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Technical note

# Fluorescent tracer tests for detection of dam leakages: The case of the Bumbuna dam - Sierra Leone

D. Battaglia [a,*], F. Birindelli [b], M. Rinaldi [b], E. Vettraino [a], A. Bezzi [b]

[a] Studio Georisk, Via Stelvio 20, Triuggio, Italy
[b] Studio Pietrangeli, Via Cicerone 28, Rome, Italy

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ABSTRACT

The first impounding of the Bumbuna dam was subject to unexpected high seepages discharge (up to 550 l/s) from the foundation drains. Fluorescent tracer tests, commonly used for hydrogeological study of porous and karst aquifer, were performed to locate the seepage zones. Solutions of 3 different fluorescent tracers (Uranine, Sulforhodamine-B and Tinopal CBS-X) were injected in the reservoir at regularly spaced points down to a depth of 80 m. Tracer concentration in the seepage water from the foundation drains was continuously monitored by high resolution fluorometers with detection limit as low as 0.02 ppb.

A total of 107 tests were performed in two separate campaigns conducted in January–February and October–December 2009. Concentration curves recorded from each test were analyzed to determine the time of first response to the injection (detection time) and the quantity of tracer returned from each test (restitution). Maps of minimum detection time and maximum tracer restitution were generated to identify the position of leakages. Seepage mitigation works were planned on the base of test results and completed in the dry season after the drawdown of the reservoir. Works consisted in the additional grouting along the grout curtain, sealing of fissures on the bituminous layer and installation of a PVC membrane on the dam upstream face.

Inspection of the upstream dam face confirmed the presence of damages in the areas identified by tracer tests. Since completion of seepage mitigation works the dam operated satisfactorily with maximum seepage from the foundation of 70 l/s.



## 1. Introduction

Seepage is a major problem for dam safety because it can produce internal erosion (piping) within the dam or its foundations, which ultimately can lead to failure (Cedergren, 1997; Flores-Berrones et al., 2010). The phenomenon is particularly critical during the first impounding of the reservoir when the dam impermeabilization system is tested for the first time. Standard practice for seepage control includes the monitoring of piezometric levels, seepage flows and solid transport from the foundation drains together with dam deformations (USACE, 1993; USBR, 2014). The investigations used for detection of anomalous dam seepages (Bedmar and Araguas, 2002), consist mainly in permeability tests, flow measurements, geophysical methods, monitoring of natural water properties and tracer testing. Their usage depends on the dam type, leakage conditions and specific site settings. Among the geophysical methods in the last years the research focused mainly on electrical resistivity and self potential surveys, usually in association with the injection of saline solutions (Slater et al., 1999; Song et al., 2005; Boleve et al., 2011; Ikard et al., 2012). Tracer test with saline, radioactive or fluorescent tracers is less common for leakage detection and few case histories are available in the published literature (Lee et al., 2007; Mohammadi and Raeisi, 2007). We illustrate an application of fluorescent tracer tests to localize and monitor anomalous seepages occurring at the Bumbuna dam during the first impounding of the reservoir.

The Bumbuna power plant (Fig. 1) is located in northern Sierra Leone along the Seli River, about 200 km north of the capital Freetown. The dam is made by rock fill (88 m high, 400 m long and 280 m wide) with a bituminous upstream face; a cut-off wall connects the impervious grout curtain with the bituminous lining. The maximum reservoir level reaches an elevation of 242 m asl, for a total volume of 430 $Mm^3$. The plant produces a total of 50 MW with 2 Francis turbines. Construction started in the 80s, but due to a civil war it was interrupted between 1997 and 2005. The dam rests on granites and amphibolite with variable degree of weathering; however, the geological model of the foundation was poorly defined because the geological mapping of the excavation was not available.

During the first impounding of the reservoir unexpected high seepages (up to 550 l/s) with peaks of solid transport were observed from the two main foundation drains. Fluorescent tracer tests were carried out to identify the position of leakage zones within the dam impermeabilization system and to monitor the evolution of seepages.

* Corresponding author.
*E-mail address:* dbattaglia@georisk.it (D. Battaglia).

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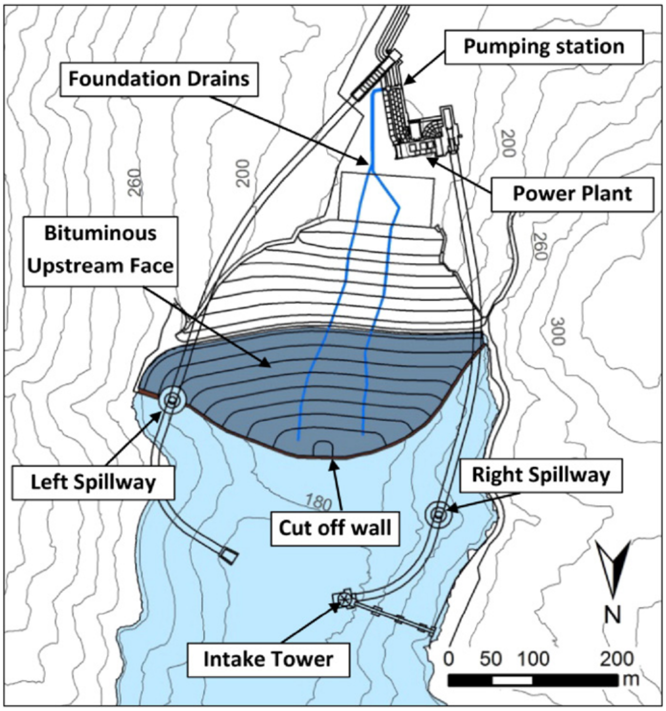


