Fluorescent Tracer Tests for detection of dam leakages: the case of the Bumbuna Dam - Sierra Leone

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Summary

The first impounding of the Bumbuna Dam was subject to unexpected high seepage (>500 l/s) from the foundation drains.
Fluorescent Tracer Tests are commonly used for hydrogeological study in porous and karst aquifer and we adapted this technique to investigate the position of seepage zones along the submerged part of the Bumbuna dam.
Test consisted in injecting in the reservoir, at regularly spaced points to a depth of 80m, solutions of 3 different fluorescent tracers (Uranine, Sulforhodamine-B and Tinopal CBS-X) and in measuring, with high resolution fluorimeters (detection limit of 0.02ppb), the tracers concentration in the seepage water from the foundation drains.
A total of 107 test were performed in two separate campaigns conducted in January-February and October-December 2009.
Time-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).
Results were used to create with geostatistical interpolation maps of minimum detection time and maximum restitution that defined the position of the leaking zones.
On the base of test results a series of seepage mitigation works were planned and completed in the dry season after the drawdown of the reservoir. The works consisted in the execution of additional grouting, the sealing of fissures on the asphalt layer and the laying of PVC membrane on the dam upstream face.
Inspection of the dam face after drawndown identified the presence of damages in the areas identified by tracer tests.
Since completion of seepage mitigation works the dam has operated satisfactorily with seepage from the foundation drains ranging from 35 to 90 l/s, including also the contribution of ground water flow from abutments.
The technique we used for the execution of tracer test proved to be effective for investigating and monitoring seepages in dam foundations.

Introduction

The Bumbuna Dam is located in northern Sierra Leone along the Seli River, about 200km north of the capital Freetown.
The structure consists of a rock fill dam (88 m high, 400 m long and 280 m wide) with bituminous upstream face (Figure 1). A cut-off wall connects the impervious grout curtain with the bituminous lining. Dam foundation consists of granites and amphibolites.
The maximum reservoir level at elevation 242 m a.s.l., for a total volume of 430 Mm^3 and a net volume of 320 Mm^3. The plant produces a total of 50 MW with 2 Francis turbines.

The construction started in the ’80, but due to a civil war it was interrupted between 1997 and 2005.
During the first impounding of the reservoir in late 2008, unexpected high seepages were observed from the two main foundation drains.
The impounding was immediately stopped and a series of actions were taken to investigate the phenomenon.

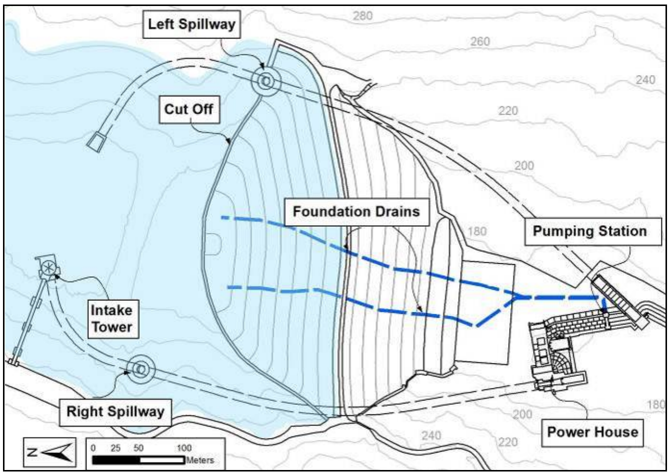

Figure 1: Bumbuna Dam - Sierra Leone.

Tracer Test with fluorescent dyes were used to locate the zones of maximum filtration along the submerged side of the dam and to plan the seepage mitigation works. Tracer Test were also used as monitoring system to evaluate the effectiveness of the seepage mitigation works.

In the following pages, the paper discusses the principles of hydrogeological testing with fluorescent tracers, the methodology specifically developed at the site and finally, the test results.

Tracer Tests

Tracer Tests have been commonly used in hydrogeology for more than a century to study the direction and velocity of groundwater flow in porous and karst aquifers [1].
Tests are performed introducing a 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 of time between injection and first detection, while other information, such as the type of flow, can be obtained from the analysis of concentration variation with time.

The use of tracer test for the detection of leakages from dam foundation is not a common practice and few examples are reported in technical literature [2], [3] and [4]. Furthermore there is no published standard for this type of test, but only few guidelines [5].

We executed tracer test at Bumbuna injecting fluorescent solutions at depth in the reservoir along regularly spaced points above the cut off wall and the upstream face of the dam. Dyes concentration in the two main foundation drains was continuously monitored at the pumping station by fluorimeters.
Time-concentration curves recorded from fluorimeters were analyzed to define for each test the time of detection, the type of response and the percentage of restitution of the tracer. Low detection times and high restitution have been associated to leakages nearby the injection point. Concentration curves also provided information about the seepage mechanism.
Geostatistical analysis of test results produced a series of map defining the most likely position of the seepage zones.

