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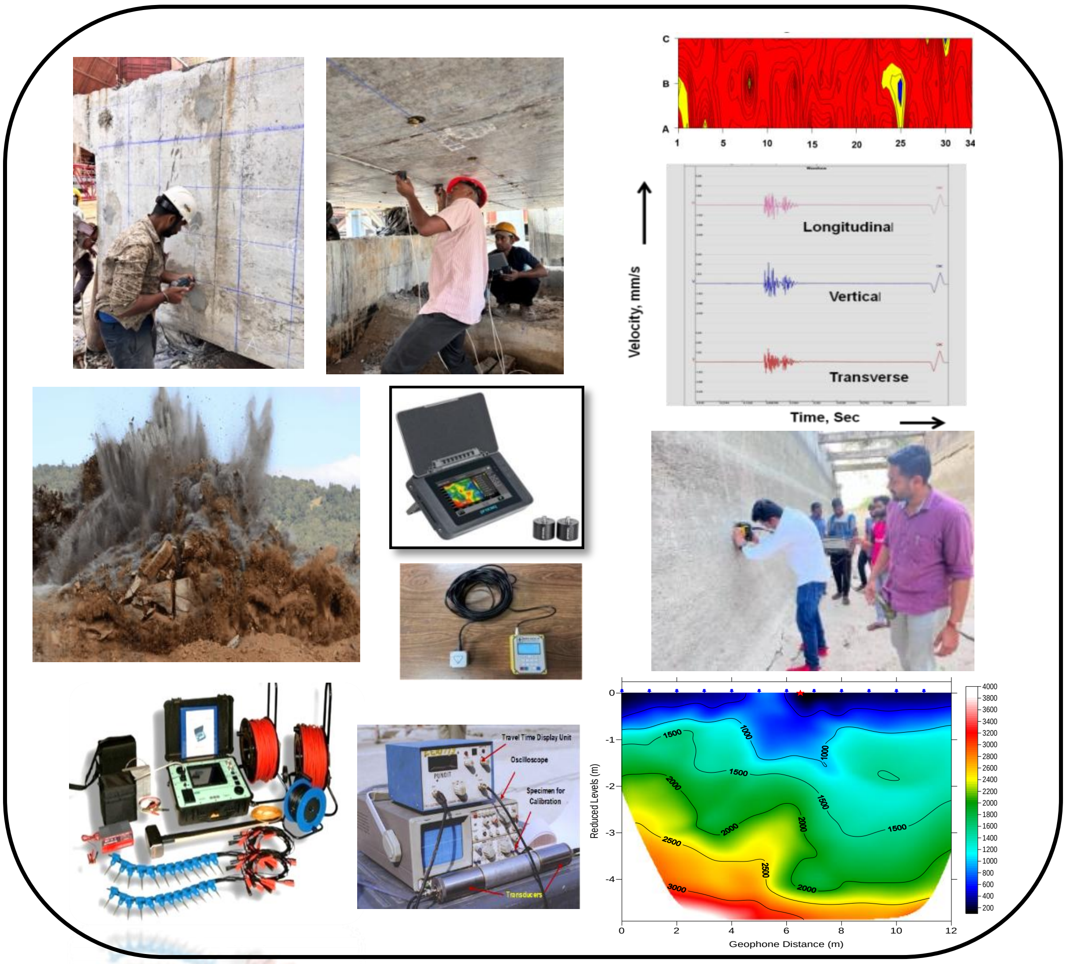
Government of India
Ministry of Jal Shakti
Department of Water Resources,
River Development and Ganga Rejuvenation



TECHNICAL MEMORANDUM
ON
QUALITATIVE ASSESSMENT OF CIVIL STRUCTURES

by
Dr M. Selva Balan, Additional Director
Dr. Prakash K. Palei, Scientist- D
Dr. Vijay Ghodake, Scientist- C

Dr. Prabhat Chandra
Director

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खड़कवासला, पुणे - 411024

CENTRAL WATER & POWER RESEARCH STATION
Khadakwasla, Pune – 411 024

September, 2025

सत्यमेव जयते

GOVERNMENT OF INDIA

MINISTRY OF JAL SHAKTI

DEPARTMENT OF WATER RESOURCES, RIVER DEVELOPMENT AND GANGA REJUVENATION

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VIBRATION TECHNOLOGY DIVISION

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PREFACE

With deep sense of pride, I present this Technical Memorandum on “Qualitative Assessment of Civil structures”. This document sums up the unique contribution of Vibration Technology Division of the Central Water and Power Research Station(CWPRS), Pune, in the field of Civil Engineering to provide substantial solutions through non-destructive testing and vibration monitoring studies, for massive civil structures like dams, hydro electric power plants, thermal power plants, bridges etc.

In the field of civil engineering, Non-Destructive Testing (NDT) have a wide range of inspection methods used to evaluate the condition and properties of materials and structures, without damaging them. These techniques are very safe, fast, cost-effective and efficient for qualitative assessment of properties of a structure, which makes them a very important tool for assessing the integrity, performance, and potential defects of various components, including concrete, steel etc., both during construction and after a structure is in service. Vibration Technology Division of the Central Power and Research Station, Pune has been actively engaged in providing project specific consultancy in the fields of Non- destructive testing for assessment of in-situ quality of massive civil structures such as, Dams, Power House, weir, aqueduct, barrages etc.

The Present technical memorandum has in its background the experience and expertise gained over the past several years by way of conducting numerous filed studies. This document can be considered as a concise handbook devoted solely for Qualitative Assessment of Civil structures by Non-Destructive Testing Methods and Vibration monitoring methods. It is expected to be useful for practicing engineers, students, researchers and for all those who are interested in knowing about any of the aspects related to evaluation of structural health of any civil structure.

Dr. Prabhat Chandra
Director

ACKNOWLEDGEMENTS

Vibration Technology Division has been actively engaged in providing project specific consultancy in the fields of Non- destructive testing for assessment of in-situ quality of massive civil structures such as, Dams, Power House, weir, aqueduct, barrages etc. Design of blasting pattern and monitoring of adverse effects of blasting operations during excavation of rock near important civil structures and vibration studies for assessment of structural safety of civil structures and power generation unit due to traffic and machine induced vibration is utmost importance. This division has provided research support to many important water resources projects, as well as Nuclear Power plants all over India.Using the state of the art technology, the division has successfully conducted more than 150 project specific studies till date.

Vibration Technology division regularly publishes various research papers, technical reports, book chapters in various peer reviewed journals and conferences. The members of this division are also part of various national committees such as Expert appraisal committee (EPC) for controlled blast studies, Bureau of Indian Standards (BIS).

Finally, the authors acknowledge the contribution of the retired members of this division. The authors are thankful to Shri Shabeer A. Lone, Scientist - B; Mrs. Varsha Jain, Assistant Research Officer; Shri Saurabh Anand, Research Assistant (Eng), Shri Rashid Ahmed, Research Assistant (Eng) & Shri Nikhil Tarde, LA-II for their timely support in preparation of this technical memorandum. Authors are also thankful to LIBIS division for extending help in providing technical references and printing of the document.

Additionally, sincere acknowledgments are extended to the project authorities comprising various state Govt. departments, PSUs, Private project authorities all over the country whose valuable inputs, insights, and cooperation have played a key role in successful completion of a variety of studies and projects. In particular, we express our sincere thanks to the CWC, New Delhi, NWA, MDL, JNPT, TATA Power, NHDC Ltd., SAIL,GSECL, WRD Maharashtra, OHPC Ltd., NPCIL, MAHAGENCO, TANGEDCO, BHEL, MeECL, JKSPDC, NHPC, WRD Gujarat, WRD MP, CIDC Ltd., and M/s WAPCOS Ltd., etc among others. Their assistance, partnership and constructive feedback have greatly enriched the quality of our work and ensured the field level applicability of the research outcomes.The memorandum would not have been a reality without their valued contribution.

Special thanks are also due to all our colleagues and support staff at CWPRS who, directly or indirectly, contributed their time, resources, and encouragement during the compilation of this work.

Last but not the least; the authors acknowledge the collective efforts of all stakeholders and institutions whose trust, knowledge-sharing, and commitment to scientific and technical excellence made this document a reality.

Executive Summary

Established in 1916, Central Water and Power Research Station (CWPRS), Pune has grown into a pivotal hub for innovation and consultation, pioneering safe and cost-effective designs for hydraulic structures critical to the efficient management of water resources, river engineering, Hydro power generation, coastal management. It also provides services for carrying out investigative studies towards repair and rehabilitation of hydraulic structures.

Vibration Technology (VT) Division, established in the 1950's, has been actively engaged in providing project specific consultancy in the fields of qualitative assessment of massive civil structures such as, Dams, Power House, weir, aqueduct, barrages etc. by using Non- destructive testing methods, design of blasting pattern and monitoring effects of blasting operations on safety of nearby structures during excavation of rockmass near important civil structures and vibration studies for assessment of structural safety of civil structures such as dams, barrages, powerhouse structures during traffic movement as well as operation of power generation units. This division has provided research support to many important water resources projects, as well as nuclear and thermal Power plants all over India. In the past several years, CWPRS has successfully carried out the above mentioned studies for more than 300 projects using the state of art technology. It has been also part of some of the landmark projects which are Sardar Sarovar Dam, Koyna Dam, Rengali HEP, Bhira HEP, Sani Dam, KRS Dam, Farakka Barrage, Umiam Dam, Kadana HEP, Rourkela Steel Plant; Rajasthan Atomic Power Plant, Ujjani Dam, Bhatghar HEP, Panshet HEP etc. The present technical memorandum has been prepared to share the experience and expertise gathered for "**Qualitative assessment of Civil Structures"**. Brief details of the topics covered in the memorandum are discussed below:

Chapter 1 "**INTRODUCTION**" discusses about the need for periodical monitoring of structural health of the structures for ensuring their safe operation as well as enhancement of their service life.

Chapter 2 "**QUALITATIVE ASSESSMENT BY NON-DESTRUCTIVE TESTING METHODS**" discusses about various techniques used for qualitative assessment of Civil structures. It also emphasizes on the selection of suitable NDT techniques based on the type of structure as well as the accessibility of the site conditions. It also addresses the use of combination of NDT techniques for strength estimation.

Chapter 3 “STRUCTURAL SAFETY ASSESSMENT THROUGH VIBRATION MONITORING” describes in detail about the methodology of vibration monitoring for structural safety assessment of civil structures as well as generation units in a Hydropower station. In addition to this, monitoring of blast induced vibration on nearby structures during expansion of existing projects has also been discussed.

Chapter 4 “QUALITATIVE ASSESSMENT OF CIVIL STRUCTURES BY NDT METHODS: CASE STUDIES” describes important case studies handled by CWPRS for qualitative assessment of civil structures. The impact of the study being carried out has also been highlighted regarding structural safety assessment of Barrages and Powerhouses from induced vibrations

Chapter 5 “CONCLUSIONS AND RECOMMENDATIONS” discusses about the overall conclusions drawn by carrying out NDT and vibration studies for assessment of various types of civil structures. Based on the experience gathered by conducting studies for several projects all over India, guidelines are framed for bringing out methodology for health monitoring of civil structures.

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CHAPTER 1
INTRODUCTION

1.1 General

India has over 6000 dams and more than 3000 power plants as the sources of power generation. Most of the existing dams and power houses are more than 40 years old. Due to ageing effect and old technologies employed in the construction of the structure during that period and exposures to frequent earthquakes, distress in various forms such as cracks, large deformations, seepage, bulging of faces of dams and galleries, loss of mortar in joints of masonry dams and dislodging of concrete from faces etc. have been observed. Due to these distresses, their conditions have become scary and have created apprehensions about their structural safety. Hence, evaluation and assessment of the present condition of the existing structures become more and more important for deciding strengthening measures. For qualitative assessment of these distressed structures, non-destructive technique is very effective and reliable tool to estimate the structural integrity of these distressed structures before deciding upon the requirements of remedial measures.

1.2 Importance of Non-Destructive Testing (NDT)

Non-destructive testing (NDT) methods have been extensively employed in qualitative assessment of various civil structures due to their reliability and effectiveness in assessing the overall quality of a structure. NDT methods are regarded as potent techniques for assessing the strength and durability of existing concrete structures. It is frequently required to evaluate concrete structures once the concrete has fully solidified to ascertain whether the structure is appropriate for its intended purpose.

