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# Evaluating stability of dam foundations by borehole and surface survey using Step Frequency Radar

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ABSTRACT : Evaluating stability of dam foundations is one of the prime areas of any rock engineering investigations. Despite best engineering efforts in the design and construction of dam foundations, the foundation regime of a constructed dam suffers deterioration due to continuous erosion from backwater current of dam discharge and dynamic effects of loading and unloading process. Even during construction, development of frequent cracks due to sudden thermal cooling of concrete blocks is not uncommon.

This paper presents two case studies from India and Bhutan. In the first case, the back current of water discharge from the Srisailam dam in India had continuously eroded the apron and has eaten into the dam foundation. In the second case with dam construction at Tala Hydroelectric Project in Bhutan, sudden overflow of river during the construction stage of dam had led to development of three major cracks across the dam blocks. This was ascribed to adiabatic cooling effect of concrete blocks overlain by chilled water flow. Non-destructive evaluation of rock mass condition in the defect regime by the borehole GPR survey helped in arriving at the crux so as to formulate appropriate restoration plan.

## 1. Introduction

Dynamic study of the deterioration of rock mass under stress in and around major excavations or in the foundation regime of superstructures is the key investigation area in rock mechanics. Even with the latest know how in modelling and sophisticated investigation tools, complete understanding of rock dynamics is seldom realised in practice, particularly because of incomplete information of input geology and improper understanding of behaviour of in-situ stresses. As a result, the rock mass under stress around excavations and foundations suffer unpredictable deterioration, which requires a proper post-failure investigation to adopt proper restorative measures. As regards, the foundation regime of large dams, the factors affecting their stability may be both inherent (construction induced) and external forces (forces of heavy water currents). This paper highlights two typical cases where external forces, though not unknown at the time of construction, played havoc to threaten the very stability of dam. Thermal cracking due to adiabatic cooling (induced by overflowing of river water) of concrete blocks during construction stage at Tala Project in Bhutan was a unique case where crack tried to approach the foundation. In yet another case, the foundation of a well-constructed dam was eroded by the eddy current of back-water from dam discharge. Mapping the existing flaws without further deterioration of foundation was extremely important in both the cases. Investigations by Ground Penetrating Radar (GPR) by surface scanning, in-hole reflection measurements and cross-hole tomography helped to arrive at the extent of damage done as well as the quality and efficacy of restorative measures planned and executed. Highlights of the site investigation practice adopted in the two cases are discussed here with relevant pictures and results.

## 2. Definition of problem

The Srisailam dam in India and the Wangkha dam in Bhutan are masonry structures of straight gravity type. While the former was constructed in 1988 across the river Krishna in Andhra Pradesh in India, the later is under construction across the river Wang Chu in Bhutan (Fig. 1). The Srisailam dam was built in 22 separate monoliths with radial construction joints and copper sealing strips. The apron of the dam extends up to 55m downstream followed by 200m long plunge-pool. In order to protect the apron from the reverse (eddy) current of the water discharged in the plunge-pool, 18m long concrete-filled iron cylinders (2m in diameter) were placed all along its face with end-to-end welding. Even then a portion of apron between blocks 8 and 11 was always found submerged in water even though the water in the plunge pool was well below the apron level. This led to the suspicion of the presence of subsurface channel or interconnected cavities below the apron extending up to the plunge pool area. An under-water videography carried out in 1998 in the plunge pool area revealed wide opening below the concrete cylinders extending into the apron and basement rock. Thus, it appeared that the apron was deeply eroded by the eddy water current over a period of time posing a direct threat to the foundation and hence overall stability of the dam. In the second case with Wanghka dam of Tala Hydroelectric project of Bhutan, three major deep-rooted cracks appeared on the surface of concrete blocks 2, 5 & 6 of the dam while it was under construction up to 15m (out of 92m) height (Fig.1). The origin of these cracks was ascribed to sudden cooling caused by overflowing of the host river (Wang-chu), whereby cold water of the river overflew the concrete blocks which remained submerged for about four-five months till the river was in spate. These cracks in the dam foundation regime posed a threat to the overall stability of dam under construction.