Fluorescent tracers

Three types of fluorescent tracer were used: Uranine, Sulforhodamine B and Tinopal CBS-X.
Uranine, also known as Fluorescine, is a fluorescent dye commercialized in powder form and it is also commonly used in biomedical research and healthcare practice. Concentrated uranine solutions are dark red and do not fluoresce, but they become fluorescent when strongly diluted with water. Solution color turns from dark red to bright fluo green. Thelimit of eye detection is a concentration of 100 ppb, while instrument detection limit was as low as 0.02 ppb.

SulfoRhodamine B (called in the following pages “Rhodamine”), is a fluorescent dye commercialized in powered form. It is made by fine crystals which dissolved in water produce a solution of dark red to fluo pink color. Limit of eye detection is 100ppb, while instruments detection limit of Rhodamine was of 0.2 ppb.

Tinopal CBS-X is a proprietary product of CIBA and it is commonly used as an optical brightener. It is commercialized in powdered form. Crystals are of light yellow color and they produce a solution with light blue to transparent color. Limit of eye detection is a concentration of 100 ppm, while instruments detection limit of Tinopal CBS-X was of 0.2 ppb.

Injection procedure

Before testing, a plan of injections was defined, which consisted of regularly spaced point with different priorities positioned along the cutoff wall and the dam asphalt face.

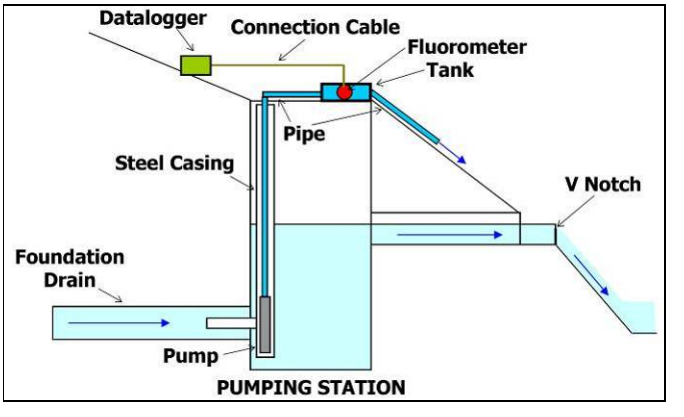

Figure 2: Detection system installed in each drain at the pumping station.

A standard injection procedure was also adopted to create systematic conditions for tracers release. The procedure consisted in the following steps:

1) Selecting the tracer type according to the concentrations detected from fluorimeters and preparing of the solution at the laboratory.
2) Positioning in the reservoir with a raft above the selected injection point, checking the position with a submeter GPS receiver.
3) Filling a latex balloon with the solution and 2-3 fishing bobbers. The balloon was then securely tight below a 40 kg anchor weight.
4) Lowering the balloon into the reservoir and exploding it at the water/ground interface. At explosion the absolute time of injection was recorded. The occurrence and position of the injection was checked by the appearance of the bobbers in the reservoirs.

