Acoustic Emission-Based Non-Destructive Technique for Integrity Assessment of Heavily Reinforced Typical Trunnion Beam of Spillway Structure

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Abstract

Owing to the large mass of concrete with heavy reinforcement in dam spillways and the long-expected life of these structures, they are susceptible to degradation mechanisms that can start as minor problems and be present for years. The presence of initial degradation tends to accelerate future problems. For example, the presence of voids/flaws in the trunnion beams lead to greater damage if unattended. However, it is highly impossible to identify the internal voids through visual means. Further, the Ultrasonic Pulse Velocity (UPV) method, which is widely used for condition assessment of concrete structures, may not be effective (sometimes a misleading) here due to the presence of heavily dense reinforcement and prestressing strands in large concrete trunnions.
In view of this, attempts were made to assess the health of a typical trunnion beam of the spillway structure employing the Acoustic Emission (AE) technique. During the investigations, ambient conditions (excitation due to water thrust on the dam), as well as the slow movement of the radial gates, were used. A three-dimensional sensor arrangement was used so that the acoustic source localization inside the massive concrete turions could be carried out. High-speed acquisition of data through multichannel was performed using an integrated and synchronized AE system (with an in-built amplifier). Due to the ambient condition and during gate operation, the noise-generated acoustic signals were carefully discarded. Through intensive signal processing, the AE parameters, such as the number of AE hits, signal amplitude, and signal strength, were considered to assess the existing health of the trunnions. The present study discusses on typical signals, acoustic characteristics and inference from the AE-based NDT, along with the method used for acoustic source localization. The present study, the procedure and the inferences are helpful to the practising NDT engineers to perform the health assessment of concrete structures with a high amount of reinforcement.
Keywords: *Non-destructive testing, Acoustic emission, Health assessment, Prestressed trunnion beam*

1. INTRODUCTION

Concrete dams have been constructed as significant infrastructure to perform the tasks of power generation, flood control, navigation, etc. However, these concrete structures are prone to face safety issues due to certain reasons, such as the presence of voids/flaws, and slow-developing cracks in the dam interior. Thus, prior monitoring of integrity before putting the structure into service is the most effective safeguard against these dangers. However, visual checking often only reveals problems that have developed into major degradation. Furthermore, some kinds of damage, including voids under a spillway slab or cracks in the interior of the dam, are challenging or impossible to detect visually. This is where non-destructive testing (NDT) techniques come into play. NDT methods use ultrasonic waves, radio waves, and other types of low-level energy to propagate through the concrete [1]. These methods can be used to locate a void under a spillway. Ultrasonic pulse velocity (UPV) testing is the most widely used NDT method towards assessing structural health. However, the presence of heavy reinforcement may influence the UPV measurements as a method of evaluating the concrete's integrity/quality. UPV-quality guidelines are framed on the basis of laboratory plain concrete specimens tested. However, the trunnion beam contains heavy steel reinforcement and pre-stressing strands that interferes with UPV measurements, thereby resulting in erroneous measurements. This work proposes an alternative NDT technique based on acoustic emission testing as it does not depend on the material characteristics and also it does not involve any input of energy into the materials.

Besides AE and UPV, Impact Echo (IE), the Spectral Analysis of Surface Waves (SASW), Ground Penetrating Radar (GPR), and cross-face sonic tomography, are some of the NDT techniques that could be used for monitoring the health of dam structures [1,2]. The main advantage of these alternatives compared to AE is that skilled labour is required to operate the equipment efficiently and accurately infer the data obtained from AE. The main disadvantage of these alternatives compared to AE is that in all other NDT techniques, external input of energy into the materials is needed, and they may hold limitations for large geometry structures Acoustic Emission (AE) testing is one such NDT technique that is based on the generation of waves produced by a sudden redistribution of stress in a material. AE has been used in field testing for various applications – source localization [3–5], crack detection [6-11], corrosion monitoring [12,13], structural integrity assessment [14-16], and health monitoring of cable stays in bridges [17-22]. Very few researchers used AE technique in dam monitoring, during grouting operation [23], post-peak cyclic loading [24]. However, assessing the health of dam structures employing the AE technique is still not explored.

In the present work, AE monitoring was conducted in order to ensure the safety of the dam spillway trunnion beam under construction. Low-frequency AE sensors were employed to detect AE waveforms since the signals with conventional frequencies may attenuate greatly during the propagation in the large-sized concrete structure. When AE-based assessment was conducted, the construction was suspended for a few days to avoid disturbance due to environmental noise. While other tools, such as ultrasonic pulse testing, can also be deployed for this specific application, the present study aims to demonstrate the potential application of AE to characterize the internal condition of such a heavily reinforced trunnion beam.