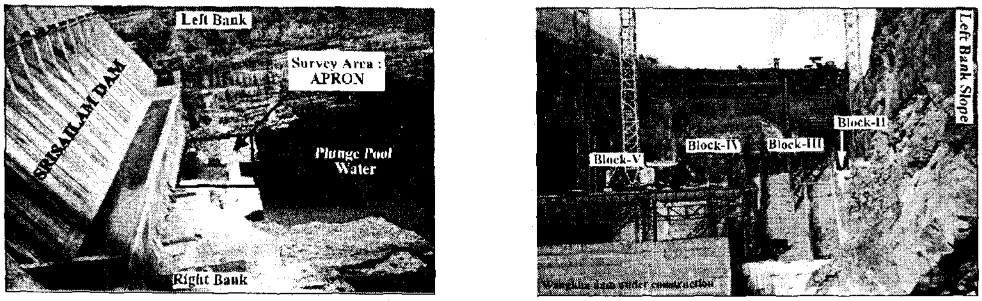


Fig. 1. Bird's eye view of Srisailam dam (India) and Wangkha dam (Bhutan) where foundation stability studies with SFR were carried out.

In both the cases, it was desired that the extent of cavities or cracks be properly mapped by appropriate investigation technique(s) so that proper restorative measures could be adopted so as to arrest any further deterioration of the foundation of these two dams. While it was proposed to carry out scanning with high resolution Ground Penetrating Radar (GPR) along closely spaced grid-lines in the suspected damage regime of the Srisailam dam, in-hole profiling and cross-hole tomography using GPR were opted for Wangkha dam. Use of GPR was helpful in non-destructive approach to damage evaluation in both these cases so as to ensure that no further deterioration takes place during the investigation stage. Further since cracks in the Wangkha dam were proposed to be cement grouted as a part of restoration plan, it was suggested that cross-hole tomography should be carried out both before and after the grouting operations so as to check the efficacy of grouting.

Innovative tools like guided borehole probe for directional profiling and attenuation tomography at various representative frequencies were adopted for investigations at Wangkha dam. In the case of Srisailam dam, the presence of cavities were re-confirmed by high-resolution seismic refraction survey across the pitfall regimes.

## 3. Strategic planning for GPR survey

At Srisailam dam in the state of AP in India, the earmarked area for investigation measured approximately 90m X 50m between block-8 and block-11. The desired depth of investigation was up to 25m, i.e. up to the foundation. Grid lines were drawn at 10m X 10m interval in the earmarked region of the apron (Fig.2). The GPR survey was done along all the 18 lines of grid measuring 1225m in length. Mapping with GPR reflection measurements was favoured as it was expected to yield a good contrast of the target (cavity - *air or water-filled*) with the host (cement concrete) medium. In order to meet the range-resolution criterion of GPR survey (Jha et. al., 2003), the mapping was done with 200 MHz frequency band and 0.5m movement step. Presence of cavities was confirmed only when similar feature appeared on both the orthogonal lines of grid at the suspected locations.

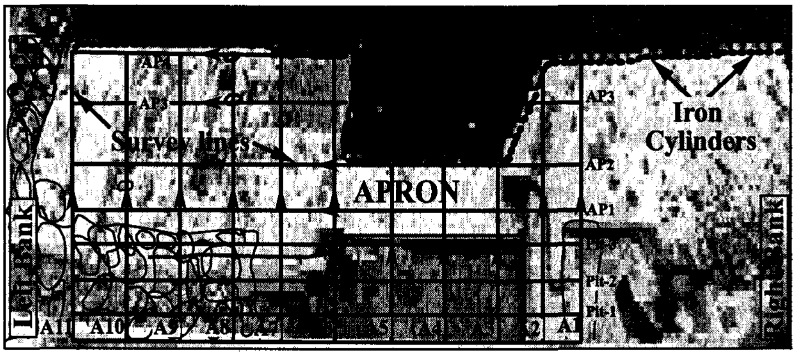


Fig. 2. Plan view of apron area between blocks 8 and 11 of the Srisailam dam (AP, India) showing grid lines at 10mX10m interval. GPR survey was done along all the grid lines with a scan depth limited to 25m (foundation).