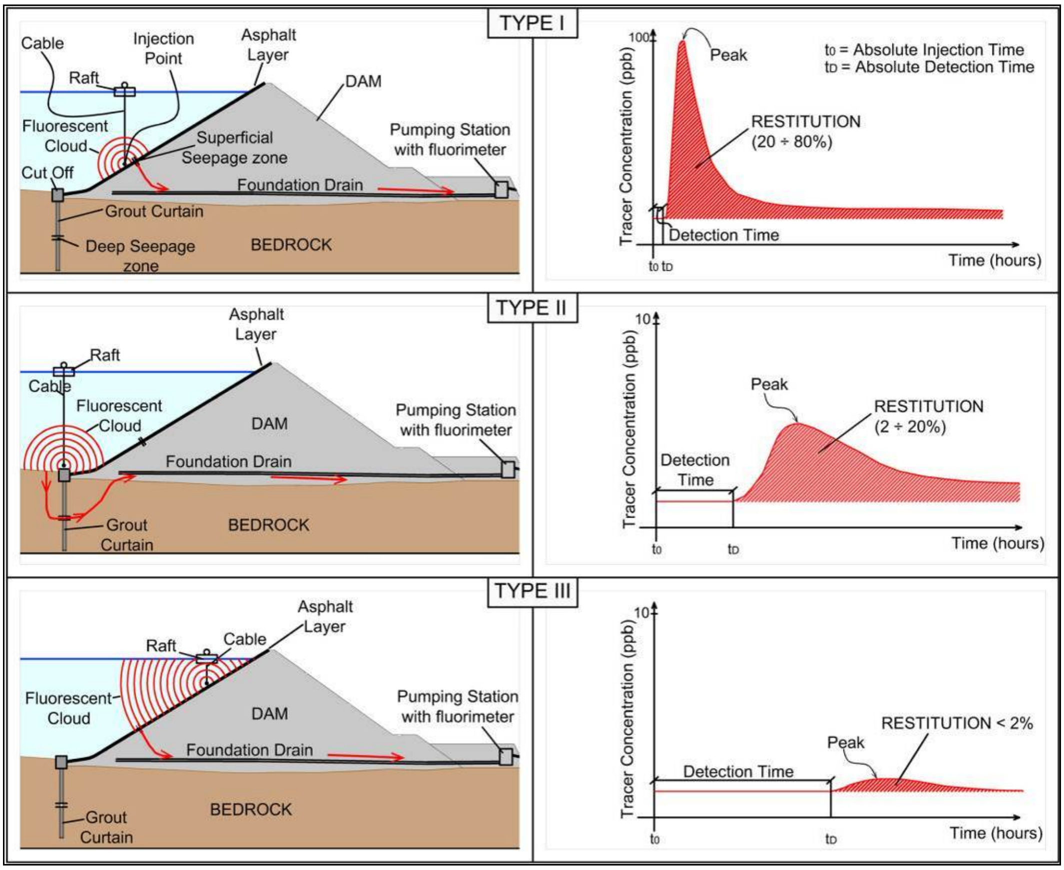

Figure 3: main types of concentration – time curves registered from the fluorimeters (right) with associated flow path of the tracer solution (left) along the dam impervious system.

Detection system

The detection system consisted of two GGUN FL30 fluorometers produced by Albillia Co (Switzerland).
FL30 fluorometer is designed for analyzing superficial water in continuous [6].

It measures the following parameters:

- temperature with a precision of 0.01°C;
- turbidity in Nephelometric Turbidity Units (NTU) with a precision of 0.1 NTU;
- conductivity with a detection range of 10-50000 mS/cm and a precision of 5 mS/cm;
- uranine concentration with a precision of 0.02 ppb;
- rhodamine and tinopal concentration with a precision of 0.2 ppb.

The setting of the detection system is illustrated in Figure 2. The fluorimeters were installed in two tanks where they received through a pumping system the seepage water collected from each foundation drains. The instruments were connected to datalogger recording with a sampling rate of 1 measure every minute.

Data processing

Data from the instruments were downloaded daily and transferred into a database where the charts of tracer concentrations were continuously updated.
Graphs were used to define the results of each injection and to refine the injection program. Measurements from the dam monitoring system, including the drain flow rate and the suspended solid concentration, were considered in order to understand the cause and evolution of the seepage.

Concentration versus time charts were the base for interpreting test results. The most valuable data were the absolute time of first appearance of the tracer in the fluorimeter, which was marked by the increase of tracer concentration above an almost constant background values reached by the previous test. The “Detection Time” was calculated from the difference between the absolute time of detection and the absolute time of injection.
After detection the response of the test could give different curves, which depended on the type path followed by the solution.

Three major types of curves have been identified:

- Type I: consists of short detection times (<1hr), followed by single or multiple sharp spikes that could reach a concentrations as high as 100 ppb, medium long tails and high restitutions.
- Type II consists of medium - long detection times (1-3h) followed by single or multiple smooth peaks with concentration usually lower than 10 ppb, long tails and medium low restitutions.
- Type III consists of long detection times (>3h) followed by very smooth peaks of few ppb, very long tails and low restitutions.

Type I curves were considered evidence of leakages very close to the injection point, which would drain immediately almost all the fluorescent solution. Type II curves were evidence of longer flow path with associated diffusion and dilution processes of the tracer solution, possibly due to filtration in the foundation around or through the grout curtain. Type III curves were considered evidence of high diffusion and dilution of the tracer solution in the reservoir before entering the drainage system.
A full transition between the three types of curve has been observed as well as mixed curved produced by the overlap of different flow path. In this case multiple peaks were present indicating the existence of more than one leakage zone near the injection point.
The comparison of the response obtained from single test on the two drains, which would give information about the mixing processes that were occurring inside the dam rock fill body, was also valuable.

Restitution was the last parameter calculated from the concentration curve. The term refers to the quantity of tracer that has been captured by the drains and it is expressed as percentage. The parameter was calculated considering the tracer concentration and the seepage flow rate measured at the pumping station.