**Fig. 1.** Bumbuna power plant with principal structures. Reservoir maximum level in cyan, bituminous layer in blue.

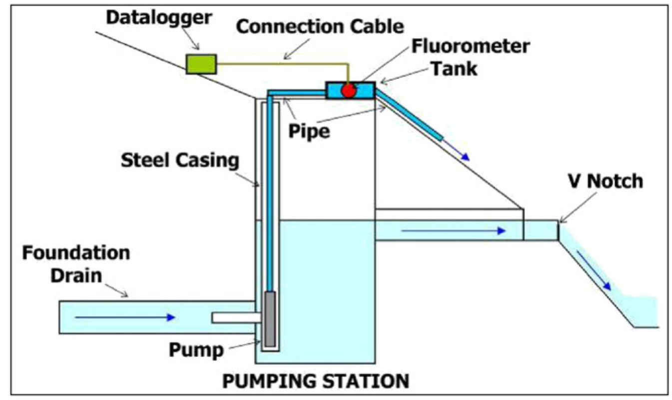


**Fig. 2.** Scheme of the detection system installed at the pumping station for sampling and analyzing seepage water from the foundation drains.

## 2. Methods

Tracer Tests have been commonly used in hydrogeology practice for more than a century to study the direction and velocity of groundwater flow in porous and karst aquifers (Kass, 1998).

Tests are performed introducing a mass of natural or artificial tracer in a water flowing system at a known time and position (injection point), which usually consists of a well, a piezometer or a sinkhole. Tracer appearance and concentration, are then monitored at target points, such as wells, piezometers or springs.

Water flow velocity is calculated from the difference between time of injection and first detection, while the shape of the concentration curve and the quantity of tracer detected at the target points (restitution) are used to define the type of flow.

There is no published standard for the test but only few guidelines (Schudel et al., 2002) which do not apply to dam seepages. In the past, the main limit for tracer testing in dam leakage detection was the need of a large number of laboratory analyses for the precise detection and measure of the tracer concentration. The analyses were performed on a discrete number of water samples and the results were available in a relatively long time – conditions that affected the test precision and overall duration. The development of high resolution field fluorometers able to monitor in continuous the tracer concentration has widened substantially the application of tracer tests.

We performed a total of 107 tracer tests, during a time frame of 4 months, injecting fluorescent solutions at the contact between the reservoir water and the ground, along regularly spaced points on the cut off wall and the upstream face of the dam (see Fig. 5). Dyes' concentration in the water flowing from the two main foundation drains was continuously monitored at the pumping station by fluorometers (see Figs. 1 and 2).

### *2.1. Fluorescent tracers*

Three types of fluorescent tracer were used: Uranine, Sulforhodamine B and Tinopal CBS-X.

Uranine, also known as Fluorescein (CAS number 2321-07-5), is a fluorescent dye commonly used in biomedical research and healthcare. Concentrated uranine solutions are dark red and do not fluoresce, but they become fluorescent when diluted with water and the color turns into bright fluo green. The limit of eye detection is a concentration of 100 ppb, while the detection limit of the fluorometers used in the study was as low as 0.02 ppb.

Sulforhodamine B (called in the following pages “Rhodamine”, CAS number 3520-42-1), is a fluorescent dye which produces a solution of dark red to fluo pink color. Limit of eye detection is 100 ppb, while the instrumental detection limit was 0.2 ppb.

Tinopal CBS-X (CAS number 38775-22-3) is a proprietary product of CIBA and it is commonly used as an optical brightener. It produces a solution of light blue to transparent color. Limit of eye detection is a concentration of 100 ppm, while instrument detection limit was 0.2 ppb.

### *2.2. Injection procedure*

Before testing, a plan of injections was defined, which consisted of a sequence of regularly spaced points positioned along the cutoff wall and the dam upstream bituminous face.

A standard injection procedure was also fixed in order to create systematic release conditions for all the tests. The procedure consisted of the following steps:

1) The tracer to be used was defined on the base of the values currently measured at the fluorometers; the selected tracer would be the one with the lowest concentration in the drain water.
2) Preparation of the tracer solution in the laboratory (200 g of tracer powder in 20 l of river water) and its transport to the reservoir in plastic containers.
3) Navigation with a raft to the vertical above the planned injection point, checking the position with a GPS receiver of submeter precision.
4) Filling a 20 l latex balloon with the tracer solution and 2–3 fishing bobbers. The balloon was then securely tightened to a steel cable below a 40 kg anchor.
5) Fast lowering by a winch of the balloon and anchor down to the reservoir bottom. The impact of the anchor with the ground produced the balloon explosion and the discharge of the tracer solution at the water/ground interface. The absolute time of injection was determined by the instant release of tension in the cable, while the success of the injection was proved by the appearance of the bobbers at the reservoir surface.