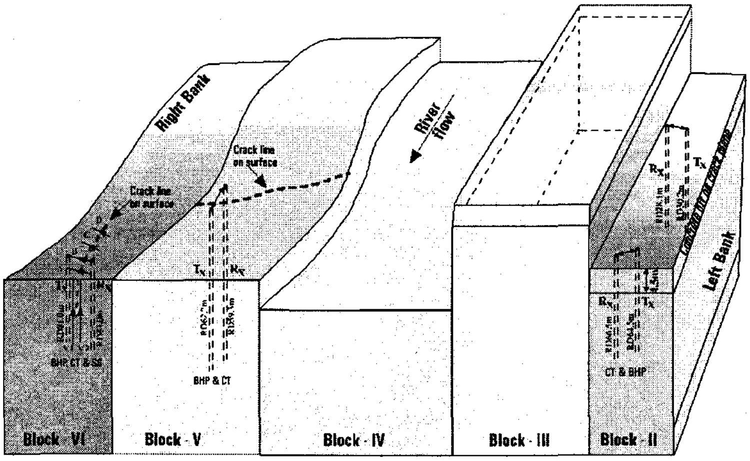


Fig. 3. Schematic view of the dam blocks II to VI of the Wangkha dam (Bhutan) showing three major cracks that appeared on surface of blocks II and VI. Locations of borehole pairs in which in-hole reflection measurements were made are shown on the either side of crack alignment. In addition, four cross-hole tomographic measurements were also made before and after the cement grouting across these four pair of boreholes.

In the case of Wangkha dam of Tala Hydroelectric Project of Bhutan, it was planned to map the thin cracks in the three concrete blocks. Since the dam was under construction, two of these cracks got buried (at the time of survey) under successive concrete lift. Therefore, it was planned to carry out investigations from boreholes drilled on either side of these crack alignments (Fig.3). Altogether four pairs of drill holes were made. Both in-hole reflection survey using guided probe and cross-hole tomography before and after the grouting were employed for mapping the status of these cracks. Use of borehole measurements with GPR have been demonstrated earlier for mapping cracks or subsurface targets in both synthetic cases and actual field condition (Kong and By, 1995; Serzu et al., 1996, Jha et al., 2002, Haeni et al., 2002). In addition to borehole measurements, surface scanning was also done in block-VI where the crack was still exposed at the time of survey.

The equipment used in these investigations was a variant of the GPR called Stepped Frequency Radar (SFR), developed at Norway. In the SFR, all measurements are made in the frequency domain and at the end IFFT is carried out to get the conventional time section. Network Analyser (NA) is used as the RF source and receiver while identical pair of resistively loaded dipole antennas serve as the transmitter and receiver for the SFR. The choice of the frequency band of operation is decided by the resonance frequency band at the site and is controlled by the operating software. A PCMCIA based data acquisition card, also called the system controller, is interfaced to the NA by GPIB interface (Fig.4, right) while antennas are just impedance matched passive elements. Theory and detailed performance analysis of this version of GPR is discussed by Kong and By (1993).

The advantage of using SFR is its ability to manoeuvre the basic survey parameters including resonance frequency, frequency band of operation and power requirement by the operating software. The SFR has a wider dynamic badwidth and a relatively noise-free data acquisition that results in a deeper probing with sharper images as compared to their impulse analogues (Daniels, 1996). In order to map the profile of crack in the vertical plane from boreholes, a guided probe was developed with an effective forward viewing angle of 20° (Fig.6). Technical details of this probe is discussed by Jha et al. (2002). Measurements were made while the probe was moved up along the borehole. Attachments were devised to control the movement and direction of this probe. This design was fairly simple and easily manoeuvrable as compared to similar directional probing devices made using four orthogonal loop antennas (Lane et al., 1994) or using optical modulator and waveguide (Ebihara and Sato, 2000).