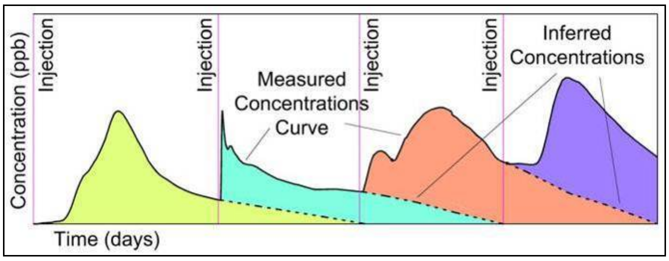

Figure 4: Restitution extrapolation.

In normal conditions, with a single test and constant flow, Restitution would be represented by the area of the time-concentration curve above the background value of the tracer, and it would include the long term tail of the response. However in our case, with the need to execute the maximum number of tests in the shortest time, it was not possible to wait for the complete dissipation of the response of each test so new tests responses were allowed to overlap with the tails of the previous one. Therefore part of the restitution in most cases had to be extrapolated from time concentration curve (Figure 4).

Interpolation maps

Geostatistical analysis has been applied to define the most likely position of the zones with minimum detection time or maximum restitution.
The variation in plane of the two parameters has been calculated interpolating the point results of the injection test using the Inverse Distance Weight (IDW) method. The method estimates cell values by averaging the results of the data points in the neighborhood of each processing cell: the closer a point is to the center of the cell being estimated, the more influence, or weight, it has in the averaging process. It is assumed that the variable being mapped decreases in influence with distance from its sampled location.
Results of the analysis were represented by interpolation maps of the detection times and restitutions.

Impounding Chronology

The impounding of the Bumbuna reservoir was completed through the following steps:

- May 2008 – December 2009: first rise of the reservoir level up to elevation 215m. Stop of the impounding due to excessive seepage from the foundation drains.
- January – February 2009: first tracer test campaign.
- April – July 2009: draw down of the reservoir and execution of seepage mitigation works.
- June 2009 – November 2009: second rise of the reservoir with completion of the impounding. During this step a second tracer test campaign was conducted to monitor excessive seepages from the foundation drains.
- January – June 2010: second draw down of the reservoir and execution of complementary seepage mitigation works.
- July – August 2010: second filling of the reservoir up to maximum reservoir level. Since then the seepages have been within the design limits, confirming the effectiveness of seepage mitigation works.

First Test Campaign

The first series of tracer test was conducted between January and February 2009, with reservoir level around elevation 215 m a.sl. and seepage flow of 120 l/s. A total of 20 tests were executed:

- # 6 Tests with Uranine;
- # 7 Tests with Rodhamine;
- # 7 Tests with Tinopal.

Injection points were distributed along the cut off wall as shown in Figure 4. The following responses were obtained:

- no response from 5 tests;
- first response from the right drain in 10 tests;
- first response from the left drain in 5 tests.

In most cases injections produced a response on both drains with more than one peak in the concentration curves showed, condition that suggested the presence of multiple flow paths. In those cases a first and a second detection time were recorded from the curves.

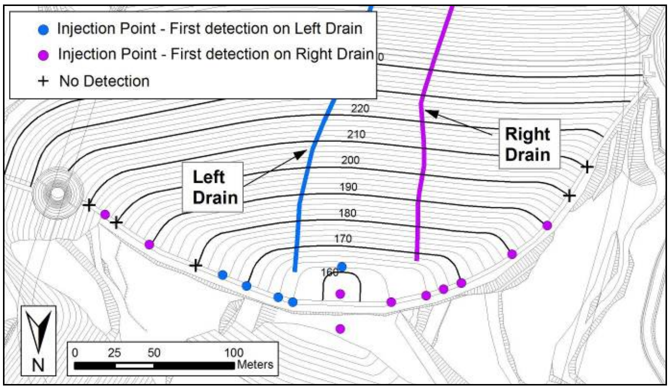

Figure 4: First test campaign injection points with indication of the drain of first response.

The map of first detection times produced on the base of the results from both drains is shown on Figure 5. It can be appreciated the presence of minimum times along the cutoff wall on the right side around elevations 165-170 m; secondary minimum are also present along the cut off on the left side between elevations 162-170 m and at the center, above the bituminous face at elevation 160 m.

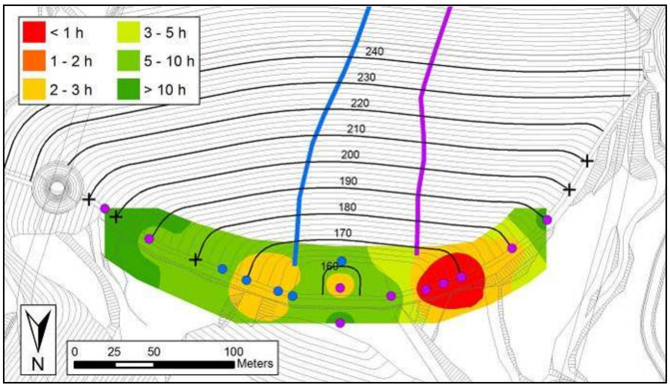

Figure 5: First campaign Map of the first detection times

Most injections were identified on both drains, but with different detection times. The times of detection registered for the same test on the two drains have been plotted in Figure 6, with the point color marked according to the drain of first appearance.