2. BRIEF ABOUT AE TECHNIQUE

The basis of the AE technique is the rapid release of energy from various internal sources that results in elastic waves [25]. Appropriate AE sensors capture the emitted acoustic waves and convert them into an electric waveform that can be processed and stored. Different AE parameters can be defined from a typical presentation of acoustic waveform, as illustrated in Fig. 1. The AE waveform's maximum voltage is called amplitude (dB), threshold is the amplitude that the user defines based on the noise level of the surrounding environment, rise time is the period of time between the initial threshold crossing and the maximum amplitude, counts are how many times an AE hit goes over the threshold, the interval between the first and last threshold crossings is known as duration, absolute energy is the integration of the squared voltage signal (V_s) over the duration divided by a reference resistance of $10k\Omega$ as expressed below [26].

$$Absolute\ energy = \frac{\sum V_s^2}{reference\ resistance} \quad (1)$$

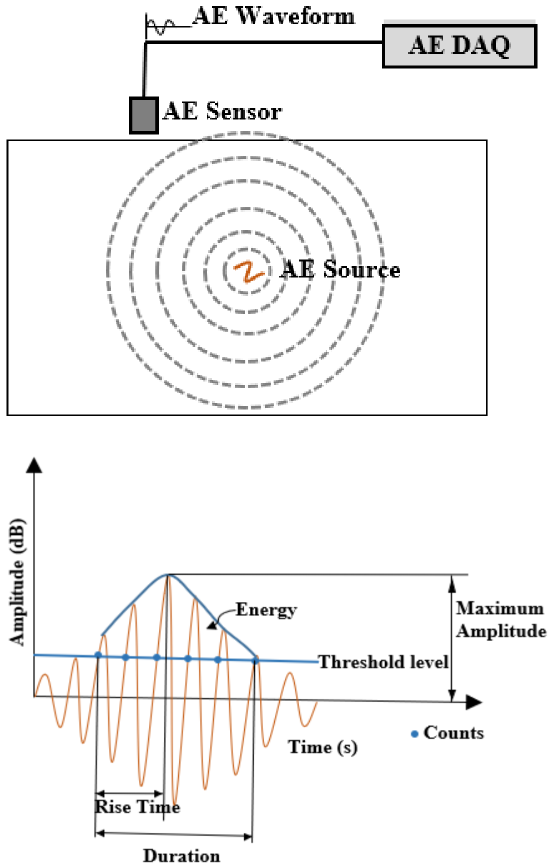


Fig. 1. *Acoustic wave formation and a typical waveform*

3. TEST PROCEDURE

3.1 Structure: Trunnion Beam

The spillway under investigation consists of radial gates which are connected with bi-directionally prestressed Trunnion beams (Fig. 2).

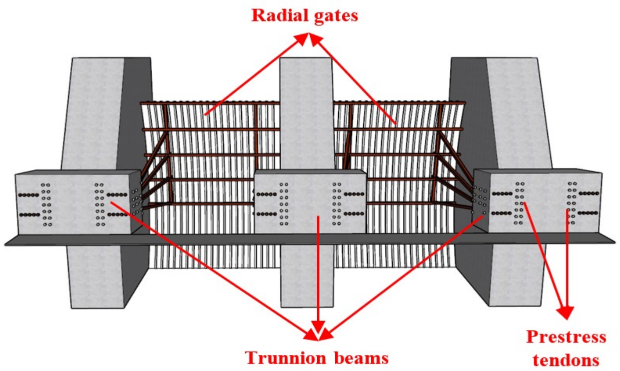
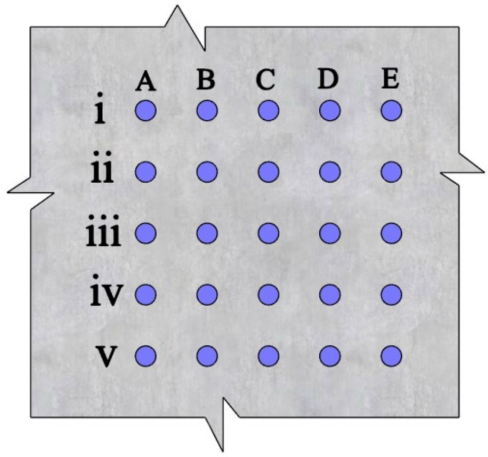