Ideally, the testing should be conducted without causing any harm to the concrete. The range of tests available for concrete testing includes non-destructive tests that do not cause any damage to the concrete, as well as slightly damaging tests like core tests and partially destructive tests. Pullout and pull off tests, where the surface needs to be fixed after the test is completed. Properties that can be evaluated using non-destructive tests and partially destructive tests are Mass Density, Elastic Modulus, Strength, Surface Hardness, Surface Absorption, and reinforcement location, size, and distance from the surface. In certain cases, it is also feasible to assess the quality by Non-destructive testing which can be applicable on both existing as well as newly constructed structures. While constructing new buildings, the primary uses of NDT are for quality control and also for addressing uncertainties regarding the quality of materials. The evaluation of existing structures is typically associated with determining their structural integrity. In either scenario, if destructive testing is the sole method employed, such as by extracting cores for compression testing, the expenses associated with coring and testing may only permit a limited number of tests to be conducted on a massive structure like Dam, Aqueduct, powerhouse, barrage etc., the results obtained may sometimes be misleading. Under these circumstances, Non-destructive testing can be used as a preliminary step before proceeding with core sampling.

Typical situations where non-destructive testing can be effectively used are as follows:

- In-situ quality assessment of concrete in old and new structures
- Removing uncertainties about the quality of concrete used during construction
- Confirming or negating doubt concerning the workmanship involved in batching,
- Monitoring of strength development
- Determination of the extent of cracks, voids, honeycombing and similar Defects within a concrete structure
- Determining concrete uniformity
- Determining the position, quantity or condition of reinforcement

Central Water and Power research Station, Pune established in the year 1916 has been undertaking studies for qualitative assessment of various types of Civil structures using suitable NDT methods. Many projects have been inspected by the scientists of CWPRS in the past and some of the cases where distresses have been prominently observed are presented below.

Damages in Wall, Piers, Breast and Divide Walls of Rihand Dam, UP

Cracks Observed in the Penstock Gallery Columns

Cracks Observed in Pier

Dampness and Seepage Observed in the Renagli Power House, Odisha

As these structures are of national interest, hence strengthening of these structures is required to be carried out for restoring their integrity. Before undertaking the repair work, qualitative assessment is required to be conducted by using suitable NDT methods. Mostly Non-destructive testing (NDT) methods such as Rebound hammer, Ultrasonic pulse transmission technique, Sonic wave transmission technique, Impact Echo test method, Resonance frequency test method etc. have been used for detection of anomalies and qualitative assessment of structural safety of various types of civil structures such as dams, power house, aqueducts, turbo generation foundations, bridges, barrages, historical monuments, etc.. These methods are being used at CWPRS for more than three decades for evaluating the condition of a structure.

Virtually all structures exposed to nature experience deterioration over time due to fire, earthquake, alkali aggregate reaction, flood, manmade disasters, ageing etc. Inspection personnel face lots of difficulty in determining the in-situ quality of concrete/masonry part of the structure that has experienced decay in absence of direct sampling of material from the structure. The disadvantage of material sampling is that an inspector must remove a portion of the structure, usually by means of coring. Removing cores from a concrete structure is an invasive process that can weaken the structure and which may lead to long-term stability concern particularly in RCC structures. Therefore, such invasive methods are not advisable to carry out on the RCC structures. Moreover, testing of cores may give information for a limited zone of the structure which may not represent the health status of the whole structure. In such scenario, completely non-invasive NDT methods have been playing an important role for assessing the overall quality of the structure. The main objective of non-destructive testing (NDT) is to obtain in-situ material properties of structure without damaging it. It gives several information about the integrity of the structure such as homogeneity, Young's Modulus of Elasticity, Modulus of Rigidity, Poisson's ratio, location of defects etc. NDT methods can be used to test the quality of a newly manufactured part, or to test the service conditions of a part already in use, and also to decide the remedial measures to be undertaken to improve the structural integrity of distressed structures. Therefore, it is a tool which has been successfully used not only in quality control, but in failure prediction and analysis also. NDT can be of immense help by reducing the risk involved and consequently can build confidence in the structural engineer. In the present memorandum, major NDT methods applied for qualitative assessment of various types of civil structures are discussed and illustrated with the help of some important case studies.

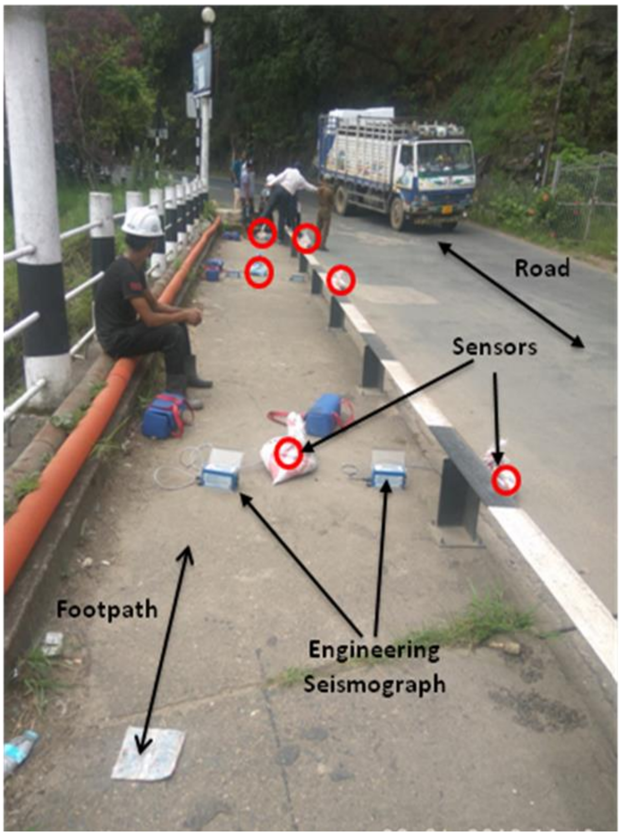
1.3 Safety Assessment of Civil Structures against Induced Vibration

During strengthening of old dams, barrages, etc. and expansion activities, deep excavations are required to be carried out in the close vicinity of existing hydraulic structures. During this process, excavation of hard rock is required to be carried out by using blasting operations as it is one of the most economical, efficient and time saving method for deep excavation of hard rock materials.

Excavation near Barrage in Progress

In the process of blasting, the energy released due to the detonation of explosives is utilized for fragmentation of rock. However, during explosion ground vibrations are generated which has the potential to cause damage to the existing nearby structures. Therefore, for ensuring safety of these structures, the blasting pattern is designed in such a way that the resulting vibration must be kept within the safe limit. Qualitative assessment of the nearby structures before and after the blasting operation is carried out for assessing their integrity.

In several cases it has been observed that the structures are subjected to vibrations due to operation of generation units in a power house as well as the traffic induced vibration on barrages and bridges.



Vibration Studies for Powerhouse and Road Bridge in Progress

If these vibration issues are not addressed before time, it may endanger the safety of the structures. Therefore, structural safety assessments of these structures are being carried out by continuously monitoring vibration levels under different conditions of traffic as well as generation. Based on the results obtained, remedial measures are taken towards strengthening of the structure.

In the present technical memorandum, usefulness of NDT and vibration monitoring methods for qualitative assessment of various types of civil structures have been discussed and illustrated with the help of some important case studies.

CHAPTER 2

QUALITATIVE ASSESSMENT BY NON-DESTRUCTIVE TESTING METHODS

Non-destructive Testing Methods

Non-destructive testing (NDT) is pivotal in qualitatively evaluating civil engineering structures, as it involves inspecting, monitoring, and assessing their strength without causing damage. This method is notably safe, fast, economical and efficient for material property assessment. NDT techniques are based on linking specific physical and chemical properties to the strength and resilience of structures. With a noticeable surge in civil engineering construction in recent years, testing and quality verification at various stages of a structure’s lifespan are essential for maintaining its safety. The quality of concrete in a structure is dependent on several factors such as cement type, type of aggregates, water to cement ratio, curing, environmental conditions etc. Besides this, the control exercised during construction also contributes a lot to achieve the desired quality.

The choice of a particular NDT method depends upon the property of concrete to be observed such as strength, corrosion, crack monitoring etc. The subsequent testing of structure will largely depend upon the results of preliminary testing done with the appropriate NDT technique.

Purpose of Non-destructive Tests

The non-destructive evaluation techniques are being increasingly adopted in various types of civil structures for the following purposes:

(i) Estimating the in-situ compressive strength

(ii) Estimating the uniformity and homogeneity

(iii) Estimating the quality in relation to standard requirement.

(iv) Identifying areas of lower integrity in comparison to other parts.

(v) Detection of presence of cracks, voids and other imperfections.

(vi) Monitoring changes in the structure of the concrete which may occur with time.

(vii) Identification of reinforcement profile and measurement of concrete cover, bar diameter, etc.

Several NDT techniques have been developed and are used for examining and assessing various aspects related to concrete's strength, durability, and overall quality. Every method possesses its own merits and demerits. Consequently, a wise strategy would be to employ multiple methods in tandem, ensuring that the strengths of one compensate the weaknesses of another.

The various NDT methods for testing different types of civil structures are mentioned below:

A. For Strength Estimation of Concrete

(i) Visual inspection

(ii)Rebound hammer test

(iii) Ultrasonic Pulse Velocity Test

(iv) Penetration Resistance Test (Windsor Probe)

(v) Permeability Test

(vi) Bond Test

B. For Corrosion Assessment of Reinforcement in Civil Structures

(i) Resistively Meter

(ii) Half Cell Potentiometer

(iii) Carbonation depth measurement test

(iv) Test for Chloride Content of Concrete

C. For Detection of Cracks/Voids/ Delamination etc.

(i) Infrared Thermographic Technique

(ii) Acoustic Emission Techniques

(iii) Short Pulse Radar Methods

(iv) Stress Wave Propagation Methods

(v) Crack Detection Microscope

(vi) Structural Scanning Equipment

(vii) Spectral Analysis of Surface Waves for Unknown Foundation

Some of the above mentioned methods have been discussed in detail in this technical memorandum.

2.1 Visual Inspection

Visual inspection testing method is one of the most crucial methods among all non-destructive testing evaluations, offering invaluable insights during the examination of a structure. The visual aspects of a structure can reveal important information about workmanship involved, the structure's functionality, and signs of material wear and tear. It is vital for engineers to discern various distress indicators they may observe, such as cracks, pop-outs, spalling, disintegration, changes in color, weathering effects, staining, surface imperfections, and lack of uniformity. These observations from visual inspections provide valuable information about the integrity of the structure which enables to take decision of using appropriate testing methods for detailed assessment of its health.

The scope of visual inspection must extend beyond the structure under investigation, encompassing adjacent structures, the surrounding environment, and prevailing climatic conditions. This comprehensive approach is crucial, despite being arguably the most challenging aspect of structural investigation or diagnostic procedures, due to the subjective nature of observations where what seems evident to one may not be perceived similarly by another. The significance and advantages of a thorough visual survey must be acknowledged, as neglecting seemingly trivial details can result in incorrect conclusions.