The graph shows that when first appearance occurs on the right drain (pink dots), the points fit almost exactly along a line with a slope equal to 1 (equal times) and an intercept (retard) on the left drain of 3:28 hours. The type of curves observed from these tests gradually changes from Type I at low detection times to Type III at high times. This behavior suggest that all the first responses from the right drain came from a single superficial leakage zone, in fact the difference in time between test was due to the time spent by the tracer to flow inside the reservoir from the injection point to the leakage zone, which caused also a continuous dilution of the solution with consequent change in the graph type. The constant delay in the left drain represented the transit time of the tracer for moving, inside the dam rockfill, from the right drain to the left drain. The leakage zone was determined to be on the right side near elevation 167 m along the cutoff wall, with a minimum detection time of 42 minutes.

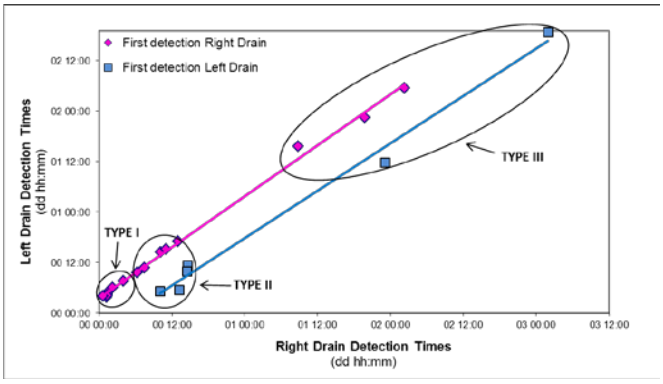

Figure 6: Detection times on the left and right drain (blue: first appearance right drain; red: first appearance left drain).

The graph also shows that in case of first appearance on the left drain (cyan dots) similar condition occurs, with an intercept (retard) of 5:40 hours on the right drain. However here the points are much more scattered at low times and the curves types ranges between type II and III. Therefore we assumed the presence of deeper flow paths occurring in the lower left portion of the dam, below elevation 170 m.

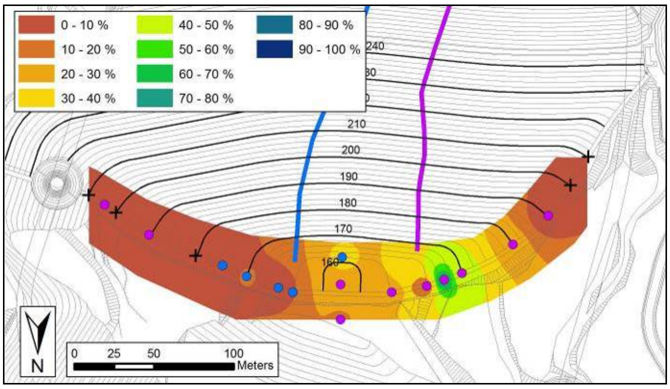

Figure 7: First campaign Map of Restitution

The restitution map, represented in Figure 7, is very similar to the detection times map and it shows the highest recovery especially from the right side (up to 82%) and from the lower center of the dam (up to 30%), while much smaller quantity of tracer (<10%) was returned from the left side.

Leakage zones

At the end of the tracer campaign it was possible to identify three zones of anomalous seepages (Figure 8):

- ZONE 1: The zone was located around the cutoff on the right side between elevation 165 m and 170 m. Response from this zone affected both drains with Types I and II curves. The anomaly was the most important one, in fact it produced a response from 15 tests located as far as elevation 205 m left side, with detection minimum time of 42 minutes and maximum restitution of 82%. It was caused by the presence of superficial defects near the cut-off structure.
- ZONE 2: The zone was located in the lower portion of the dam, below elevation 163 m and it was associated to medium response times and medium-high restitution in long term. The response from this zone affected mostly the left drain and it was related to Types II and III curves. It was associated to deeper and longer flow paths across the grout curtain.
- ZONE 3: The zone was located around the cutoff on the left side between elevation 165 m and 170 m. The response was related to Type I curve, but with low restitution. It was due to a small superficial defect close to the cut-off.