***Fig. 2.** Schematic view of a typical trunnion beam with radial gates*

A typical prestressed trunnion beam is proposed to be instrumented and tested to investigate on structural integrity. First, a detailed non-destructive evaluation (NDE) using conventional UPV testing is carried out on the prestressed trunnion beams to evaluate the concrete durability and strength. The quality of concrete is assessed by taking UPV responses at different locations, as shown in Fig. 3. UPV measurement is taken by making 5×5 grids with dimensions of $300 \times 300\,mm$ (see Fig. 3). Commonly used instrument PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) instrument as shown in Fig. 3(b) is used for UPV testing in indirect /surface transmission mode. It includes a pulse generation circuit, consisting of an electronic circuit for generating pulses and a transducer for transforming electronic pulse into a mechanical pulse having an oscillation frequency in the range of $40\,kHz$ to $50\,kHz$, and a pulse reception circuit that receives the signal. The following test procedure for determining the ultrasonic pulse velocity as described in IS 13311(Part-I) is adopted:

- Dividing the members into well-defined grid points with preferred spacing of 200-300 mm.
- Each grid point is prepared to obtain a smooth surface by thorough cleaning.
- Attain good acoustical coupling by applying grease or petroleum jelly.
- Transmitting the pulses by placing the transmitter on one end and the receiver at the other end.
- Recording the transit time displayed by the instrument - a reliable, steady reading to be recorded (T)
- Measurement of distance between transmitter and receiver (L)
- Calculation of velocity, $V = L/T$



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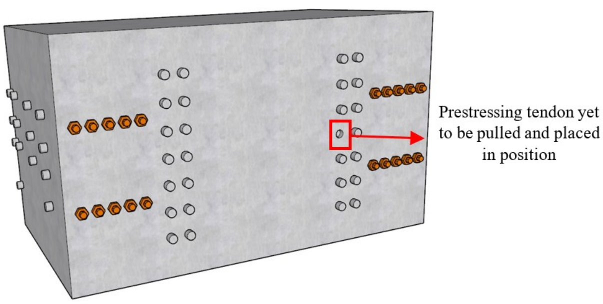
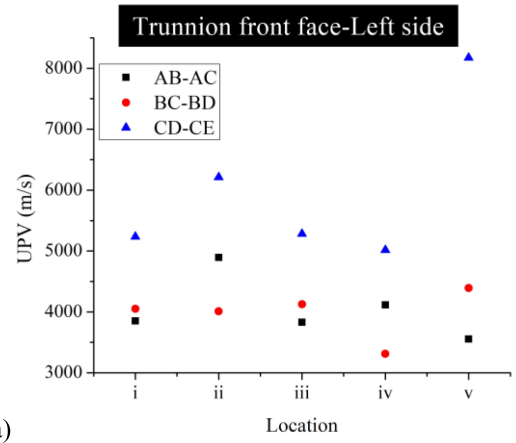


(c)

***Fig. 3.** (a) Experimental setup of UPV measurements; (b) PUNDIT LAB+UPV Test Equipment and Transducers; (c) View of the front face of prestresses trunnion beam*

UPV value is found to be around 3000 to 5000 m/s, and in many locations, it is above 3500 m/s (see Fig. 4). According to BIS 13311-1:1992 [27], the general guideline is that when the UPV values range between 3500 m/s and 4500 m/s, the concrete is referred to as good quality. Thus, the quality of the concrete of trunnion is found to be excellent in terms of its integrity/uniformity checking. However, it is evident from visual inspection that the prevailing situation is not properly reflected through the UPV results. UPV value is influenced by the elastic moduli and the density of the material, which in turn are mainly governed by the number of various phases present. It is mainly due to the fact that the heavy reinforcement, irrespective of the concrete equality, causes high UPV values in the present study, and it can mislead the results [28-30]. Hence it is required to further investigate the homogeneity of prestressed concrete trunnion beams, and, therefore, for assessment of discontinuity exists due to interior cracking/ deterioration/ honeycombing/ variations in mixture proportions. AE testing does not depend on the material characteristics and also it does not involve any input of energy into the materials.



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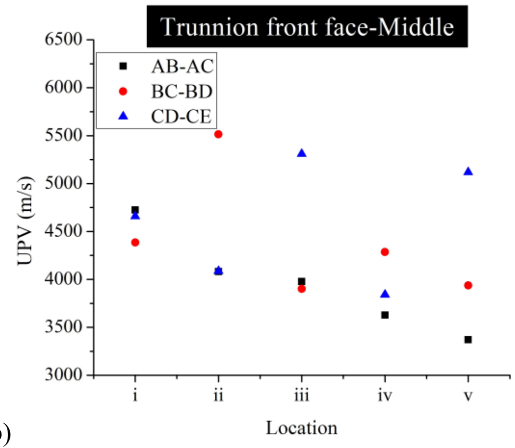

