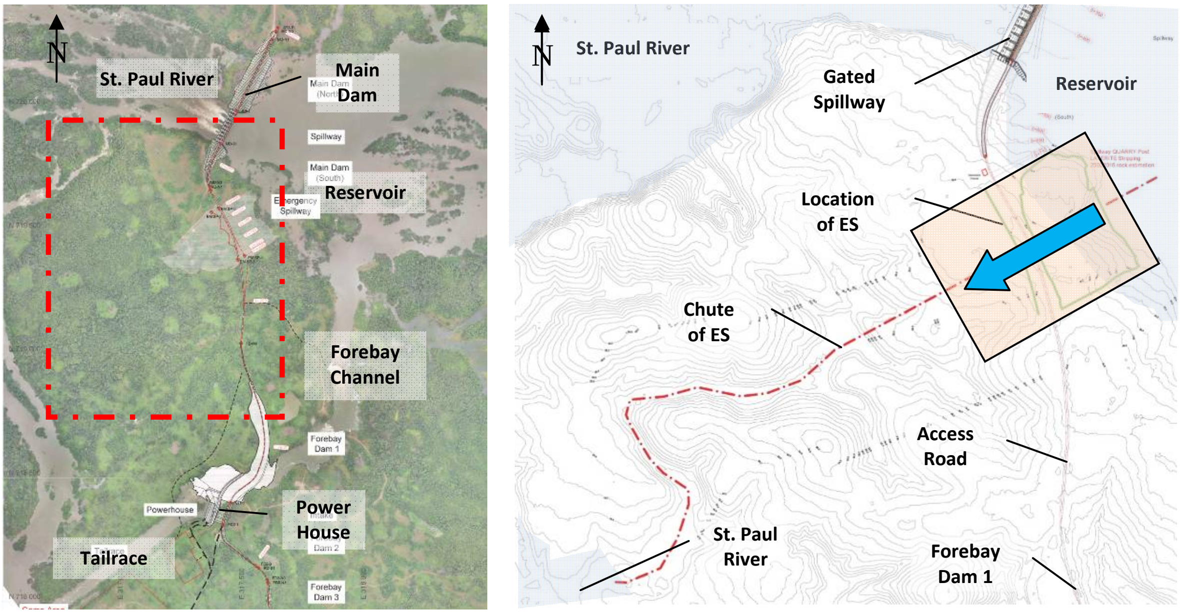

Figure 3 - General arrangement of the new Emergency Spillway (ES)

3.2 Spillway Access

Access to all parts of a hydropower scheme is an important safety aspect. The selected location of the Emergency Spillway is between the main access road from the power house and the gated spillway at the Main Dam. Therefore, if no bridge over the spillway is provided, operation of the new spillway would effectively prevent direct access to the Main Dam and radial gates. The ES could be activated in either of the following two scenarios:

- Condition A: when unplanned outage occurs and the main spillway gates are not opened
- Condition B: during a major flood, even with all 10 spillway gates opened, whereby the reservoir level rises (as would occur for floods in excess of about the 1:10 000 AEP flood).

Therefore, for safety considerations and due to public interest for crossing the river, the design includes a bridge connecting the Main Dam section with the Power House. This will allow quick access to all parts of the dam at all times, as required by international guidelines[4,5] , but especially during emergencies. Even more, the main spillway itself has several in-built redundancy systems, such as diesel generator at the spillway and manual lifting of the gates that require presence of the personnel at the site during their activation and emergency operation. Without access to the main spillway there will be no possibility to activate these backup systems.

3.3 Layout and Hydraulic Design

In order to identify the most optimal spillway layout, alternatives such as straight, curved and other overflow crests (piano key-spillway, multiple curved-spillway) were investigated. Also different crest forms such as bloc, crump weir, sharp crest or hydraulically shaped weir were studied.

For the most economical solution the total length of the spillway needs to be minimized since this reduces the overall excavation and concrete costs for the bridge. Therefore, the selected spillway design is a curved layout with a hydraulically shaped weir form. To avoid any pier effects the bridge is separated from spillway axis with sufficient distance.

To simulate the flow along the upstream channel, the weir and the downstream geometry, hydrodynamic numerical calculations proved that this alternative is suitable from a hydraulic point of view. By varying the significant parameters such as slope and width of the chute and the width of the approach channel an optimization was carried out which resulted in the minimum excavation volumes.