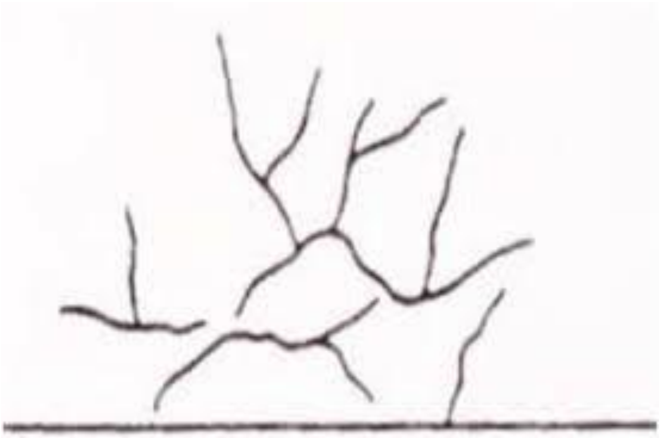
Before conducting any visual examination, the engineer is obliged to thoroughly review all pertinent structural drawings, plans, and elevations to gain a comprehensive understanding of the structure. Furthermore, available documents such as technical specifications, historical test or inspection reports, construction records, details of materials utilized, methods, and dates of construction must be meticulously examined. The survey ought to be performed in a systematic manner, encompassing existing defects, both previous and current usage of the structure, the state of neighboring structures, and prevailing environmental conditions. It is imperative that all defects are accurately identified and their severity assessed, akin to the classifications used for fire-damaged concrete, while endeavoring to ascertain their underlying causes whenever feasible. The distribution and scope of the defects must be clearly recognized and precisely documented. For instance, it is crucial to ascertain whether the defects occur sporadically or follow a distinct pattern, and whether they are restricted to specific areas of the components or are widespread throughout the structure. Conducting a visual comparison among similar components is essential as a preliminary step before testing, aiming to estimate the severity of the issues in these situations. Examining analogous structures or others within the vicinity that are built using similar materials can offer valuable 'case study' evidence, notably if these other structures differ in age from the structure under examination. It is imperative to identify any related or accompanying defects, with particular emphasis on determining which defect is most prevalent.

As the inspection advances, it is imperative to meticulously document all observations. This includes the careful annotation of drawings, which may be marked, colored, or shaded to effectively represent the local severity of each feature. Commonly, defects requiring thorough documentation include the following:

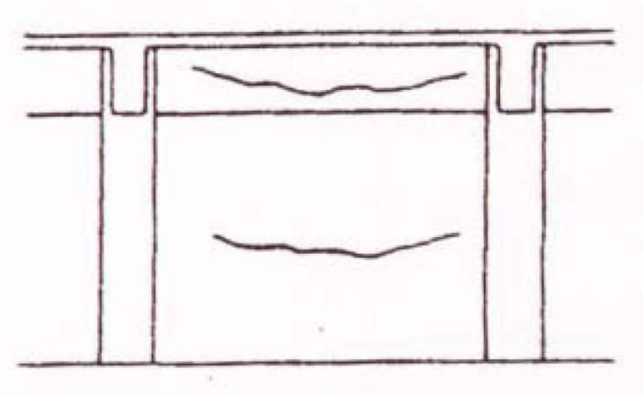
- surface pitting and spalling
- surface staining
- differential movements or displacements
- variation in algal or vegetative growths
- surface voids

- honeycombing
- bleed marks
- constructional and lift joints

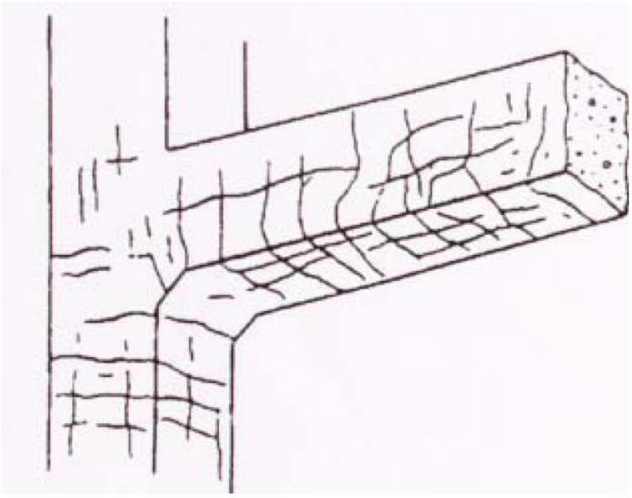
Classification of the degree of damage or condition requires experience and engineering Judgment. Typical defects which are seen in the concrete structures are shown below.




Appearance of Surface Cracks in Concrete



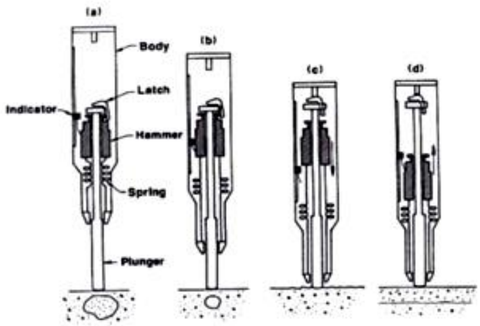

Appearance of Cracks in Concrete due to Settlement




Fire effects on Concrete column

2.2 Rebound Hammer Test (Schmidt Hammer)

In 1948, a test hammer for measuring the hardness of concrete was developed by Ernst Schmidt, a Swiss Engineer. This instrument is a handy non-destructive testing instrument which is easy to operate and can produce fairly accurate result from the estimated average of a number of tests conducted on the same location of the surface of the structure. There is a theoretical relationship between the strength of concrete and the rebound number of the hammer. However, within limits, empirical correlations have been established between strength properties and the rebound number. The test can be conducted by following the guidelines mentioned in IS: 13311 (part 2): 1992 and ASTM: C 805-02. It works on the principle that, the rebound of an elastic mass, depends on the hardness of the surface against which, the mass impinges.



Digital Rebound Hammer Instrument (Make: Proceq., USA), N -Type

Operating principle of Rebound Hammer

With the hammer pushed hard against the concrete surface, the body is allowed to move away from the concrete until the latch connects the hammer mass to the plunger. The plunger is then held perpendicular to the concrete surface and the body pushed towards the concrete. This movement extends the spring holding the mass to the body. When the maximum extension of the spring is reached, the latch releases and the mass is pulled towards the surface by the spring. The mass hits the shoulder of the plunger rod and rebounds as the rod is pushed hard against the concrete. During rebound the slide indicator travels with the hammer mass and stops at the maximum distance the mass reaches after rebounding. The rebound number is displayed digitally. The rebound number depends on the strength of the member under test. Higher rebound number indicates high strength of the member under test.

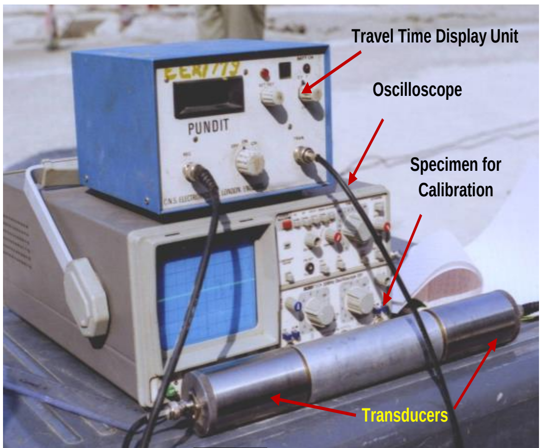
As such no criterion is available which discusses about the standard rebound number values for classifying the quality of concrete and hardness of the surface. However, based on the experience gained by conducting large number of studies by CWPRS for different grades of concrete by using rebound hammer test and following the available published literature in the field, the following Rebound Number criteria as presented in the Table has been adopted for classifying the quality of concrete.

Rebound Hammer Test Criteria

Sr. No.	Average rebound number	Quality of concrete
1.	>40	Very Good hard layer
2.	30 to 40	Good layer
3.	20 to 30	Fair
4.	< 20	Poor concrete

2.3 Ultrasonic Pulse Transmission Technique

Waves with frequencies more than 20 kHz are above the audible range and are termed as "ultrasonic" waves mostly used for testing of relatively homogeneous structures like concrete, metal and rock samples. Non-destructive testing by transmission of ultrasonic waves is a widely used method to assess the in-situ quality of the material of various hydraulic and civil structures. The method is based on the principle that the propagation velocity of elastic (mechanical) waves through a specimen of the structural member is related to parameters such as density, porosity, degree of saturation etc. and is independent of the shape and size of the structural member. Thus, the propagation velocity of elastic wave gives an indication of the quality and homogeneity of the material in the direction of wave transmission.



(a

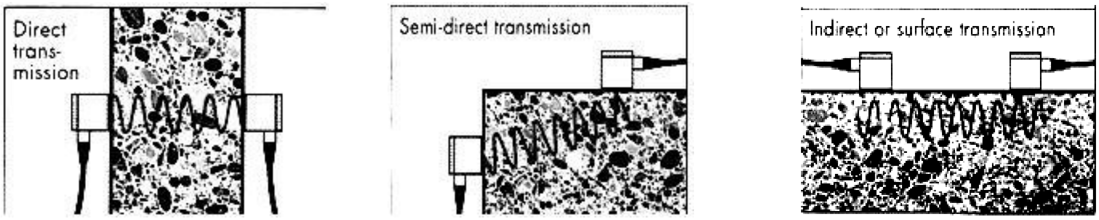
(b

Portable Ultrasonic Tester (a) PUNDIT from M/s CNS electronics, U.K. and (b) PUNDIT PL 200 (SA, Switzerland)

Ultrasonic instruments are basically designed to measure accurately the travel-times of ultrasonic pulses through elastic solid medium under test. Photographs of the Portable

Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) from M/s CNS electronics, U.K. and Concrete Ultrasonic Testing Equipment PUNDIT PI 200 (SA, Switzerland) Instruments with 54 kHz transmitting and receiving transducers are shown as above. The instrument mainly consists of an electronic control unit to display the transit time in microsecond (μ-sec.) and two transducers, one to transmit and the other to receive the ultrasonic pulses. Both transducers are to be held firmly on opposite surfaces of the concrete mass with the help of a suitable couplant (silicon grease). An electronic timer device provided in the main instrument measures the transit time between the onset and the received pulses and displays it digitally in terms of microseconds.

The path travelled by the waves after getting damped due to the medium through which it passes can also be viewed on an oscilloscope display, amplitude of which can be used to assess, the relative amount of energy of elastic waves available at the receiving transducer. There are three possible ways in which transducers can be arranged viz. Direct transmission arrangements, Semi-direct transmission arrangements and Indirect or surface transmission arrangements as shown below.



Where opposite faces are accessible | Where opposite faces are not accessible | Where only one surface is accessible

For Column like Structure | **Wall and Beam Structure**

Schematic diagram showing various arrangements for Transducer placement

UPV test is carried out by following the guidelines mentioned in IS-516(Part 5/Sec 1):2018. The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks and segregation, etc, indicative of the level of workmanship employed; can be assessed using the guidelines given in IS-516(Part 5/Sec 1):2018 as shown in Table 1, which have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.

Table: Velocity Criteria for concrete quality grading (IS 516: (Part 5/Sec 1):2018)

Sl. No.	Velocity, km/s	Concrete Quality Grading
1.	Above 4.40	Excellent
2.	3.75 to 4.40	Good
3.	3.00 to 3.75	Doubtful
4.	Below 3.0	Poor

2.4 Sonic Wave Pulse Transmission Method

Sonic waves (50 Hz – 200 Hz) are generated by mild impact of a hammer on the surface of the structure. By measuring the travel times of these waves along different travel paths through a structure, sonic wave velocities are evaluated. This method is used to evaluate in-situ quality of massive concrete and masonry structures and to detect the weak portion in a structure as the ultrasonic waves cannot penetrate a thickness of more than five meters in an inhomogeneous material.

Sonic waves are generated by mild impact of a hammer on the surface of the structure. By generating elastic waves and detecting the arrival of compressional wave, velocities after travelling through the material are evaluated. Quality of concrete is assessed based on the velocity criteria mentioned in IS-516(Part 5/Sec 1):2018.