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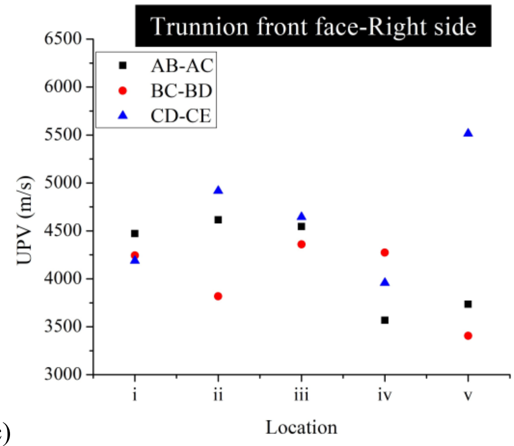

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Fig. 4. *UPV testing results on the trunnion beam*

3.2 AE Instrumentation and Test Protocol

A comprehensive and multi-point AE technique was used to investigate the health of the trunnion beam. The acoustic signals are captured at a very high speed (sampling frequency) so that no signals from minute dislocations are missed out. Accordingly, the signals were captured using the state-of-the-art multichannel AE data acquisition system. Twenty-two low-frequency AE sensors (PAC R15) were employed to detect AE signals in large-sized concrete trunnion. The resonant frequency of the AE sensor is 15 kHz, and the operating frequency range is between 10 kHz and 50 kHz, which is low as compared to the conventional sensor frequency. It is obvious that the attenuation during wave propagation is very high in concrete so the conventional high frequencies are not useful enough to capture AE signals in such a large concrete structure as a dam. The pencil break calibration test was conducted and showed that this frequency range is effective enough to detect meaningful AE signals over a defined threshold.

Data was acquired using 2 MSPS (Mega Samples Per Second). Grease was applied as a coupling agent between AE sensor bottom and the concrete surface. Screw-on type clamping holder was also used to keep the sensors in position during the tests. A threshold limit of 30 dB was chosen, and the signals were amplified using 40 dB in-built pre-amplifier and input into an AE system (SAMOS 48-channel AE system procured from Physical Acoustics) connected with a computer which has AEwin software for further post-processing.

A schematic representation of the trunnion beam along with the instrumentation plan for multichannel AE studies, is shown in Fig. 5 and the detailed instrumentation plan for the trunnion beam's three faces (front, left and right) adopted is shown in Fig. 6.

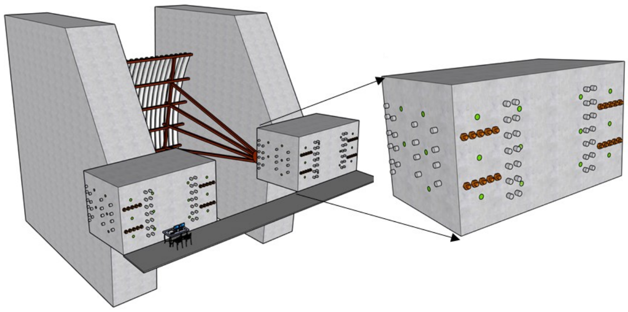
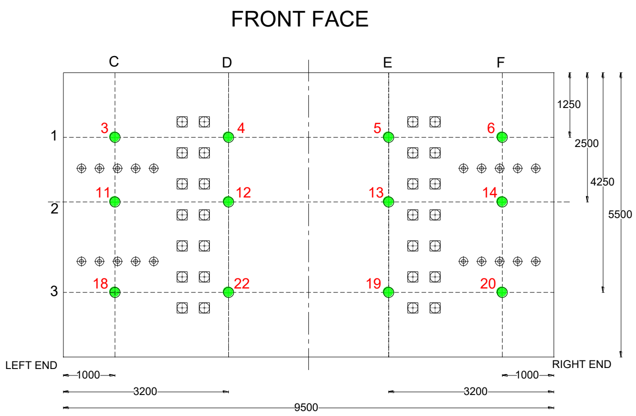
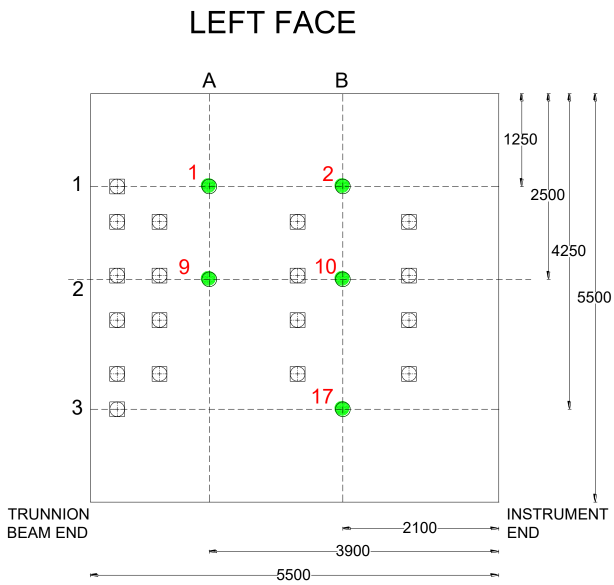


Fig. 5. *Schematic representation of trunnion beam along with instrumentation plan for multichannel AE studies*

The radial gates were planned to be operated to activate the system to generate the acoustic parameters. The followed test protocol for the field investigation is given below.