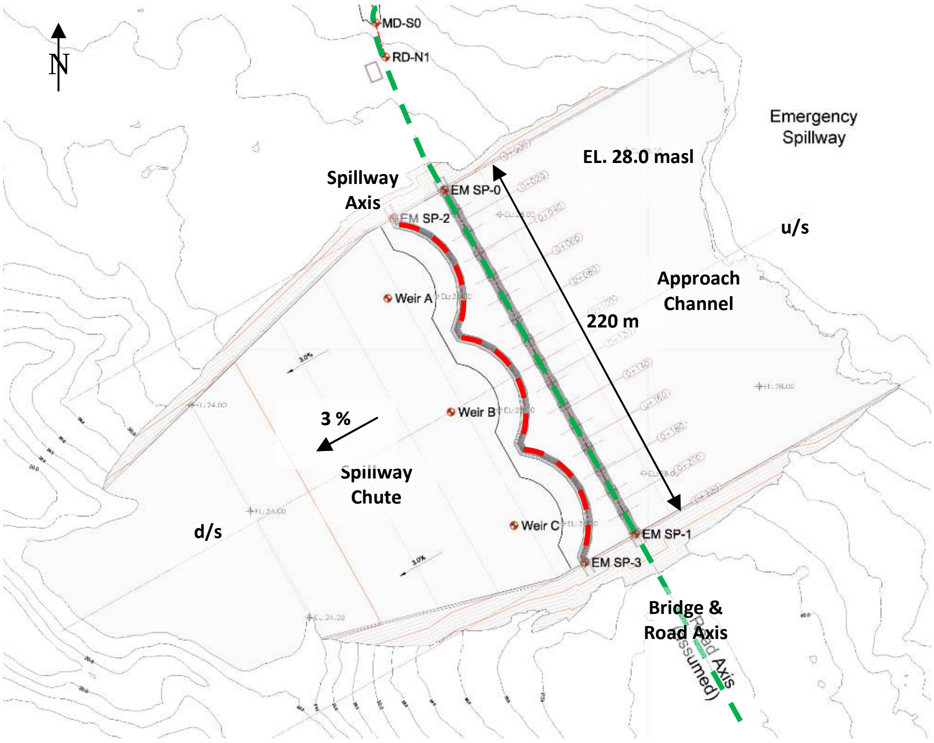

Figure 4 - Layout of the Emergency Spillway

3.3 Design Criteria and Spilling Capacity

In case of a gated spillway unavailability scenario the overtopping of the gates will provide a certain capacity in addition to the spilling capacity of the Emergency Spillway. The theoretical value of the possible flow over all 10 radial gates (in their closed position) at the reservoir level of 33.4 masl would be approximately Q = 2 150 m³/s. Considering this discharge over the closed radial gates at maximum water level (MWL) following table summarizes the required additional spilling capacity for different flood AEP's :

	AEP flood (years)				
	1:2	1:5	1:10	1:20	1:50
Design Flood [m^3/s]	2 770	3 655	4 260	4 840	5 580
Discharge over closed radial gates at MWL [m^3/s]	2 150	2 150	2 150	2 150	2 150
Required ES capacity [m^3/s]	**620**	**1 505**	**2 110**	**2 690**	**3 430**

Table 1 - Required additional spilling capacity for different flood AEP at a gated spillway unavailability scenario

Since no movable or mechanical elements should be considered and the hydropower generation needs to be provided, the fixed spillway sill has to be above the full supply level of 29.0 masl. The top of the closed radial gate of the spillway is at elevation 29.1 masl and therefore is the lowest element of all the water retaining structures of the facility. The emergency spillway sill is set at 29.5 masl which provides 0.5 m of "freeboard" above the Full Supply Level and avoids a constant spilling. The sealing system of all water retaining structures reaches up to the crest level at 33.4 masl and, since no freeboard is considered, 3.9 m of theoretical overflow height is available for the spillway.

Within these given boundary conditions, the decisive parameter, the required spillway length, is controlled mainly by the design spilling capacity. But which Annual Exceeding Probability (AEP) should be considered for the capacity of an *Emergency Spillway*?