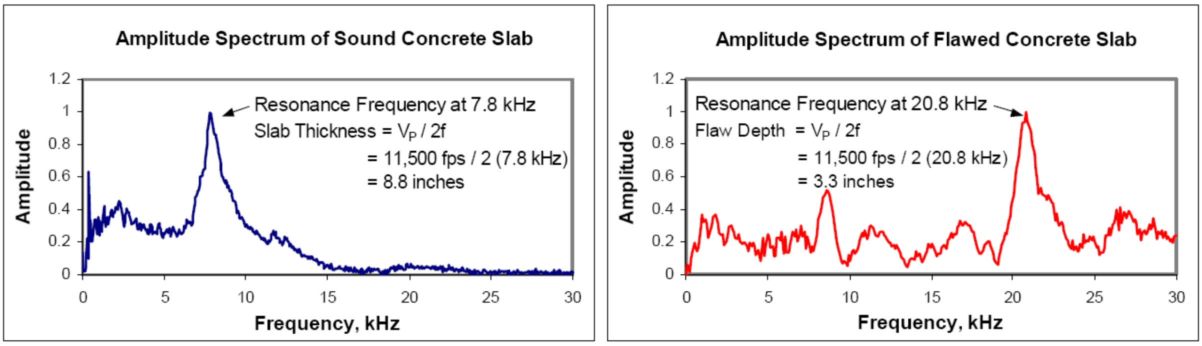
Sonic wave transmission and refraction survey set up (M/s PASI, Italy)

2.5 Impact Echo Test Method

Impact Echo is a method for non-destructive evaluation of concrete and masonry. It is based on the use of impact-generated compression waves that travel through the structure and are reflected by internal flaws and external surfaces. The test is being carried out by following the guidelines mentioned in ASTM C 1383: 98a. Impact Echo method can be used to measure the thickness of slabs, plates, columns and beams, and hollow cylinders. It can also be used to determine the location and extent of flaws such as cracks, delaminations, voids, honeycombing and de-bonding in plain, reinforced and post-tensioned concrete structures. Voids in the sub-grade directly beneath slabs and pavements are easily detected through Impact Echo testing. Photograph of the impact echo test set up is shown in below Fig. Impact Echo testing consists of measuring both the time record and frequency spectrum associated with a mechanical impact on the surface of a structure. As stress waves propagate through the structure, they reflect off internal and external boundaries and. cause periodic displacements on the surface.

Impact Echo Test Set Up

These motions are monitored by a transducer and digitized. The waveform is transformed into the frequency domain, so that the periodicity of stress-wave arrivals can be accurately determined. As part of Impact Echo testing, direct measurements of compression (P-) wave velocity are also made. Given the P-wave velocity and the arrival period (or frequency), the depths to internal flaws or external boundaries are calculated.



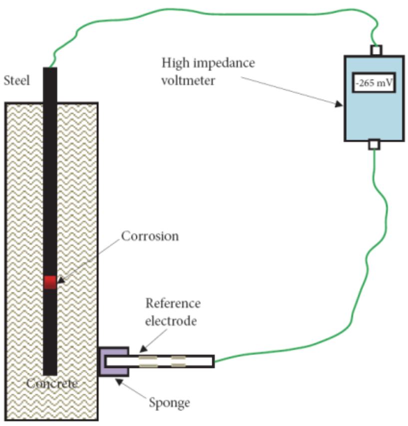
Amplitude Spectrum Obtained on Sound and Defective Concrete

Impact Echo testing has many applications, including:

- Quality control programs, such as measuring pavement thickness or assessing pile integrity
- Routine maintenance evaluations to detect cracks, voids, or delaminations in concrete slab

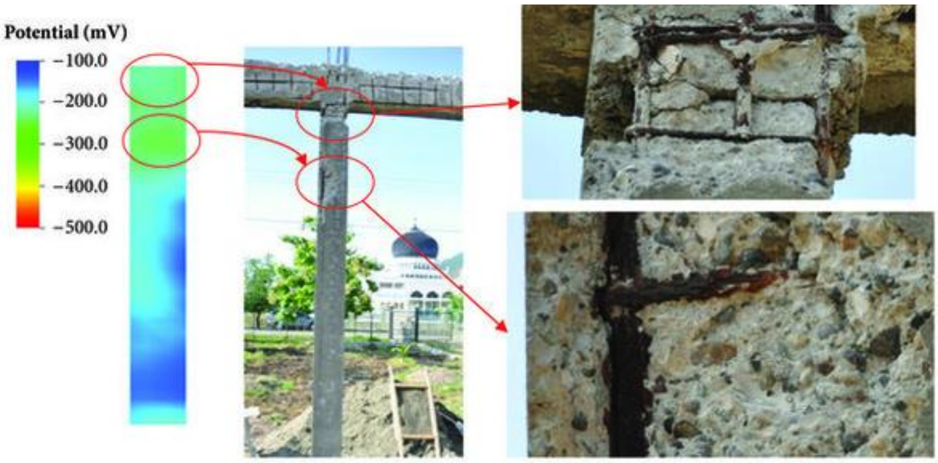
2.6 Half-Cell Electrical Potential Method

The half-cell electrical potential method is a crucial technique extensively utilized for assessing and monitoring the corrosion state of reinforced concrete structures. This method entails measuring the electrical potential of an embedded reinforcing bar against a reference half-cell positioned on the concrete surface. Typically, the half-cell used is either a copper/copper sulfate or silver/silver chloride cell.



Schematic Diagram of the Corrosion Test Set Up

Corrosion is a natural process which occurs when the structure is exposed to CO_2 or chloride, which penetrates through the concrete surface all the way to the steel reinforcement. This can have serious durability and safety consequences; hence it is very much important to monitor corrosion using an accurate and reliable method. The half-cell potential test is the only corrosion monitoring technique standardized in ASTM C876 – 15: Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. Schematic diagram of the corrosion test set up is shown here.



Comparison of Half-Cell Potential Result to the Actual Corrosion

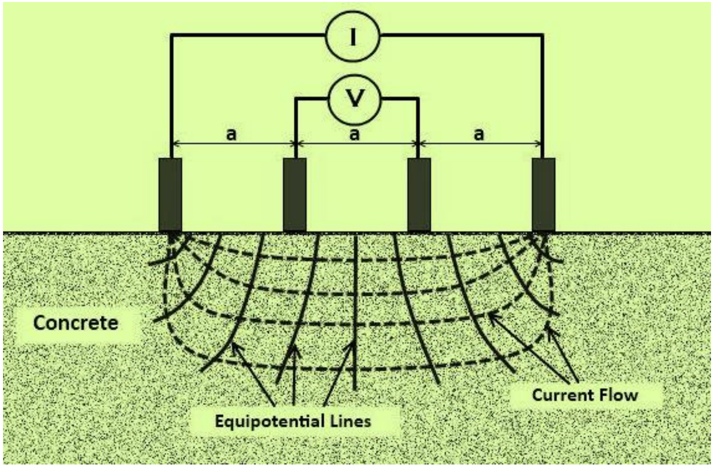
The potential risks of corrosion probability of the reinforcement can be assessed based on potential difference readings obtained by comparing with the values mentioned in the following Table.

Table: Criteria for Corrosion Risk Levels with Referring to ASTM C876

No	Reference Electrode (mV)				Corrosion risk level
	$Cu/CuSO_4$	Ag/AgCl	Standard Hydrogen	Calomel	
1	> (-200)	> (-100)	> (+120)	> (-80)	Low (10% risk of corrosion)
2	(-200)– (-350)	(-100)– (-250)	(+120) – (-30)	(-80) – (-230)	Intermediate corrosion risk
3	< (-350)	< (-250)	< (-30)	< (-230)	High (>90% risk of corrosion)
4	< (-500)	< (-400)	< (-180)	< (-380)	Severe corrosion

2.7 Resistivity Measurement

Evaluating the corrosion risk of steel within concrete structures involves various technical approaches, with the most widely adopted method being the half-cell potential measurement. This technique is instrumental in identifying areas where corrosion activity is present, yet it falls short in offering any insights into the actual rate of corrosion progression. Resistivity measurement is a fast, simple and cheap in situ non-destructive method to obtain information related to the corrosion hazard of embedded reinforcement. This approach provides vital information concerning the corrosion threats to embedded reinforcement, emphasizing the importance of employing comprehensive strategies in assessing structural integrity.



Schematic of Wenner 4 Probe Resistivity Meter

Resistivity measurements determine the current levels flowing between anodic and cathodic portions, or the concrete conductivity over the test area, and are usually used in conjunction with the half-cell potential technique.

Resistivity set up consists of four electrodes (two outer current probes and two inner voltage probes) which are placed in a straight line on or just below the concrete surface at equal spacings. A low frequency alternating electrical current is passed between the two outer electrodes whilst the voltage drop between the inner electrodes is measured. The apparent resistivity (ρ) in “ohm-cm” may be evaluated as follows:

$$\rho = 2\pi a \frac{V}{I}$$

Where,

V is voltage drop,

I is applied current,

a is electrode spacing.

The calculation assumes the concrete to be homogeneous and the inhomogeneity caused by the reinforcement network must be allowed for by properly placing the probes to minimize its effect.

There are no generally accepted rules relating resistivity to corrosion rate. However, a commonly used guide has been suggested for the interpretation of measurements of the likelihood of significant corrosion for non-saturated concrete where the steel is activated.

Table: Guide for Interpretation of the Measurements during Corrosion Assessment

Resistivity (ohm cm)	Likely Corrosion Rate
Less than 5,000	Very high
5,000 – 10,000	High
10,000 – 20,000	Low / Moderate
Greater than 20,000	Negligible

2.8 Carbonation Depth Measurement

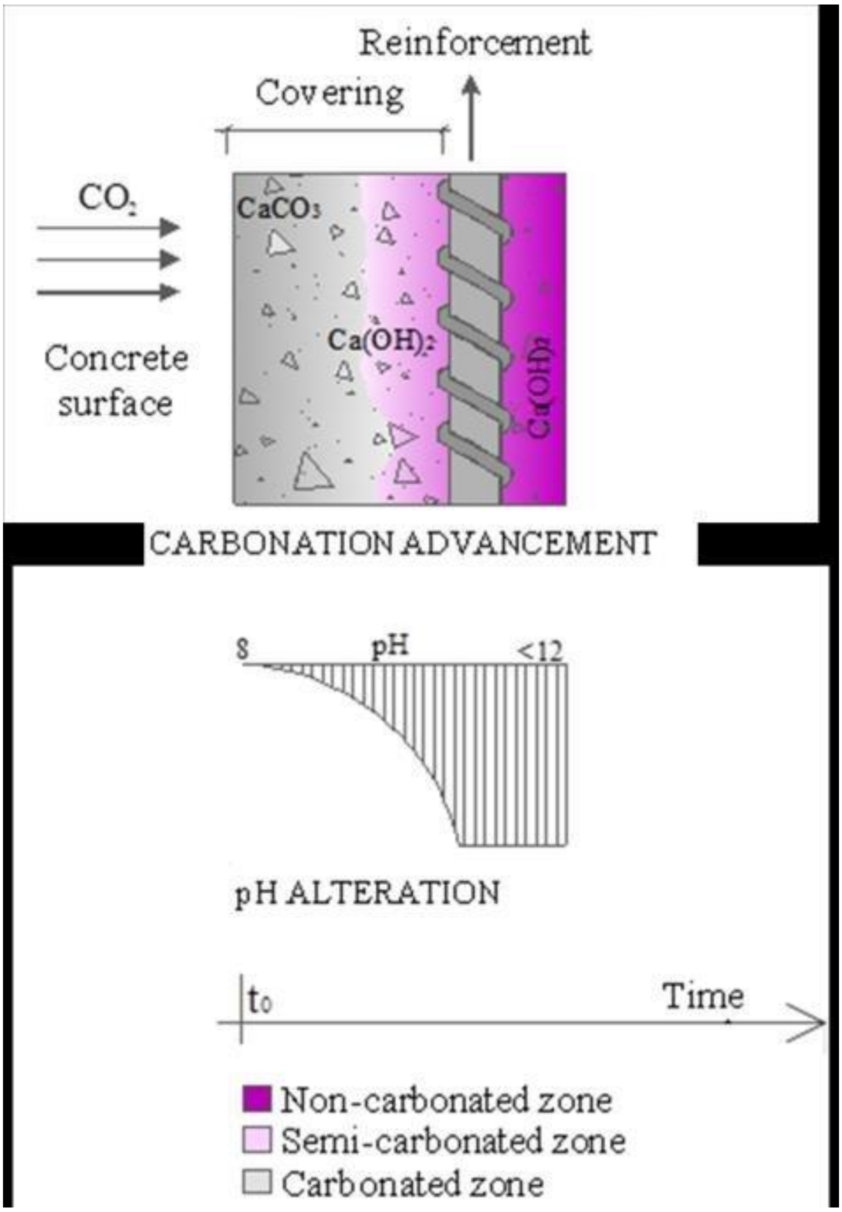
Concrete carbonation happens when atmospheric carbon dioxide, combined with moisture, reacts with the minerals in hydrated cement to form carbonates like calcium carbonate. This process, known as depassivation, gradually infiltrates beneath the concrete's exposed surface at a very slow rate. The time required for carbonation can be estimated knowing the concrete grade and using the following equation:

$$t = (\frac{d}{k})^2$$

where
t is the time for carbonation,
d is the concrete cover,
k is the permeability.