1. The trunnion will be instrumented with a grid of instruments. Testing of trunnion beam comprises of the following three phases:
   a) Phase 1 - Radial gate movement from water level to spillway bed level
   b) Phase 2 - Both radial gates are fully closed and kept at rest position
   c) Phase 3 - Radial gate lifting out up to water level





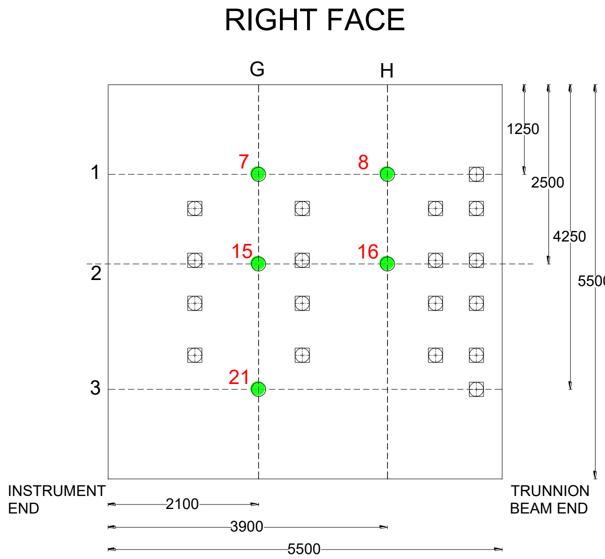


Fig. 6. *Detailed instrumentation plan in trunnion beam three faces (green marking represents AE sensor locations)*

2. Each time of testing, both the radial gates will be operated simultaneously
3. During the opening and closing of the radial gates, data will be acquired using multi-channel AE DAQ with a specific frequency
4. It is planned to carry out 5 times gate operations for the trunnion (as mentioned in point #1) to check for consistency

4. AE DATA ANALYSIS AND RESULTS

AE activity monitored during testing through the acquisition setup is analysed. Detailed and comprehensive data processing of all the AE signals acquired during testing in all 22 channels is done. However, few AE parameters and pertinent information are provided for Sthe trunnion beam in a brief manner. Typical AE signal obtained during the testing is shown in Fig. 7.

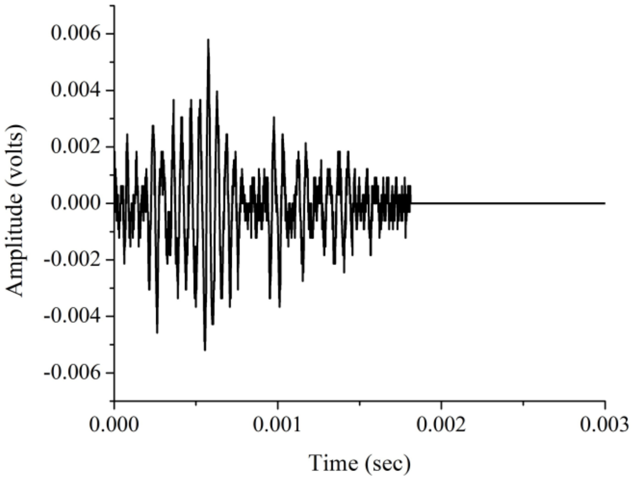


Fig. 7. *Typical AE signal recorded during testing*

4.1 AE Signal - Time Domain Analysis

Fig. 8 presents the plots of AE features in the time domain at different phases of testing. Time domain analysis of these signals reveals that the signal amplitude of AE hits is found to be in the range of 30-65dB. In addition, hits are found to be more concentrated in the front face (middle and bottom regions) of the beam. The occurrence of a greater number of such hits may be due to discontinuous regions/internal voids/cavities. Increasing AE hits at the critical location is evidence of AE energy released during the interaction of acoustic waves with internal discontinuity. During field investigations, it was observed that prestressing tendons were yet to be placed in the front face at a similar location where a greater number of hits are recorded (see Fig. 3b). Wall dampness was also noticed in the front face. Though qualitatively, the high AE activities could be attributed to the local discontinuity.