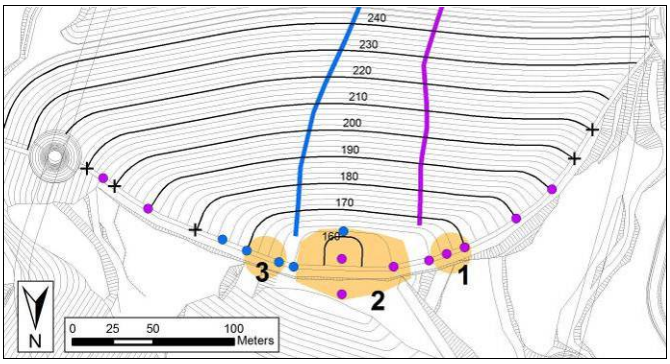

Figure 8: First campaign Seepage zones.

Seepage mitigation measures

Seepage mitigation measures were planned on the base of tracer test results. Works were executed between April and July 2009, after the complete draw down of the reservoir and the rise of the fore dam to safely operate at the dam base. The mitigation focused on the portions of the cut-off wall were lower times of detection and higher restitutions were observed and they consisted in:

- additional grouting in the impervious curtain along the whole cut off wall;
- micropiles curtain along the cut-off in the zones identified by the tracer test;
- cleaning and sealing of cracks observed in the asphalt layer;
- installation of a laterite blanket at the dam foot.

Second Test Campaign

The impounding restarted in July 2009 with a controlled breach of the cofferdam, which was made to gradually fill the pond at the base of the dam without any erosion of the blanket layer.

Reservoir filling run smoothly up to maximum elevation reached in the previous phase (215 m a.s.l.), with seepage from the foundation drains about half of the amount recorded before the mitigation works.

In October 2009, with the level rising, peaks of turbidity associated with seepage increase were observed from the foundation drain. Therefore a second tracer test campaign was executed with injections located both on the cut-off wall and the dam face.

The second campaign consisted of a total of 83 tests:

- # 12 Tests with Uranine;
- # 36 Tests with Rodhamine;
- # 35 Tests with Tinopal.

Positions and drain of first appearance of the injections are shown in Figure 9. For monitoring purposes multiple injections were also executed at different times in the same position.

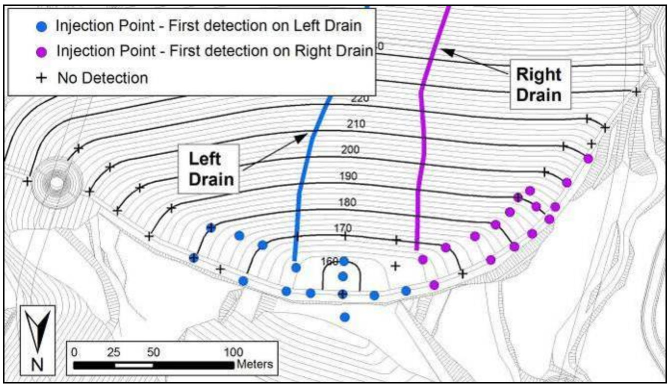

Figure 9: Injection points of the Second test campaign.

Three main phases in test response can be defined:

Phase 1 was characterized by moderate seepage flow and low solid transport with reservoir water level steadily raising from elevation 220 m to 230 m. A total number of 51 tracer tests were performed in this phase. Results, illustrated in the map of Figure 10, showed the presence of low detection times from injections located along the asphalt layer and on some portion of the cut-off wall. The lower detection times (1 hour) were observed on the left drain for injection executed between elevations 170-175 m along the asphalt layer in the left side. These injections were associate with restitutions up to 28%.

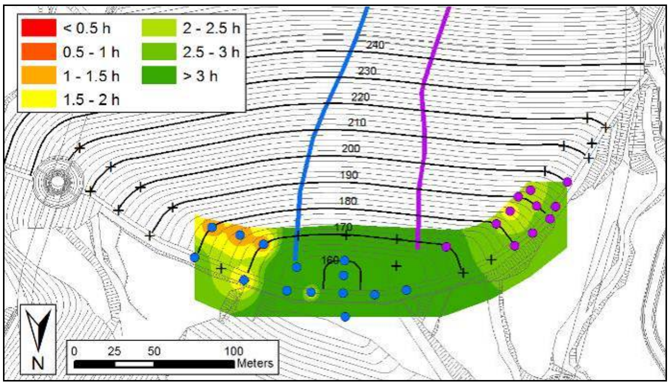

Figure 10: Second campaign Map of the first detection times in Phase 1.

Phase 2 refers to the period when the reservoir water level was raised from elevation 230 m to 238 m (left spillway overflow) and anomalous solid transport with seepages increase were observed from the foundation drains. In this phase a total of 13 tracer tests were performed both along the cutoff and the upstream asphalt face. Sharp decrese of detection times was observed for injections located along the asphalt layer on both sides, with associated increase in the restitution.