The significance of carbonation is that the usual protection of the reinforcing steel generally present in concrete due to the alkaline conditions caused by hydrated cement paste is neutralized by carbonation. Thus, if the entire concrete cover over the reinforcing steel is carbonated, corrosion of the steel would occur if moisture and oxygen could reach the steel.
Extent of carbonation can be determined easily by spraying a freshly exposed surface of the concrete with a 1% phenolphthalein solution. The calcium hydroxide is coloured pink while the carbonated portion is uncoloured.

If the concrete still retains its alkaline characteristic the colour of the concrete will change to purple. If carbonation has taken place the pH will have changed to 7 (i.e. neutral condition) and there will be no colour change.

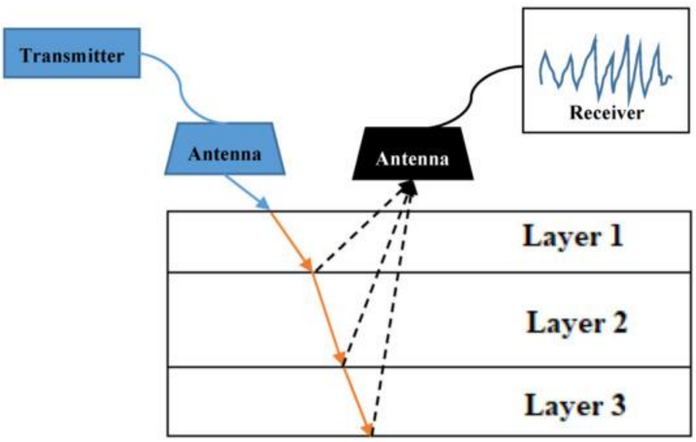


Representation showing the advance of carbonation and Ph change in concrete over time

2.9 Ground Penetrating Radar

Ground-penetrating radar (GPR) is one of the most used electromagnetic (EM) wave-based techniques in civil engineering owing to the non-invasive, low costs, and rapid monitoring nature of the technique. GPR is used for the evaluation of the stability of concrete and masonry structures, maintenance of the structures, and structural health monitoring of infrastructure. In addition, the GPR technique is used to inspect the asphalt pavements in order to detect voids, fractures, or other types of defects.

The working principle of the GPR technique is the use of the microwave region of the EM spectrum that employs a transmitter and a receiver (antennas) to send and capture the reflected wave. Radiated short pulses of high-frequency EM energy are generated by pulse mode GPR systems that penetrate through an object via a transmitting antenna and then detected by a receiver. Various frequencies are used depending on the requirement of the measurement, namely resolution versus penetration depth, i.e., the higher the operating frequency, the higher the resolution, and the lower the penetration depth of the system. To maintain the accuracy of the GPR systems, they must be calibrated with a core sample of the tested material. The measured signal is amplified, processed, and analyzed based on the altered signal, i.e., the transmitted energy is partially absorbed and transmitted by the material under investigation, and the rest is reflected and captured by the system. The changes in the reflected energy, namely, electrical conductivity, dielectric permittivity, and magnetic permeability, help to detect, for instance, cables, pipes, rods inside structures and to monitor the corrosion in reinforced concrete (RC) structures.



Principle of Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a geophysical method that consists in emitting short electromagnetic (em) pulses from the radio spectrum (UHF and VHF frequencies, tens of MHz up to several GHz) and detecting the reflected signals from subsurface structures. The pulse (a few tens of nanoseconds long) propagates in a shape of a cone. The technique is based on the determination of the difference of speed of light in different type of materials. The principle involved is similar to reflection seismology, except that electromagnetic energy is used instead of acoustic energy, and reflections appear at boundaries with different dielectric constants instead of acoustic impedances.

Basic features: The instrumentation is based by an emitting antenna, a receiving antenna, a control unit and a process unit that also can act as a visualization tool. Control and processing units are powered by a battery pack, with an autonomy of several hours, depending the ambient temperature.

Resolution and penetration: The depth range of GPR is limited by the electrical conductivity of the ground, the transmitted centre frequency and the radiated power. As conductivity increases, the penetration depth decreases. Lower frequencies can reach depths up to tens of meters (e.g. 100 MHz can travel up to 20 meters) with a resolution of tens of centimeters, while higher frequencies can give a resolution of centimeters but up to depths of several meters.

2.10 Acoustic Emission (AE) Testing

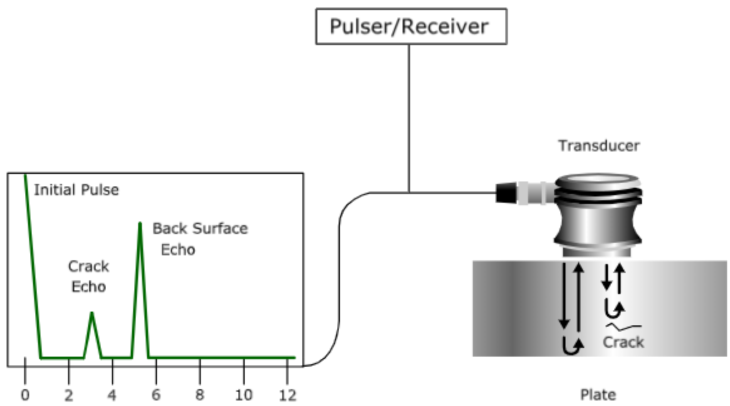
Acoustic Emission (AE) testing is a powerful method for inspecting and monitoring the behaviour of equipment and materials performing under stress. AE inspection is distinct from other NDT inspection methods in a few ways. Most notably, rather than transmitting waves into the structure and detecting the changes to determine the presence of defects, AE detects the emission of the energy that gets released from the material under stress. This ensures that any active concerns to structural and operational health are detected. It is the release of sound energy (both audible and sub-audible), that are generated when a material undergoes irreversible changes, such as those due to cracking. In general, acoustic emissions are defined as the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material. These wave propagate through the material, and their arrival at the surface can be detected by the piezoelectric transducers.

This method is used mainly to detect the cracking in concrete, whether due to externally applied loads, drying shrinkage or thermal stresses. This method can be helpful in determining the internal structure of the material and to know the structural changes during the process of loading. The method can also be used to establish whether the material or the structure meet certain design or fabrication criteria. In this case, the load is increased only to some predetermined level. The amount and nature of acoustic emissions may be used to establish the integrity of the specimen or structure and may also be used to predict the service life.

2.11 Ultrasonic Flaw Detection Method

Among all the applications of industrial ultrasonic testing, flaw detection is the oldest and the most common method. Since the 1940s, the laws of physics that govern the propagation of sound waves through solid materials have been used to detect hidden cracks, voids, porosity, and other internal discontinuities in metals, composites, plastics, and ceramics. High frequency sound waves reflect from flaws in predictable ways, producing distinctive echo patterns that can be displayed and recorded by portable instruments. Ultrasonic testing is completely non-destructive and safe, and it is a well established test method in many basic manufacturing, process, and service industries, especially in applications involving welds and structural metals.

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization etc.. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below will be used. A typical UT inspection system consists of several functional units, such as the pulser/ receiver, transducer, and display devices.



Principle of UT testing

A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected. back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when an echo was received. Signal travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

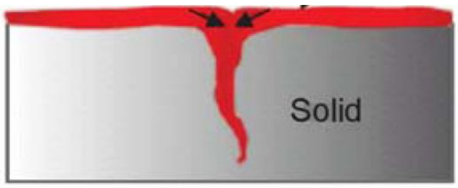
Ultrasonic Inspection is a very useful and versatile NDT method. Some of the advantages of ultrasonic inspection that are often cited include:

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape.
- Minimal part preparation is required.
- Electronic equipment provides instantaneous results.
- Detailed images can be produced with automated systems.
- It has other uses, such as thickness measurement, in addition to flaw detection.

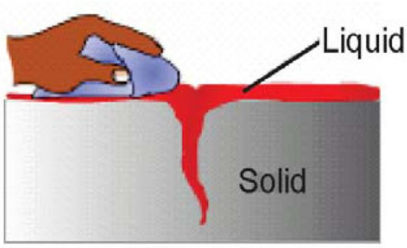
2.12 Dye Penetration Test Method

Dye penetration test is a method that is used to reveal surface flaws by bleed out of a colored or fluorescent dye from the flaw. The technique is based on the ability of a liquid to be drawn into a "clean" surface breaking flaw by capillary action. After a period of time called the "dwell," excess surface penetrant is removed and a developer applied. This acts as a "blotter." It draws the penetrant from the flaw to reveal its presence. Colored (contrast) penetrants require good white light while fluorescent penetrants need to be used in darkened conditions with an ultraviolet "black light". The advantage that a dye penetrant inspection offers over an unaided visual inspection is that it makes defects easier to see for the inspector.

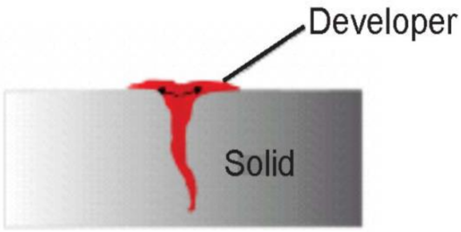
One of the most critical steps of a dye penetrant inspection is the surface preparation. The surface must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws. The sample may also require etching if mechanical operations such as machining, sanding, or grit blasting have been performed. These and other mechanical operations can smear the surface of the sample, thus closing the defects.



Application on the Surface



Removal of Excess Liquid



Application of Developer

A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible. This method has several advantages such as

- The method is highly sensitive to small surface discontinuities.
- Metallic and non-metallic, magnetic and non-magnetic, and conductive and non-conductive materials can be successfully inspected.
- Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.
- Parts with complex geometric shapes are routinely inspected.
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.

CHAPTER 3

STRUCTURAL SAFETY ASSESSMENT THROUGH VIBRATION MONITORING

3.1 Introduction

In our everyday lives, we often encounter number of civil structures which are constructed many years ago, which may have surpassed their intended lifespan. Due to the lack of new alternatives and considering the importance of these structures, we continue to take service from these old structures. These structures encompass bridges, dams, aqueducts, and weirs, typically made either from steel or concrete. Steel structures consist of road or rail bridges, penstocks, turbine shaft, offshore platforms, and towers. On the other hand the examples of old concrete structures are dams, bridges, aqueducts etc. These structures still serve the needs of the public even after all the adverse conditions of static and dynamic loading during the entire period since their construction. The nature of loading may be even higher and complex than that might have anticipated by the designers during construction. Damage is assumed to be equivalent to stiffness deterioration, i.e. to a reduction of the Young’s Modulus in one or more regions inside the structure. The concrete is supposed to behave as an isotropic elastic material. Reduction of elastic modulus and tensile strength may be due to past extreme static/dynamic loadings such as earthquakes, blasting; and/or it can occur slowly in time in the presence of alkali–silica reaction (ASR), also denominated alkali-aggregate reaction (AAR). For example, studies show that along decades of service life, physico–chemical process determines a correlated deterioration of both strength and stiffness in dam concrete particularly in the presence of diffused cracking at the micro-scale, due to concrete ageing.

3.2. Importance of Vibration Monitoring

Construction-induced vibrations can have far-reaching consequences, particularly in urban environments where construction sites often coexist with sensitive structures, historical landmarks, and occupied buildings.