## 4. Case studies

### Srisailam Dam, India

As stated earlier 4500 sq. m area of the survey was divided into 10m X 10m grids. Of the 18 grid lines along which GPR survey was carried out in the earmarked region between blocks 8 and 11 of the dam, 7 lines ran parallel to dam axis from right bank to left bank, while 11 lines ran perpendicular from the toe of the dam towards the edge of the apron. The SFR surface scanning was done with a 200 MHz frequency bandwidth in discrete steps at every 0.5m. The survey in progress is shown in Fig.4(left). The cavity pockets were identified based on their signatures on both the orthogonal grid lines crossing the cavity region. The area underlain by such cavity pockets were plotted on the plan of survey area and their depth extent was estimated from the GPR section. Thus, a fair estimate of the volume of cavities was made so as to decide upon the extent of fill material (grout) required to pack them.

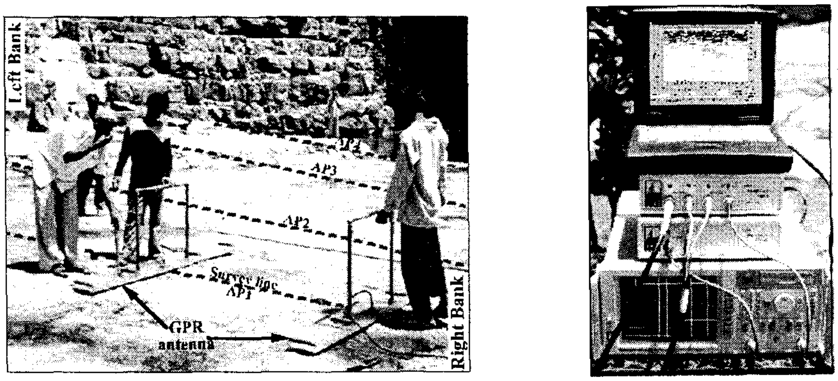


Fig. 4. GPR survey in progress along line AP1 on the apron of Srisailam dam (left). On the right is the set-up of data acquisition unit of the SFR with Network Analyser (NA) at the bottom followed by RF amplifiers. Data acquisition PC (shown on right, top) and NA are connected by PCMCIA-GPIB interface.

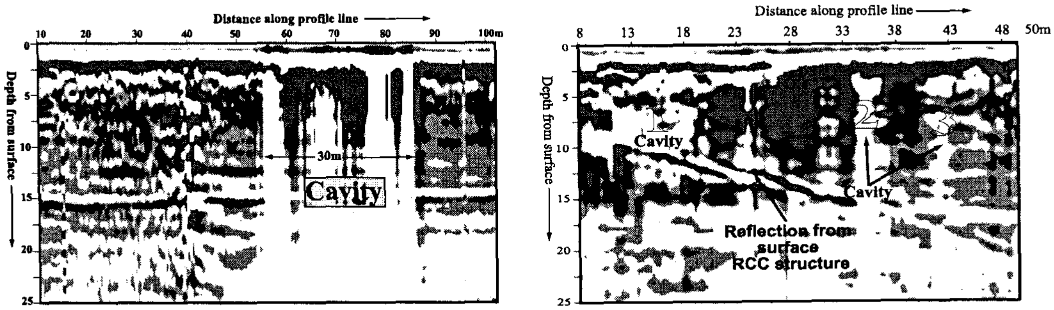


Fig. 5. Radargrams along the line AP1(left) and A7 (right) showing locations of prominent cavities. The major opening seen on the GPR section of line AP1 (left picture) is reflected as cavity pocket marked 3 on the radargram of line A7 (right picture).