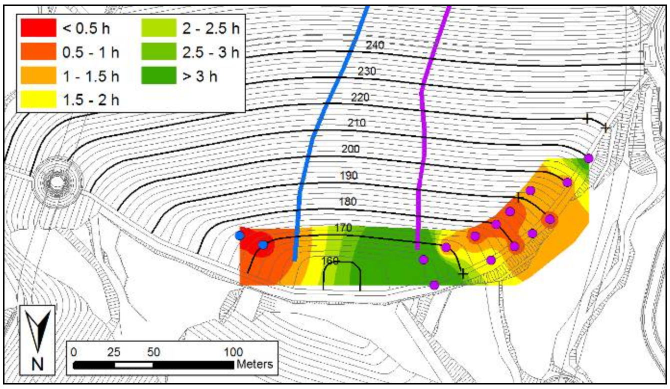

Figure 11: Second campaign Map of the first detection times in Phase 3

Phase 3 refers to the period after the anomalous solid transport when, with full impounding, solid transport reduced to low values and the seepage flow stabilized around 550 l/s. A total of 19 tracer tests were performed in this phase and they confirmed the position and extension of the damages on the asphalt face. Minimum detection times were around 25 to 40 minutes with restitution as high as 46.8%.

Monitoring the response of multiple tests (executed at the same injection point in different times) moving from Phase 1 to 3 we appreciated a continuous reduction of the detection times, especially for injections below elevation 190 m. Figure 12 shows the variations recorded at the right drain: a very sharp reduction can be observed for a couple of tests located along the asphalt layer at elevation 170 m and 175 m indicating the opening of new cracks during the Phase 2. It can be also appreciate that injections over the asphalt face produced detection times lower than the tests executed at the same elevation on the cutoff wall.

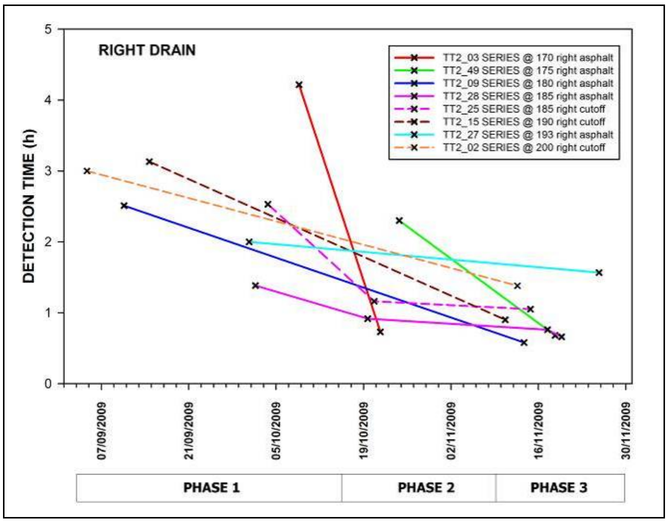

Figure 12: Second campaign decrease on the right drain of Detection times from tests performed at the same injection point.

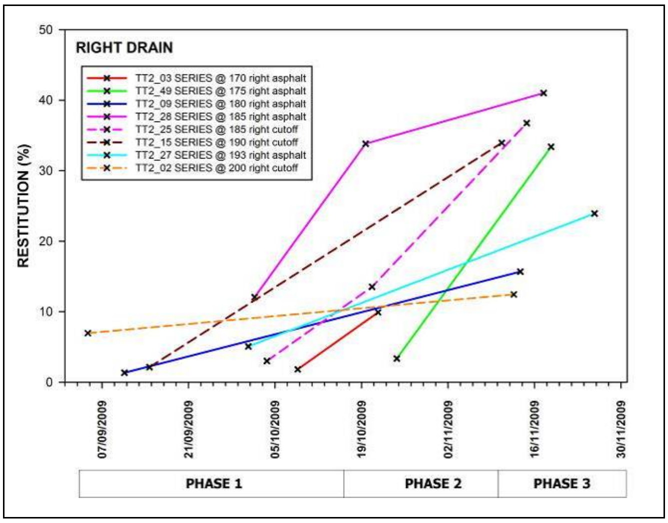

Figure 13: Second campaign Increase on the right drain of Restitutions from tests performed at the injection point.

Tracers restitutions for all the tests executed during the Phase 1 have been quite low, with a maximum value of 28% for the

tests executed on the left side asphalt, at elevation 170 m. On the right side the highest restitution recorded was of 12% for tests executed at 185 m a.s.l. asphalt.
Restitutions from tests performed during Phase 3 showed a higher response than in Phase 1 confirming the indications given by the detection times.
The highest restitution of 46.8% was recorded for the test performed at elevation 175 m asphalt left, which during phase 1 was only 5.4%; high values were also measured in the right side with a peak of 41% at elevation 185 m asphalt.
Restitution measured in Phase 2 and 3 were underestimated due to the effect of water turbidity on the fluorimeters precision.