The importance of vibration monitoring extends beyond compliance with regulatory standards. So, it ensures that construction activities are performed within acceptable thresholds, preserving the safety of surrounding structures and minimizing disruptions to occupants. Moreover, it aids in maintaining public confidence and upholding the reputation of contractors and consultants involved in large-scale infrastructure projects.

a) Protecting Structural Integrity

Unmonitored vibrations from activities like blasting, pile driving, mining or demolition can compromise the integrity of adjacent structures. High-frequency vibrations may cause cracking in masonry or concrete, while prolonged exposure to lower-frequency vibrations can lead to cumulative fatigue in structural materials. Monitoring ensures that vibration levels remain within safe thresholds, reducing the likelihood of damage.

b) Preventing legal and financial liabilities

Construction projects are frequently subject to strict contractual obligations and regulatory requirements. Vibration-related complaints from neighbouring property owners can lead to disputes, project delays, or costly litigation. Effective monitoring provides an objective record of compliance, safeguarding against claims and reinforcing accountability.

c) Supporting sustainable construction practices

Modern construction emphasizes sustainability, including minimizing its environmental footprint. Excessive vibrations can disrupt soil stability, affect underground utilities, and disturb ecosystems. Vibration monitoring supports sustainable practices by mitigating these risks and ensuring construction activities remain environmentally responsible.

3.3 Risks Associated with Unmonitored Vibrations

Failure to monitor and control construction-induced vibrations can result in significant risks, spanning structural, operational, financial, and reputational domains. These risks can escalate without precise measurement and mitigation strategies, leading to severe consequences for the project and the surrounding environment.

a) Structural Damage to Adjacent Buildings

Unmonitored vibrations, particularly those generated by pile driving, blasting, mining or demolition, can cause immediate or cumulative damage to nearby structures. Key risks include:

- Cracking or spalling: Vibrations can cause cracks in concrete, masonry, and plaster surfaces, weakening structural components.

- Differential settlement: Soil vibrations may lead to uneven settlement, jeopardizing the foundations of neighbouring buildings.
- Fatigue in structural components: Repeated vibration exposure can degrade materials over time, reducing the lifespan of critical infrastructure.

b) Damage to Sensitive Equipment and Infrastructure

Certain environments, such as hospitals, laboratories, and manufacturing facilities, house sensitive equipment that is highly susceptible to vibrations. Impacts include:

- Disruption of calibration in precision instruments.
- Malfunction of critical medical or research devices.
- Interference with automated industrial processes.

c) Soil Instability and Underground Utility Damage

Ground vibrations may destabilize soil and affect underground utilities, leading to:

- Compromised load-bearing capacity of the soil.
- Ruptures in pipelines or conduits for water, gas, or electricity.
- Disruptions to telecommunication cables or other buried infrastructure.

d) Environmental Impact

Unmonitored vibrations may harm ecosystems, particularly in areas near wildlife habitats, water bodies, or unstable geological formations. Potential impacts include:

- Disturbance to wildlife due to ground vibrations.
- Alteration of groundwater flow patterns in sensitive areas.
- Soil erosion or destabilization of slopes, particularly in hilly or mountainous terrains.

3.4 Health Monitoring of Civil Structures

Vibration is one of the most troublesome phenomena which is encountered almost in all civil engineering projects. It affects the stability and integrity of the structures in various ways. It can be caused by natural events, such as earthquakes and wind, or by some manmade activities, such as blasting operation, traffic and construction works. Vibration can have serious detrimental effects on the performance, safety, and comfort of buildings, bridges, dams, foundations, and other civil engineering works if remains unattended for longer period.

Therefore, it is important to measure and monitor vibration in structures using appropriate methods and monitoring system.

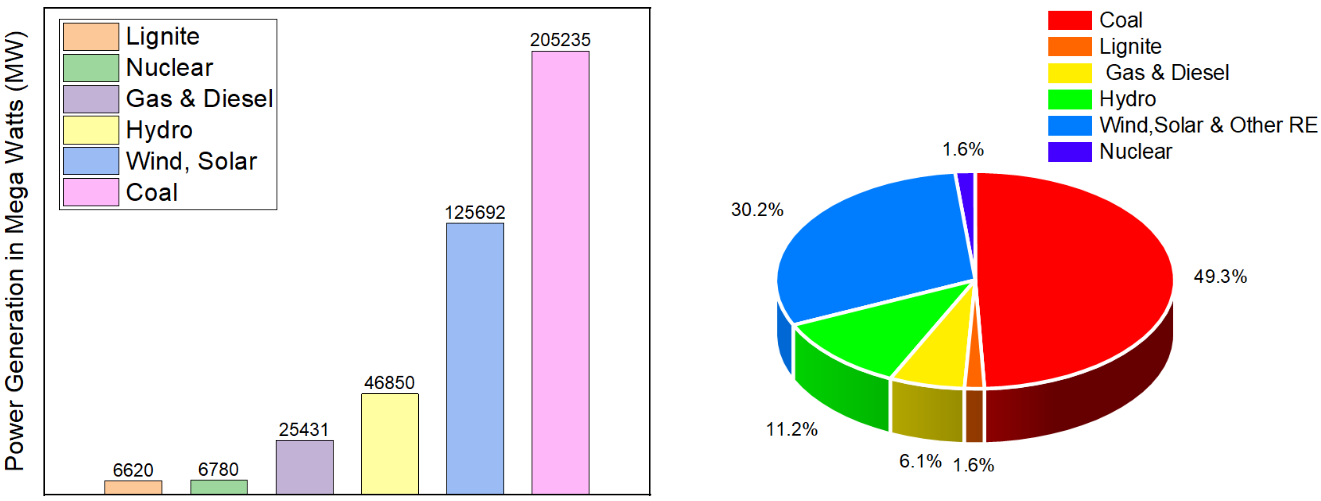
The significance of monitoring the structural integrity of civil engineering structures including long span bridges, tall towers, dams, barrages, power houses and offshore platforms is growing due to safety concerns. Offshore platforms face risks such as corrosion, fatigue, and short-term damage from accidental collisions with supply vessels, falling objects, and severe cyclones. Long span bridges can experience stress from increased load and heavy traffic. Dams may experience reduced stiffness from extreme earthquake forces or reactions involving alkali-silica or alkali-aggregate. It is not possible to strengthen all the existing structures rapidly due to economic reasons, especially in developing nations like India. Therefore, efforts must be taken for assessing safety of these structures by undertaking periodical vibration monitoring. This enables to detect serious damages much before the failure occurs. Vibration monitoring which monitors the vibration parameters of the structure is reported to be one of the best methods for assessing the integrity of these structures. Vibration parameters usually used for monitoring are acceleration, velocity, displacement, natural frequencies, mode shapes and response signatures. For determination of natural frequencies, the structure has to be vibrated at various frequencies and the response has to be recorded. This cannot be easily adopted for heavy structures like long span bridges, dams and offshore platforms. Hence, alternate methods like impulse and relaxation, which can be easily applied, are used. The application of impulse causes the structure to undergo damped free vibrations, which can be used to determine the dynamic parameters necessary for assessing the integrity of the structures.

Vibration monitoring is based on the fact that any structure has certain dynamic parameters such as natural frequencies of vibration and corresponding mode shapes. These inherent characteristics of the structure do not change unless there is a change in stiffness or mass distribution. The responses at several points of the structure due to the impact load can be measured using sensitive accelerometers and recorded. The frequency plot of the response can be obtained from the time series of displacement by performing a discrete Fourier transform. The peaks in this plot represent the different natural frequencies of the structure. The displacement vectors corresponding to these peaks (for all nodes) for the first and second modes are normalized to get the corresponding response signatures. These response signatures are similar to mode shapes but do not contain any negative values. The changes in these impulse response signatures are used for diagnosing the damages caused in the structure.

3.5 Vibration Issues in Hydropower Plants

India is the sixth largest producer of hydroelectric power in the world, in terms of installed capacity after China, Canada, Brazil, US and Russia. As per the government estimates, the total hydroelectric power potential of India is around 145 GW. However, only 32 percent of the hydroelectric power potential is being utilized in India at present i.e. 46.8 Giga Watt. On the other hand, India's total installed power capacity considering all forms of energy is about 416.05 GW. This clearly indicates that there is a further scope for hydroelectric power generation which is a renewable energy source.

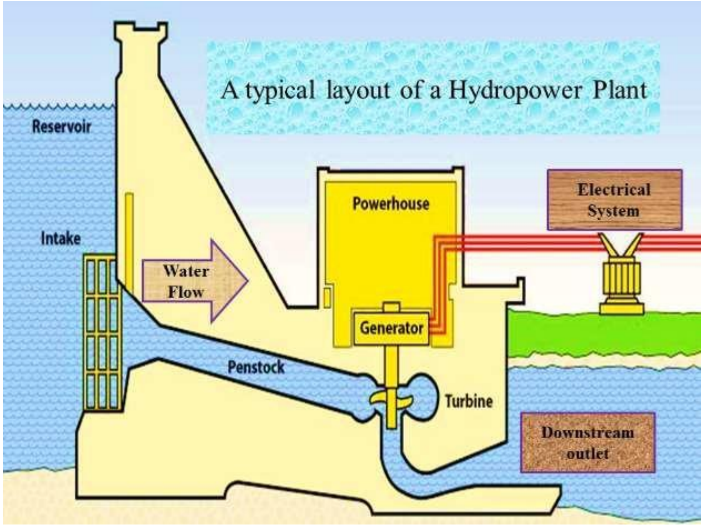
Vibration issues in Hydropower station is one of the major reasons for failure of the equipment. Vibration of equipment has been a severe problem in Hydro Power Stations (HPS) from the very beginning of power generation. Failure of the equipment due to vibration causes shut down, or sometimes, even a disaster like situation occurs. Vibrations in Hydropower station occur from various sources like Turbines, Draft Tubes, Generator, Transformers and penstock. Penstocks play a vital role in power generation; however these are the parts which are vulnerable to damages as they carry water under high pressure. These vibrations are also transmitted to the powerhouse structures and when the safe limit exceeds, it may endanger the safety of the powerhouse.



Installed Capacity by Source in the Utility Sector as on June 2023

3.6 Sources of Vibrations in Hydro power Station

In a hydroelectric power station, various components work together to generate electricity by utilizing the potential energy of water. The various components of a Hydro Power Station are shown in Fig.2.2. There are several reasons due to which excessive vibration levels are generated in a hydropower station. The main reasons for these vibrations are Electrical, Mechanical and Hydraulic issues. Vibrations occur not only on rotating equipment like motors, turbines and Rotor, but also on non-rotating equipment such as Transformer, Draft tube and Penstock. This vibration also gets transmitted to the structure and induces damage. Reasons for the vibrations on various equipment have been listed below.



Various Components of Hydro power station

3.6.1Turbines

Vibrations of hydraulic turbine are due to extreme force fluctuations caused by cavitations. The main reason for turbine erosive wear is cavitations only. Vibrations in Turbines also occur due to defective bearings, this is due to normal erosion during use.

Improper lubrication may also lead to vibrations as improper lubrication of mechanical parts with unsuitable parameters of the lubrication system causes turbulence of oil film and results in damage. Imbalance is a major perpetrator of vibration, it occurs when rotor weight is unequally distributed about its rotating centreline. The vibration due to imbalance is radial and increases with rotational frequency. Eccentricity also contributes a fair share in vibration in Hydropower station. It is the situation of fluctuating air gap between rotor and stator. When this eccentricity is high, imbalanced magnetic pulling takes place which causes the surface of stator rubbing against that of the rotor. This results in vibration. A maximum of 10% air-gap eccentricity is permissible. When the air gap of generators varies 10–15% of its minimum length, a significant imbalance occurs after 15–20 years of the commissioning of the Unit. In this condition, within 2– 3 years, if a remedial measure has not been taken, stator-winding fault will occur due to mechanical abrasion of stator insulation. Non-uniform velocity distributions in various waterways of the turbine cause hydraulic unbalance. There are also draft-tube flow instabilities. These occur in Francis turbines even during steady-state operation outside the optimum efficiency ranges.

Cavitations are also another major contributor to vibration. This is caused by incorrect flow conditions around the runner or impeller blade profiles and occurs mostly within the higher load ranges. Hydro elastic vibrations occur due to an incorrectly shaped discharge edge of hydraulic profiles (blades, wicket gates, and stay vanes etc.). Self-excited vibration occurs in places where the movement of mechanical parts (seals and clearances, etc.) can influence the flow around or through them.

Turbine Damage by Cavitations

Misalignment in line of shaft also results in vibration; this is in both radial as well as axial direction. These vibrations increase with rotational frequency of lower order harmonics. It also leads to bearing failure and overheating. The shaft misalignment can be either angular or offset. If it is angular, the angle between the machine moved and the shaft centreline of a stationary machine is different in vertical and horizontal planes. This misalignment in shaft may also lead to bearing failure and overheating. Breakage of wicket gate linkage is also due to misalignment. These situations are shown below.