4.2 AE Signal - Frequency Domain Analysis

Data acquired during experimentation was in the time domain (say function $f(t)$), so, Fourier analysis was used to visualize acoustic signals in the frequency domain, $F(\omega)$ as expressed in Eq. (2). Fast Fourier Transform (FFT) of a signal is a representation of its frequency versus amplitude. FFT of the acquired acoustic signals is calculated using the in-built algorithm with SAMOS AE system. The typical distribution of the peak frequency of AE signals is shown in Fig. 9. Through the observation, it can be found that the AE signals have several frequency-concentrated bands. Among them, the frequency concentration bands around $50\,kHz$ and $350\,kHz$ were obvious. These signals may reflect different characteristics of AE sources. The two frequency bands almost existed and were widely distributed in all phases of testing except in phase 1, where only a frequency band around $50\,kHz$ exists. This makes it difficult to find the characteristics of the signals for a source characterization. Further in-depth studies on laboratory scale model specimens are needed to arrive at the correlation between the AE source and the mechanism associated with it.

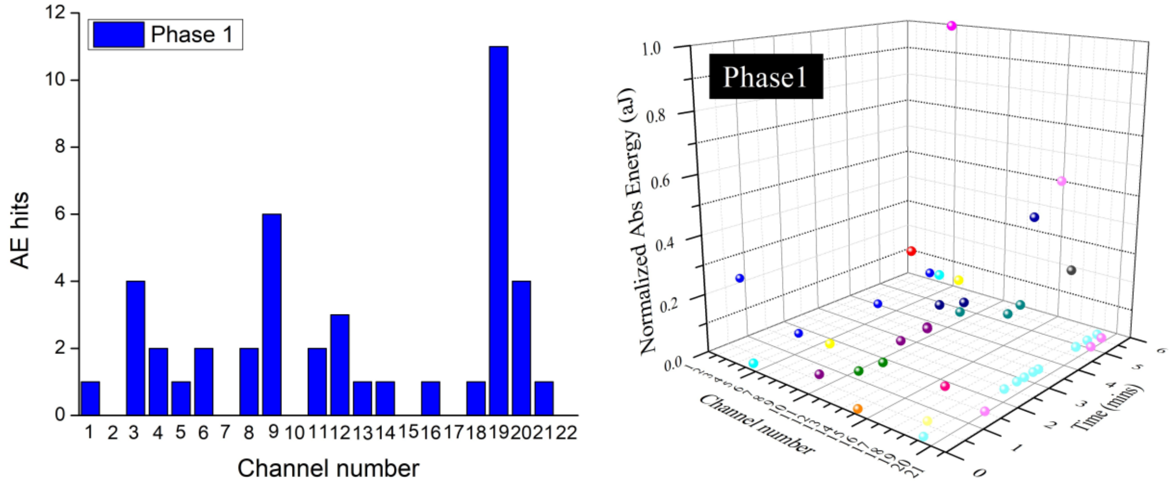
$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt \qquad (2)$$

4.3 AE Source Localization

With the help of multi-point AE technique and with the use of multi-sensors, the relative position of AE sources is determined. The 3D-Location algorithm, which is in-built with the AE-win software is used to locate the source position. The 3D-Location algorithm incorporates a "Smart Location Algorithm" to take advantage of the geometry of sensor placement as well as data from all the sensors that detected the event (up to 8), in calculating an accurate source. A minimum of 4 hits in an event is needed to determine and display a 3D location. The 3D location principle of an AE source assumes an AE source $s(x_i, y_i, z_i)$ to be in some medium, as illustrated in Fig. 10. The AE sensors are mounted on the structure with the coordinates of an arbitrary sensor $i(x_i, y_i, z_i)$. The distance d between the AE source s and sensor i can be expressed by Eq. (3)

$$d(s,i) = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2 + (z_s - z_i)^2} \qquad (3)$$

This equation provides the basis to obtain the solution of the analytic problems [31]. The 3D localization technique has been shown diagrammatically in Fig. 9. Readers are advised to see references [32-34] for detailed description about the AE source localization employed in the present study.



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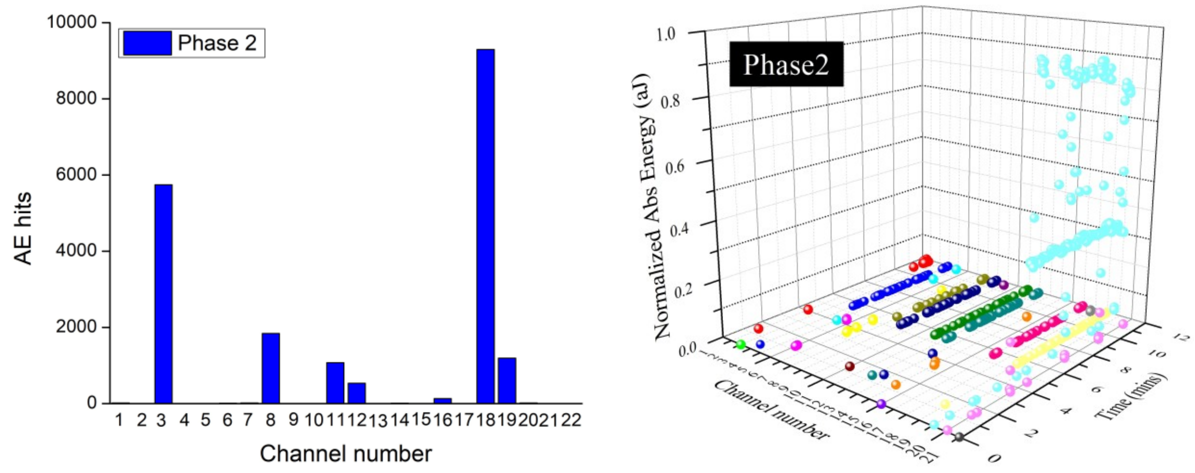