The interpolation maps of detection times and restitutions defined the position and evolution of the seepage zones along the dam impervious system (Figure 14).
Seepages of Phase 1 were caused by the presence of damages on the asphalt layer located along the right side at elevation 185 m and along the left side between elevations 170-180 m. Minor damages were also assumed at the dam bottom and along the left cutoff, close to elevation 170 m.
Increase of seepages and solid transport observed in Phase 2 were produced by the widening of existing fissures on the asphalt along the left side between elevations 170-180 m together with the opening downward of new fissures on the asphalt along the right side between elevations 170-185 m.

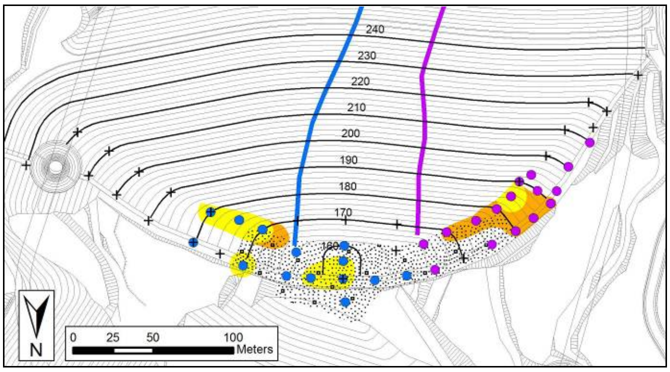

Figure 14: Second campaign Seepage zones: yellow zones observed in Phase 1, orange: extensions produced in Phase 2.

Tracer Tests demonstrated that new cracks were developing on the bituminous asphalt layer and that they were extending with the rise of the reservoir level.
In fact the increase of hydraulic head over the dam face above the maximum value reached during previous stage of impounding was causing a localized compaction of the rockfill with associated deformations and cracking of the above asphalt layer.
The flow of water throught the cracks caused the peaks of solid transport due to the erosion of the fine fraction in the subgrade layer below the asphalt and/or in the laterite blanket placed above the asphalt as mitigation measure.

Definitive remediation of the damages required the complete development of all the deformation in the asphalt that would be produced by the impounding. Therefore it was decided to raise the reservoir level monitoring continuously the position of the cracks in the asphalt with tracer tests.
The impounding was completed in November 2009 with seepages from the foundation drains that reached 550 l/s.
It is important to note that during the whole process the deformations of the dam structure measured from the monitoring system were always within the design limits.

Complementary seepage mitigation measures

Tracer tests results permitted to define during the impounding the remediation measure and to provide well in advance the order for the supply of the needed quantities. This made it possible to minimize the times needed for seepage mitigation and, as a consequence, the downtimes of the power plant.
Complementary remediation measures focused on the rehabilition of the bitouminous layer with the sealing of the cracks and the installation of an impervious PVC membrane along the lower section of the dam face. Additionally a laterite blanket was re-placed at the upstream dam toe.
At the end of the raining season the reservoir was drawn down again and complementary mitigation measured were executed.
A careful inspection, executed after the complete exposure of the dam face, showed the existence of numerous open fissures located inside or immediately nearby the areas indicated by the tracer tests.


Figure 15: Open cracks on the bituminous asphalt layer exposed after reservoir drawdown

The installation of the PVC blanket was completed in June 2010 (Figure 15), since then the dam is performing satisfactorily with flow collected by the foundation drains ranges between 35 and 90 l/s.
It should be noted that dam seepages at maximum reservoir level after seepage mitigation works were about 50 l/s.

Figure 16: PVC membrane installed on the dam face.

Discussion and conclusion

Tracer tests have been executed during the first impounding of the Bumbuna dam as an investigation tool to identify the position of zone of excessive seepage occurring through the dam impervious system.

Three types of fluorescent tracers were used: Uranine, Sulforhodamine B and Tinopal CBS-X. They were injected at depth in the reservoir and their concentration was monitored in the 2 main foundation drains using high resolution fluorimeters.

A total of 107 tests were performed in two separate campaigns conducted in January-February and October-December 2009.

Two main parameters were obtained from each test: the detection time, which is the differences between the times of detection and injection, and the restitution, which is the amount of tracer recovered from the drains.

Geostatistical interpolation maps with the spatial distribution of the two parameters were used to define the seepage zones where mitigation works had to be executed.

Tracer test were also used to monitor the widening of the seepage zones during the impounding.

According to our experience we believe that the Fluorescent Tracer Technique can be effectively applied for the detection and monitoring of seepages through dam impervious systems.

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