The radargram (GPR section) along two representative line AP1 and A7 crossing each other in the centre is shown in Fig. 5. Along line AP1, a major gap in the concrete is mapped between 55-75m from origin (Fig.5, left). Line A7 crosses line AP1 at around 35m from dam toe. Corresponding location of cavity in the radargram of line A7 is marked as 2 (Fig.5, right). The seismic section along this cavity region reflected a pocket with a seismic velocity of 1200m/sec, suggesting a water-filled pocket. Thus, a combination of survey along two orthogonal GPR lines and seismic refraction survey confirmed the presence of a prominent cavity pocket, occupying an area of 110 square meters with an estimated volume of around 500 cubic meters. This way the entire surface scanning with SFR and the seismic refraction survey in the suspected cavity regions led to the identification of five major cavity pockets in the earmarked area of apron. Altogether these cavities occupied a surface area of 640 square meters (15% of the surveyed apron area) with an estimated fill volume of 4200 cubic meters.

**Wangkha dam, Bhutan**

In Wangkha dam of Tala hydroelectric project, the objective was to map the thin sub-vertical (not known) cracks that appeared during construction stage in three out of eight dam blocks. These cracks were proposed to be cement grouted. Hence the efficacy of grouting operation needed to be evaluated. In total, borehole profiling with SFR was done in the three pairs of holes, one each in at RD =29m in block-II, RD= 61m in block-V and RD= 81m in block-VI. In all the cases, measurements were made from bottom to top of a hole. Cross-hole tomography was also performed both before and after grouting operation to evaluate the extent of cement grout.

Special directional probe with graduated and threaded PVC pipe attachments was devised for borehole profiling (Fig.6). All measurements were made from bottom to top in steps of 0.50m. While probing, directional marks on the PVC pipes ensured the antennas remained focused in the direction of target (crack plane). In order to authenticate the findings, the borehole GPR profiling was repeated in the conjugate hole pair also wherein a mirror image of the crack plane was expected to be mapped. In the reflection measurements, the orientation of crack plane was inferred based on continuous reflection along the borehole axis. Tomogram was generated by SIRT technique inverting the 30X30 data matrix formed out of measurements made at every 0.5m movement of $T_X$ and $R_X$ antenna pair. The tomographic picture revealed the crack plane as anomalous high attenuation zone(s). Study of frequency based attenuation properties yield more reliable information and this has been in practice for many years (Liu et al., 1998). Several iterations were carried out at various representative frequencies to authenticate the survey results. Two typical results, one each of borehole profiling and cross-hole tomography are are discussed here with the respective GPR section and tomograms.

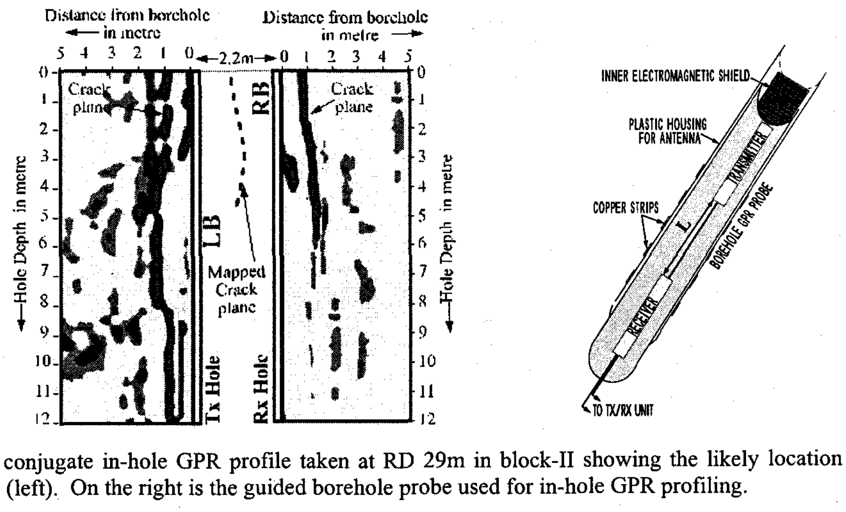


Fig. 6. A pair of conjugate in-hole GPR profile taken at RD 29m in block-II showing the likely location of crack plane in between the holes (left). On the right is the guided borehole probe used for in-hole GPR profiling.