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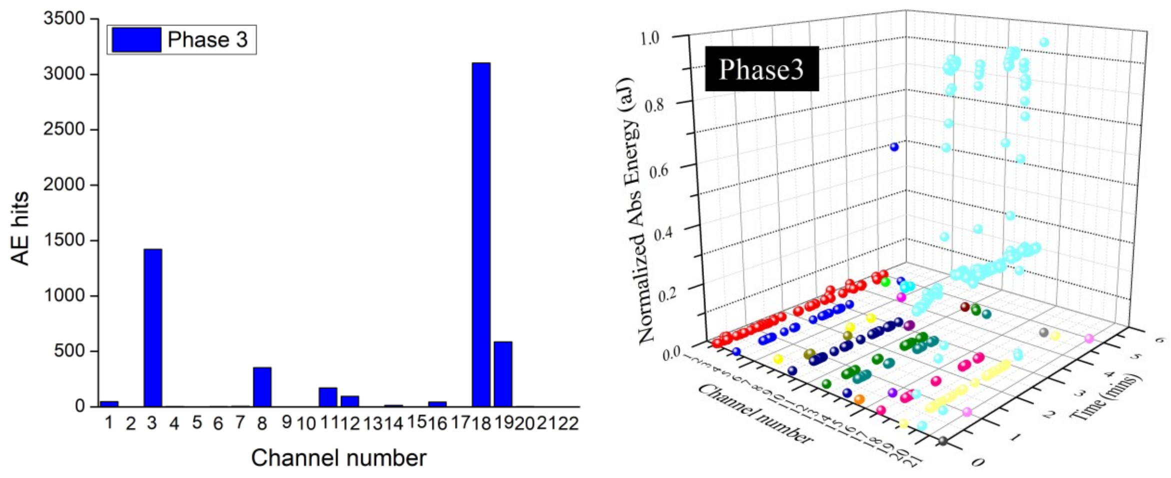

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Fig. 8. *AE features in time domain at different phases of testing*

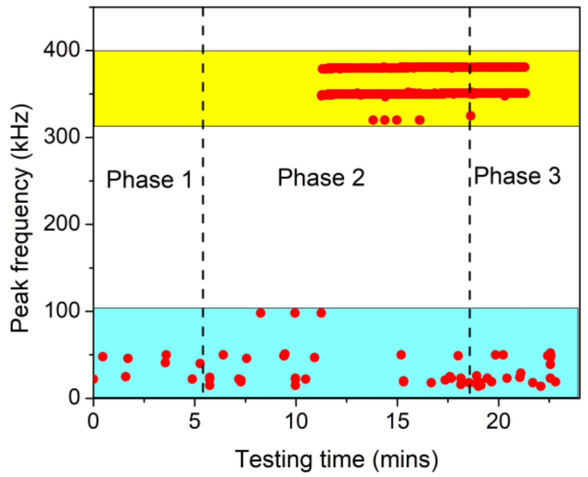


Fig. 9. *Typical distribution of the peak frequency of AE signals during testing*