Turbines Misalignment Detection

3.6.2 Rotor

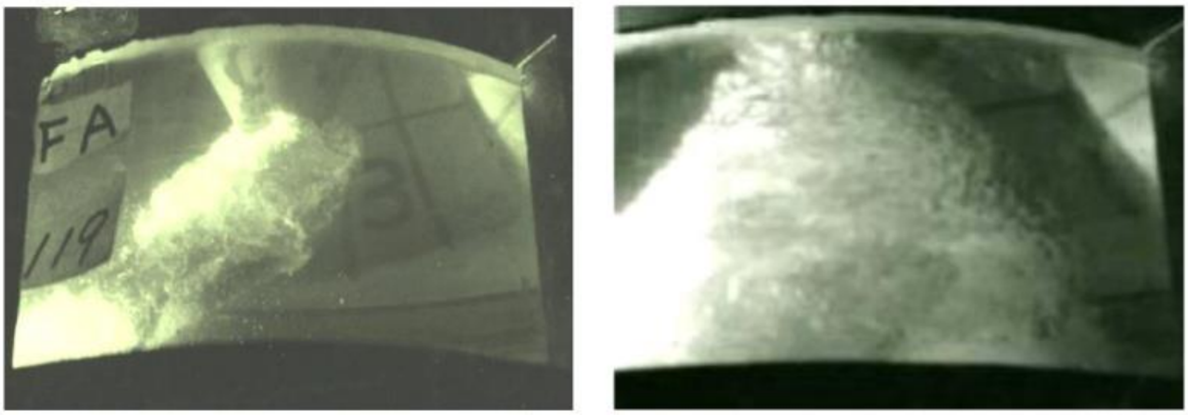
When insulation of rotor poles fails, the unequal current in windings creates non uniform magnetic field and thus the vibrations increase. Due to rotor winding inter-turn fault, the air-gap distorts cause imbalanced magnetic pull on the rotor. This causes pulsating magnetic pull on the stator that ultimately results in stator vibrating.

3.6.3 Penstock

Penstock is a pressurized conduit through which the water can be transferred from the reservoir to the turbine. Sometimes vibrations are caused due to unstable support conditions, less thickness of shell due to omission of minimum thickness criteria. The penstock vibration depends upon local hydraulic conditions in the area surrounding penstock outlets and on the dynamic properties when filled with water. Change in water flow may be occurring due to unit start up, shut down, operational errors, operating mode changes, load rejections and load variations. Sudden change in water flow generates water hammer which is the critical issue in the penstock. To prevent water hammer, protection devices like pressure relief valves, surge tanks, intake gates, air chambers and air valves, load and flow control equipment such as turbine wicket gates, penstock control valves and governor should be inspected periodically for proper operation.

3.6.4 Draft Tube

The hydro power station’s power production is directly connected to the grid. And there is no such thing as a constant power requirement; it always fluctuates based upon the demand from users or grid. Accordingly, the Hydro power Stations increase or decrease the power production based on the requirement. This is known as part load or over load. So when there is part load or over load operation of turbine, the swirling flow causes vortex inside the draft tube. This results in cavitations and hence the vibration.



Vortex at Turbine during Partial Load and Overloads

In view of the above, it is very much essential to carry out vibration monitoring in order to examine the performance of such equipment and to know the status of complex systems used in hydropower generation. In Hydropower stations, vibration monitoring is conducted in various parts of hydrogenating equipments including relative shaft vibration, bearings absolute vibration, turbine cover vibration, thrust bearing axial vibration, stator core vibrations, stator bar vibrations, stator end winding vibrations. Non-contact capacitive proximity probes are usually deployed to monitor the motion of the generator/turbine shaft relative to the bearings. Low-frequency accelerometers are usually provided to monitor the absolute vibration of the bearings and of the turbine cover. A multi-channel, multi-tasking, on-line programmable digital processing unit is provided for system configuration for processing vibration data from vibration probes. Vibration monitoring is very important as it provides early indication of impending failure. By doing this, any technical person can easily detect the fault or abnormal condition before it causes failure of the unit. Thus, unnecessary maintenance can be avoided and the resources can be saved. The condition of a machine can be estimated by measuring the vibration levels which will enable to take necessary measures for rectification of the same for preventing further damage.

3.7 SAFETY CRITERIA

3.7.1 Monitoring of Machinery Vibrations

Safety criteria mentioned in different National/International standards have been reviewed in order to protect the rotating machines from the induced vibrations. Organisations that have established their own standards or guidelines for limiting the vibration level within the safe limit for ensuring smooth operation of the pumps/turbines include; the International Organisation for Standardisation (ISO) for turbines, motors and pumps; the Hydraulic Institute (HI) for pumps; American National Standards Institute (ANSI); German Association of Engineers (VDI) and the National Electrical Manufacturers Association (NEMA) for electric motors. In addition, some sector-specific associations, such the Submersible Wastewater Pump Association (SWPA) and the American Petroleum Institute (API) for refineries, have established vibration standards.

The HIS standard (ANSI/HI 9.6.4-2000) specifies allowable vibration levels based on input power at the time of test conditions for different types of pumps and suggests the methodology for measurement of vibration and noise. The most appropriate parameter for measurement of machine vibration is RMS value of velocity in mm/s or cm/s. The vibration level are measured in three perpendicular directions, viz.; vertical, horizontal and transverse directions and the maximum of these three is used for comparing with the allowable vibration level. HIS standard (ANSI/HI 9.6.4-2000) specifies an allowable safe vibration level of 7.11 mm/s RMS for pumps with input power varying from 0.75 kW to 2238 kW.

ISO 20816-5:2018 recommends safe vibration level for "Evaluation of Machine Vibration by measurements on Non-Rotating Parts - Part 5; especially for the "Machine Sets in Hydraulic Power Generating and Pumping Plants". The code recommends a velocity (RMS) level of 1.8 mm/s at the turbine guide bearing for safety of power generating machines in hydropower plants. In the present study, the guidelines mentioned in ISO 20816-5:2018 have been followed for evaluating the severity of vibration in Hydro turbines as mentioned in the Table.

Table : Vibration Limits for Turbine (ISO 20816-5:2018)

Machine type:	Relative shaft vibration S_{p-p}, µm			Bearing housing vibration v_{rms}, mm/s		
Francis vertical	T	GE-DE	CE-NDE	T	GE-DE	GE-NDE
Action limit 1 (A–B/C)	180	180	160	0,9	0,5	0,5
Action limit 2 (C/D)	280	280	250	1,4	0,8	0,8
Normal operating range for Francis vertical: from 70 % to 100 % of rated power						
Machine type:	Relative shaft vibration S_{p-p}, µm			Bearing housing vibration v_{rms}, mm/s		
Pump-turbine vertical	T	GE-DE	CE-NDE	T	GE-DE	GE-NDE
Action limit 1 (A–B/C)	170	160	220	1,9	0,7	0,9
Action limit 2 (C/D)	260	250	350	3,0	1,1	1,5
Normal operating range for pump-turbine vertical: from 70 % to 100 % of rated power						
Machine type:	Relative shaft vibration S_{p-p}, µm			Bearing housing vibration v_{rms}, mm/s		
Kaplan vertical	T	GE-DE	CE-NDE	T	GE-DE	GE-NDE
Action limit 1 (A–B/C)	110	170	170	1,1	0,6	0,7
Action limit 2 (C/D)	170	270	260	1,8	1,0	1,1
Normal operating range for Kaplan vertical: from 30 % to 100 % of rated power						
Machine type:	Relative shaft vibration S_{p-p}, µm			Bearing housing vibration v_{rms}, mm/s		
Pelton vertical[a]	T	GE-DE	CE-NDE	T	GE-DE	GE-NDE
Action limit 1 (A–B/C)	140	150	180	0,8	0,8	1,0
Action limit 2 (C/D)	210	230	270	1,2	1,3	1,5
Normal operating range for Pelton vertical: from 10 % to 100 % of rated power						
Machine type:	Relative shaft vibration S_{p-p}, µm			Bearing housing vibration v_{rms}, mm/s		
Pump vertical	P	GE-DE	CE-NDE	P	GE-DE	GE-NDE
Action limit 1 (A–B/C)	200	170	180	2,3[b]	0,8[b]	0,8[b]
Action limit 2 (C/D)	310	270	280	3,6[b]	1,2[b]	1,2[b]

3.7.2 Safety Criteria Adopted for Vibration on Civil Structures

Civil structures like buildings, dams, aqueducts, weirs, bridges, barrages etc, are fairly resilient to vibrations. However, excessive vibration levels can induce different levels of structural damages such as initiation of new cracks, widening of existing cracks etc., which may escalate further damage probability. The risks of vibration-induced damages are commonly evaluated by taking into account of the magnitude and frequency of recorded vibration together with consideration of the type of structure. For ensuring the safety of various structures against ground vibrations, safety standards are commonly suggested in terms of the peak particle velocity (PPV) and associated predominant frequencies in order to ensure a minimal risk of vibration-induced damage. However, very few safety standards are available to ensure safety of structures against machine induced continuous vibrations. Traditionally, Industrial/Power House structures, subjected to dynamic loads due to machine induced vibrations, are designed in such a way that, the major natural frequencies of the structure do not coincide with the frequency of machine vibrations and in addition, the design of the structure with adequate factor of safety has been made so that it can withstand higher levels of vibrations. A review of few safety criteria being followed worldwide for various types of Civil Structures against both transient and continuous vibrations are as follows:

- The **Bureau of Indian Standards (IS – 14881, 2001)** recommends frequency dependent safety criteria to ensure safety of different structures against blast vibrations which is transient in nature. For protection of concrete structures, the code recommends safe PPV of 25 mm/s for frequencies below 40 Hz and 25 – 75 mm/s in the frequency range of 40 – 100 Hz.

- The **British Standards (BS 7385: Part 2: 1993)** recommends peak velocity level of 50 mm/s at 4 Hz and above for ensuring safety of reinforced or framed structures, Industrial and heavy commercial buildings against transient vibrations. For continuous vibrations, this value needs to be reduced by 50 %.

- The **German Standard (DIN 4150: Part 3: 1999)** provides guidelines in terms of peak particle velocity (PPV) for assessing continuous vibrations on different types of structures. The code recommends a PPV level of 10 mm/s, 2.5 mm/s for all frequency ranges for the safety of the industrial buildings, dwellings and sensitive structures from continuous ground vibrations as shown below.

- In the present study, vibration measurements have been undertaken at the different floor of the powerhouse. Though several criteria as mentioned above are there, in order to safeguard different type of civil structures, subjected to continuous vibrations, in the present case, after reviewing recommendations by different standards as well as CWPRS experience gathered from various case studies, a conservative safe vibration levels of 10 mm/s have been adopted as the safe vibration level for the Power house civil structure.

Table: Vibration Standards for Evaluating Long Term Vibration on Structures, DIN 4150–3:1999

Sl. No.	Type of Structure	Vibration Thresholds for Structural Damage, PPV (mm/s)				
		Short Term				Long Term
		Vibration (mm/s) at the foundation – frequency (Hz) range			Vibration (mm/s) at highest floor	Highest Floor
		0- 10	10 – 50	50 – 100	All Frequencies	All Frequencies
1	Buildings used for commercial purposes, industrial buildings and buildings of similar design	20	20 - 40	40 - 50	40	10
2	Dwellings and buildings of similar design and/or use (Residential Structures)	5	5 - 15	15 - 20	15	5
3	Structures that because of their particular sensitivity to vibration, do not correspond to those listed in Lines 1 or 2 and have intrinsic value(Sensitive/Historic Structures)	3	3 - 8	8 -10	8	2.5

3.7.3 Safety Criteria for Blast Induced Ground Vibrations

Many times blasting is being carried out for rock excavation near important structures like dam, barrages, bridges, power houses, historical monuments, nuclear power plants etc. during expansion of the existing structures. During a blasting operation, it is desirable to utilize the maximum portion of explosive energy for breaking and displacing the rock mass. However, depending upon the geological condition and blast design parameters, a significant amount of explosive energy is generally wasted in the form of undesirable effects like ground vibration, airblast and flyrock having potential to cause damage in a structure. The ground vibration has been recognized as the major cause of damage to structures, and hence the safety criteria are mostly specified in terms of the amplitudes of blast vibration.