For a main spillway the criteria for selecting the Design Flood or the Safety Check Flood is given by local guidelines or recommendations such as the ICOLD Bulletin 125[3]. But, there exists no guideline or standard which defines the required safety which has to be provided against "Total Spillway Failure".
The occurrence probability of the spillway unavailability scenario that occurred in 1990 is virtually impossible to quantify with any degree of assuredness, which makes also the definition of the Design Flood difficult. For the Emergency Spillway at the Mt Coffee Hydropower Plant it was agreed to select a Design Flood of 1:50 years.

The decision was based on an assessment of Emergency Spillway implementation costs for different Design Floods with an AEP of 1:10 to 1:50 years. Only a slightly higher investment for an Emergency Spillway with the highest capacity provides a significant higher safety for the entire scheme compared to Design Flood of 1:10 years.
The selection of the Spillway Design Flood took also into consideration the history of the plant and the total importance of the hydropower scheme for power supply in Liberia. Furthermore, and as an additional benefit, the total spillway capacity, assuming all radial gates are fully open, is increased during extreme flood events from 13 750 to 17 350 m^3/s, thereby also allowing the probable maximum flood (PMF) event to be passed through the improved spillway systems.

The provision of the emergency spillway as designed will require the excavation of 220 m wide spillway approach channel and 3% inclined spillway chute with a total excavation volume of around 575 000 m^3, of which 65 % are in rock. To provide access a bridge will cross the approach channel and a weir with a total length of 250 m and a total volume of 2 500 m^3 concrete will be constructed.

3.4 Construction Methodology

The purpose of the new spillway sill is to provide a defined flow control section, which is sufficiently resistant to erosion in case of operation and durable for the designed life time. Since field investigations confirmed a competent rock quality and a solid foundation with a sufficient resistant to erosion, the feasibility of a rock sill eliminating any concrete weir structure was analyzed. The smaller hydraulic coefficient of a natural sill would require the increase of the total spillway length, increasing also the costly excavation works, in order to provide the required capacity. Therefore, the design considers a concrete weir structure with a hydraulically shaped form.

For the choice of the most suitable construction methodology Rubble Masonry Concrete (RMC) was adopted as this was found to be an efficient and highly cost-effective approach for such types of weir structure. RMC is a matrix of large stones in a mortar binder. The mortar used provides typical 28-day compressive strengths between 9 MPa and 14 MPa. Rock varies in size from approximately 50 mm to maximum 300 mm, the largest dimension being dependent on the thickness of the member under construction and the restrictions of manageable weight. RMC for dams is not a series of stones cemented together using mortar, but rather a monolithic matrix, containing large stone within a body of mortar, similar to mass concrete with a significant bigger maximum aggregate.[6,7]

RMC uses ancient labour-based construction practices which were used for mass gravity masonry dams, first constructed several hundred years ago. This is today still economically possible, since developing countries provide low labor cost compared to the material costs similar to early days of dam construction. In addition to economical reasons, applying this construction methodology will provide important benefits in terms of local employment and in turn uplifting the low income communities around the facility whilst introducing into the country new and effective construction techniques.

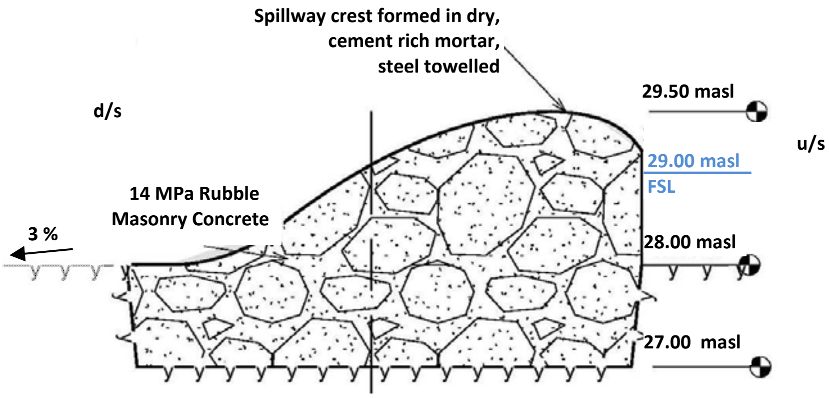

Figure 4 - Typical cross section of the spillway crest

4. Conclusion

"It's a damn good idea to have an emergency spillway. […] But it's cheaper to *not* pour concrete there," continued Ron Stork, the policy director of a Sacramento environmental group.
The auxiliary/emergency spillway at Oroville dam, which consists of a uncontrolled, free overflow gravity dam section, provides neither a concrete liner for the spillway chute nor a structural element for energy dissipation or any other measures against erosion caused by spilling water. The first operation of the structure since commissioning caused erosion of the hillside. The spilling water washed trees, boulders and dirt into the Feather River below and started to erode even the emergency spillway foundation which endangered the stability of the structure.
In consequence, nearly 200,000 people living downstream were ordered to evacuate as a precaution and the authorities were forced to continue releasing water via the main spillway which caused even more damage to the main spillway chute.[1]