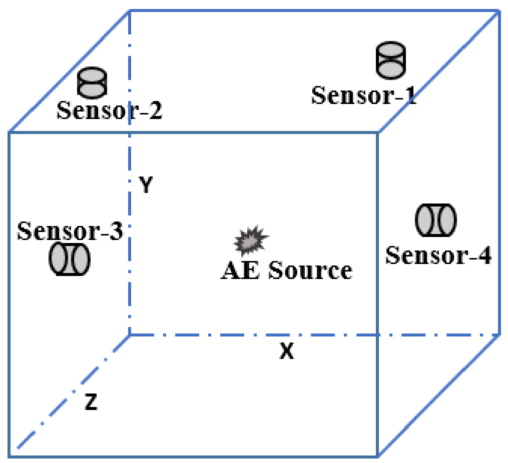
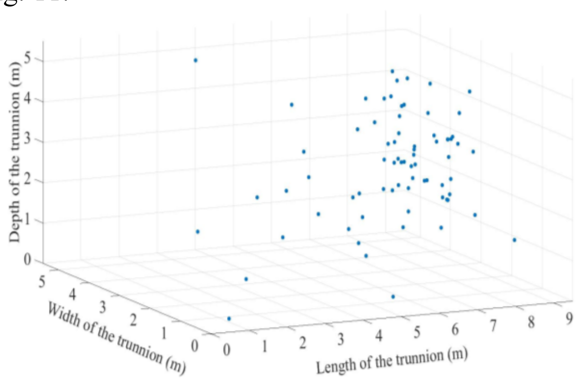
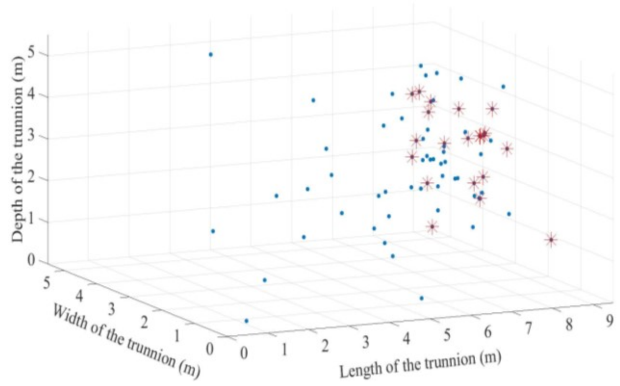


Fig. 10. *Localization of AE sources in 3-D structures*

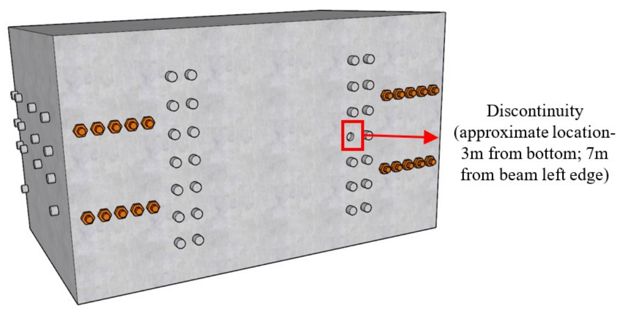
From the determined AE source positions, critical location is arrived/categorised based on the signal strength of AE events. For the investigated trunnion beam, critical locations are obtained and presented in Fig. 11.



(a) Localized AE sources



(b) Identified critical locations



(c) Front face of trunnion beam

Fig. 11. *Localization and critical zone mapping in trunnion beam*

The source of significant events is localized and plotted in Fig.11(a). Among these critical sources are highlighted in Fig.11(b). The critical sources, as approximately obtained from the acoustic source locations from the captured signals and acquired data, are based on the acquired acoustic signals (of different acoustic parameters) generated through gate operation/ambient conditions. The acoustic signal strength and acoustic parameters have an influence on structural configuration, gate operation and ambient conditions during field investigations. The information on locations provided here as sources may be treated as indicative. However, it is to mention here that, the testing being carried out during construction of dam, few prestressing tendons were yet to be placed and the inhomogeneity arises due to absence of prestressing tendons are well captured by the AE critical source localization (see Fig, 11(c)).

5. CONCLUSION

The present work has demonstrated the possible application of AE technique in assessing the health of heavily reinforced concrete dams. AE activities in the dam spillway pre-stressed concrete trunnion beam under ambient conditions (excitation due to water thrust on the dam), as well as the slow movement of the radial gates, were analysed in order to determine AE features towards assessing its health. The following conclusions may be drawn from this limited research work.

1. AE-based NDT technique presented can provide details on the health of the trunnion beam that a visual inspection alone cannot. Even conventional UPV testing failed to fully capture the discontinuity in a heavily reinforced structure along with prestressing steel tendons.
2. Increasing AE hits at the critical location is evidence of AE energy released during the interaction of acoustic waves with internal discontinuity.
3. From the frequency analysis based on peak frequency, it is observed that the frequency concentration bands around $50\,kHz$ and $350\,kHz$ are present.
4. The critical sources, as approximately obtained from the acoustic source locations from the captured signals and acquired data, are based on the acquired acoustic signals (of different acoustic parameters) generated through gate operation/ambient conditions.
5. Together, AE activity monitoring and critical source, provide a powerful first-hand tool that dam operators can employ to make sure the structures continue to operate securely.

The potential observations made from the present work are further extended, and extensive experimental works are being carried out to categorically bring out the frequency-based sensitive acoustic parameters that can be helpful to use as a tool to assess the health of heavily reinforced concrete dam structures.

6. ACKNOWLEDGEMENT

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