The GPR profiles (radargrams) of in-hole reflection measurements carried out along the two holes across RD=29 are shown side by side in Fig. 6 (left) in which the left bank and right bank holes are marked LB and RB respectively. The x-axis represents the distance from the borehole axis and y-axis represents the distance along the borehole. A conspicuous reflection along the borehole axis is the most likely crack plane, which is shown by a dashed line between the two boreholes. Only the portion of reflection common in the two conjugate holes were taken for the extent of well-defined crack plane, which in this case was found extending up to 5m depth.

This was also confirmed in the corresponding tomographic picture shown in Fig.7 (left). A high attenuation patch (>50 dB/m, as against background attenuation of 10dB/m in the host concrete) is seen in the attenuation tomogram plotted for 200 MHz frequency generated before grouting. This high attenuation zone in the centre of holes extended up to 4m depth, corresponding to the crack plane mapped earlier in the borehole profiling. However, the tomogram obtained in the post-grouting condition (Fig.7, right) showed that the attenuation in this anomalous patch had scaled down to 10-15 dB/m (reduction by almost 70%) indicating that cracks might have been cemented due to effective grouting.

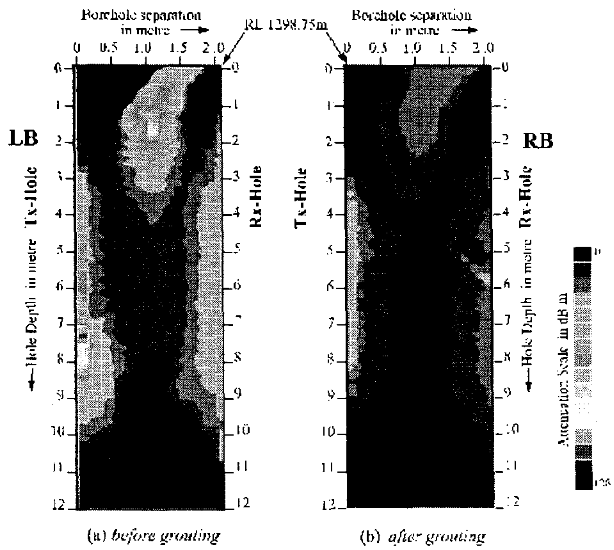


Fig. 7. Attenuation tomogram at 200 MHz before and after the cement grouting. Predominant high attenuation (50-60dB/m) zone is seen in the centre up to 4m depth. After grouting, this zone had a relatively very low attenuation, indicating good compaction with the cement grout.

Similar was the situation in block-VI also, wherein a comparison of two tomographic plots (before and after grouting) revealed that crack was well cemented after grouting operation. But there was virtually no change in the twin tomographic plot for block V, where a repeat grouting was suggested. Thus, a comparative study of attenuation tomographic plot of radio waves at 200 MHz frequency before and after grouting operations proved helpful in deciding the efficacy of planned restorative measures. This was a unique application of borehole GPR survey in addressing a typical civil engineering problem.

## 5. Conclusions

Drilling during restorative measures at the apron of Srisailam dam confirmed the presence of all the five cavity pockets at precisely the same locations. Even the actual fill volume was 4500 cubic meter, which was very close to the predicted cavity volume of 4200 cubic meter. The crackmeter installed at the Wangkha dam did not record any movement subsequent to grouting, indicating that inference from borehole GPR measurements was in unison with actual condition.

The results of these investigations showcase the capability and potential use of GPR in the site characterisation practice for foundation evaluation of major and critical superstructures like dams. It is expected that in future the SFR will have a much wider role to play in the site characterisation practice (Daniels, 1996) during construction, operational maintenance and post-failure investigation of major civil structures.

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