This incident illustrates the dilemma and challenge regarding choosing the right design philosophy for an auxiliary/emergency spillway which needs to give attention to various risks and possible scenarios, but also needs to consider the economic analysis of the best use of the money invested. This has to be balanced for the most appropriate design at each particular project considering among others the hydrological records, level of maintenance, political and social situation of the region, type of spillway, etc. This is even more challenging for an emergency spillway compared to other structural elements since the risk assessment for scenarios the spillway is designed for is by its nature rather subjective and prone to uncertainty as shown by Mt Coffee or Oroville dam.

Mt. Coffee is an exemplary project, illustrating that a certain failure scenario, that may be negligible in many other similar projects, had the most decisive role in the overall safety project determinations.
The safety considerations of the design case "total non spillway gate unavailability" lead to introduce an additional auxiliary spillway in order to safeguard the most valuable energy generation capacity in the country and determined the necessity to put the project's flood release capacity in this load case at AEP 1:50. At the same time this capacity provided for an overall safety capacity of all structures in operation that correspond to the PMF and therefore fully complied to the current international recommendations.

References

1. **Rogers, Paul,** "Oroville Dam crisis eases, but incident highlights risk of aging U.S. facilities", *The Mercury News*, Web. 10 February 2017
2. **Brunes, Bente T., Skuncke, Olof, Trifkovic, Aleksandar, Hakin, William D.** "Rehabilitation of Mt Coffee Hydro Power Plant in Liberia - A substantial increase of capacity and a number of challenges", *Hydro*, 2016
3. **ICOLD Bulletin 125**, "Dams and Floods/ Guidelines and cases histories", Paris 2003
4. **ICOLD Bulletin 59**, "Dam Safety Guidelines", Chapter 4.8.2 and Checklist, Chapter D.2.1, 1987
5. **ICOLD Bulletin 154**, "Dam Safety Management", Chapter 5.1.1
6. **Shaw, Quentin H W.**, "Rubble masonry concrete dam design and construction", *SAICE Journal*, 1998
7. **ICOLD Bulletin draft, "**Rock-Filled Concrete Dam", Version 12.07.2016

The Authors

M. Stangl is a Civil Engineer in the Hydropower Department of Fichtner Consulting Engineers, Germany. He completed his Masters in Civil Engineering at the Technische Universität Munich in 2009. In 2010 he joined Fichtner Consulting Engineers and since then contributed to a number of small and large hydropower projects, mainly in the stage of Tender and Detailed Design in Europe, Africa and Asia, including post-conflict countries. He is specialized in dam engineering, geotechnics and hydropower project implementation.

A.Trifkovic graduated in Civil Engineering has a MSc in Environmental Engineering from Imperial College and PhD from University of Stuttgart, Germany. Within hydropower, he specialized in fields of hydraulic design, power production, layout development and optimisation, rehabilitation and upgrade of hydropower projects and structures. He leads the design teams for the detailed design of the hydropower projects and already participated in successfully implementation of project such as Bujagali, Isimba and Nyagak in Africa, Middle Marsyandy, Faizabad and Golen Gol in Asia and some medium size project in Balkan countries such as Cijevna 3. Position in the project: One of the JV Directors for the Owner Engineer for the Mount Coffee HPP.

W. Hakin (Bill) graduated from the University of Bradford, UK with a B Eng in civil and structural engineering. He has worked in the dams and hydropower sector for over thirty years in Africa, Australia and Europe and has been involved in the upgrade of over twenty dams during his career as project director. As the author of multiple papers presented at ICOLD and various national committees, he has a strong interest in ensuring engineering approaches take into account the social, political and environmental factors in which the projects will operate. Bill works for Manitoba Hydro International and his role on the Mt Coffee Project is the Project Director for the Project Implementation Unit.