In addition to the amplitudes of ground vibration, the associated frequencies also play a dominant role in deciding the damage potential of the blast induced ground motion. If the predominant frequency of ground motion is very close to the structural frequency, even low amplitude vibrations may be damaging due to resonance effects. In addition to the distance from the blasting site, the ground motion frequencies depend significantly on the charge weight and the site geologic conditions.

By analyzing a large amount of blast data, Duvall and Fogelson (1962) of the United States Bureau of Mines (USBM) established that the damage to structures is related quite closely to the peak particle velocity (PPV) of ground vibration. Since then, almost all the safety criteria for blast induced vibrations are defined in terms of the PPV alone or the PPV and its associated predominant frequency. This is because the peak particle velocity response of a structure is directly related to the strain, ε , produced in the structure as (Dowding, 1985)

$$\varepsilon = \frac{V_{resp}}{V} \times 10^{-6} \tag{3.1}$$

Here, V_{resp} is the peak velocity response of the structure in mm/s and *V* is the wave propagation velocity through the structural material in km/s. As *V* is fixed for a structure, the strain is directly proportional to V_{resp} . It has been further observed that the peak response velocity is proportional to the peak particle velocity, V_P , of the ground motion (Siskind et al., 1980a). Hence, the safety criteria are generally specified in terms of the peak particle velocity of ground motion near the structure.

The effects of blast vibrations on structures and the various existing safety criteria for different types of structures are reviewed in this chapter. The chapter also describes the various instruments used in the past as well as those in vogue at present for recording the blast vibrations.

3.7.4 Safety Criteria for Residential Structures

As mentioned before, the peak particle velocity (PPV) of ground motion is the most convenient single ground motion parameter to define the damaging potential of blast vibrations. Thus, most of the early safety standards against blast vibrations are prescribed in terms of the peak particle velocity only. However, it is a well established fact that a structure having natural frequency close to the predominant frequency of ground motion and a small damping coefficient may get damaged at much lower peak particle velocity than that having natural frequency away from the predominant input frequency and higher damping value. Therefore, many later studies recognized the importance of the frequency of ground motion in causing damage to structures and proposed frequency-dependent safety criteria. This section reviews the various existing safety standards, both frequency-independent and frequency-dependent, for different kinds of residential or other similar structures.

3.7.5 Frequency-Independent Safety Criteria

Most of the existing safety/damage criteria have been established by measuring the ground vibrations due to quarry and mining activities near several test structures and correlating the resulting damage to the amplitudes of ground motion. The initiation of damage to a house is indicated by extension of old plaster cracks or dust falling from old plaster cracks. An increase in severity of ground vibration can cause intensified cracking of plaster, falling of plaster and cracking of mortar in masonry walls.

Many of the early studies on safety criteria were conducted by the United States Bureau of Mines (USBM), which suggested a peak particle velocity of 50 mm/s (2.0 inch/s) as the damage criteria for residential structures (Duvall and Fogelson, 1962). Using three different sets of damage data then available, one from Canada (Edwards and Northwood, 1960), one from Sweden (Langefors et al., 1958) and one of the USBM itself (Theonen and Windes, 1942), it was shown that a PPV of 2.0 inch/s in any one of the components of vibration provides a reasonable separation between the safe zone and a probable damage zone (Fig. 4.2). In 1971, Nicholls of USBM reanalyzed the data used by Duvall and Fogelson (1962) and confirmed the 50 mm/s as the damage criteria. However, it was later found that vibration levels below 50 mm/s can also cause damage in a structure under resonance. Also, damage may be produced at lower vibration levels in poorly constructed structures or in already stressed structures by settlement or unstable soil conditions. Some of these safety criteria based on the condition of the structure and the type of the foundation are also described in this section.

Damage criteria due to Langefors and Kihlstrom (1978) as mentioned below takes into account the effects of the type of ground upon which the foundation is laid. Higher PPVs are considered safe for better type of foundations characterized by higher values of compressional wave-velocity, because the predominant frequencies of ground vibration become higher than the frequency range of the structures. Chae (1978) has classified various structures into four different categories and has recommended the safe vibration levels ranging from 12.5 to 100 mm/s, along with safe scaled distances as given below. In case of repeated blasting or in the absence of instrumentation for monitoring, he has suggested to lower the category by one.

Table: Safety Criteria for Different Foundation Conditions due to Langefors and Kihlstrom (1978).

Type of Foundation Rock	Compress-ional Wave Velocity (km/s)	Peak Particle Velocity (mm/s) for			
		No Noticeable Cracks	Threshold of Cracking	Significant Cracking	Major Cracks
Sand, Shingle, Clay	0.3 – 1.5	4 – 18	6 – 30	8 – 40	12 – 60
Moraine, Slate, Soft Limestone	2.0 – 3.03	35	55	80	115
Hard Limestone, Sandstone, Gneiss, Granite	4.5 – 6.0	70	110	160	230

Table: Safety Criteria for Four Different Types of Structures due to Chae (1978).

Class of Structure	Description of Structure	Peak Particle Velocity (mm/s)	Scaled Distance (m/√kg)
I	Structures of substantial construction	100.0	4.5
II	Relatively new residential structures in sound condition	50.0	9.0
III	Relatively old residential structures in poor condition	25.0	13.5
IV	Old residential structures in very poor condition	12.5	22.5

Esteves (1978) has classified various structures into three different categories as Type-I (constructions like hospitals, historical monuments and tall buildings requiring special care), Type-II (current constructions), and Type-III (reinforced constructions designed to withstand earthquakes). For these types of structures, he has recommended safe vibration levels varying from 2.5 to 60 mm/s by taking into consideration the effects of the characteristic properties of the foundation (wave propagation velocity) and average number of daily blasts (up to three and more numbers of blast designated as A and B, respectively).

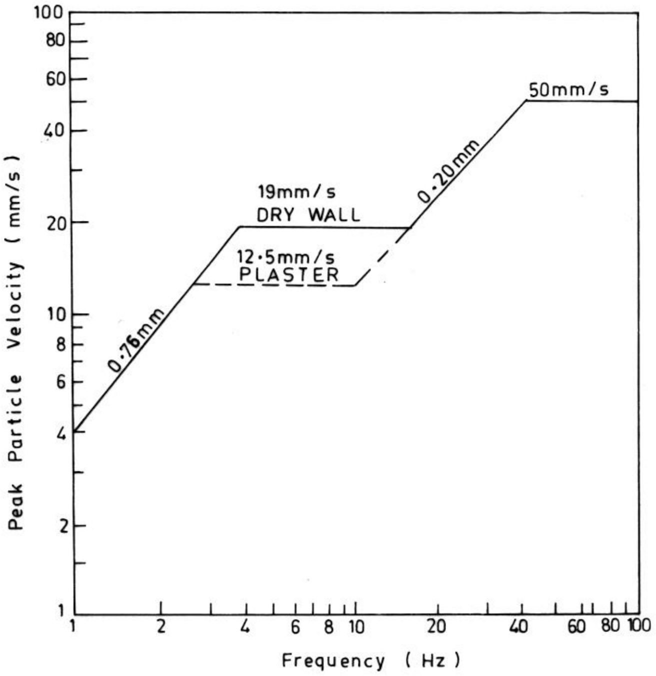
Table: Safety Criteria for Different Types of Foundations and Constructions due to Esteves (1978).

Compressional Wave Velocity (km/s)	PPV (mm/s) for Different types of Constructions					
	Type – I		Type – II		Type - III	
	A	B	A	B	A	B
< 1.0	2.5	1.7	5.0	3.5	10.0	7.0
1.0 – 2.0	5.0	3.5	10.0	7.0	20.0	14.0
> 2.0	15.0	10.5	30.0	21.0	60.0	42.0

The Indian Standards (IS : 6922-1973) recommend the peak particle velocities of 50 and 70 mm/s for structures founded on soft and hard rocks, respectively. From the foregoing description it is seen that these high levels of blast vibrations may not be safe in many conditions. This stresses the need for site-specific studies to arrive at more realistic safety criteria.

3.7.6 Frequency-Dependent Safety Criteria

Structures respond most to ground motions at resonance; i.e., when the excitation frequency matches the structure's fundamental frequency. The frequency independent safety criteria described in the previous section do not consider explicitly the dependence on the predominant frequency of ground vibration and the natural frequency of the structure. But, in reality, they are not truly independent of the frequencies. The early safety criterion of 50 mm/s is based on the fact that the frequencies of the structures considered were mostly below the frequencies of ground motion. For the ground motion from surface coal mines at long distances, the predominant frequencies of which covered the range of structural frequencies, the safe level was lowered to 12.5 and 19 mm/s (Siskind et al., 1980a). The higher safe levels for structures with hard rock foundations were also based on the fact that hard rocks generate more of high frequencies of vibration. Thus, strictly speaking, the safety criteria against blast induced ground vibrations are inherently frequency-dependent. Some of the important safety criteria considering the frequency dependence in an explicit way are described in the following.



Frequency Dependent Safety Criteria due to Siskind Et Al. (1980a)

The most popular frequency-dependent safety criterion is due to Siskind et al. (1980a), which is shown above. This criterion was developed using the damage data of USBM from several test structures subjected to ground vibrations due to mining blasts and the other damage data mentioned before. According to this criterion, for frequencies between 2.7 and 10 Hz, a peak particle velocity of 12.5 mm/s is safe for older plaster on wood lath interiors and 19.0 mm/s for modern dry wall houses. For frequencies beyond 40 Hz, a constant peak particle velocity of 50 mm/s is safe for all houses. For frequencies below 2.7 Hz and those between 10 Hz and 40 Hz, constant displacements of 0.76 mm and 0.2 mm are suggested as safe levels. The Australian standards specify a displacement of 0.2 mm for frequencies below 15 Hz and a peak particle velocity of 19 mm/s for frequencies above 15 Hz (Siskind et al., 1980a). The displacement of 0.2 mm corresponds to peak particle velocities of 6.3 and 12.6 mm/s at frequencies of 5 and 10 Hz, respectively.

The German Standards DIN 4150 (1938, revised 1984) recommend safe vibration levels for different types of structures for three different frequency bands of ground motion. These recommendations are generally held to be overcautious and unworkable. The Swiss Association of Standards (1978) suggests safe vibration levels for different types of structures as listed below.

Table: German Vibration Standards, DIN 4150 (1984)

Structural Type	Safe Particle Velocity, mm/s			
	Foundation Level			Top Story at Floor Level (all frequencies)
	< 10 Hz	10 – 50 Hz	50 – 100 Hz	
Office and industrial premises	20	20 – 40	40 – 50	40
Domestic houses and similar constructions	5	5 – 15	15 – 20	15
Ancient and historical buildings	3	3 – 8	8 – 10	8

Table : Safety Criteria due to Swiss Association of Standards (1978)

Type of Structure	Frequency Range (Hz)	Safe PPV (mm/s)
Steel or reinforced concrete structures such as factories, retaining walls, bridges, open channels, underground tunnels and chambers.	10 – 60	30
Buildings with foundation walls and floors in concrete, walls in concrete or masonry, underground chambers and tunnels with masonry linings.	60 – 90	30 – 40
Buildings with masonry walls and wooden ceilings.	10 – 60 60 - 90	12 12 – 18
Objects of historic interest or other sensitive structures.	10 – 60 60 – 90	8 8 – 12

They provide safe vibration levels varying from 8 to 40 mm/s for two different frequency bands of 10 to 60 Hz and 60 to 90 Hz. Singh (1998) has recommended the safe vibration levels for different types of structures for three different frequency bands (< 10 Hz, 10 to 25 Hz and > 25 Hz) of ground motion as listed in the following Table. The Director General of Mines Safety (DGMS), Dhanbad, India has recommended the safety criteria for different types of structures in mining areas as given below.

Table: Frequency-Dependent Safety Criteria due to Singh (1998)

Type of Structure	Safe Particle Velocity, mm/s		
	< 10 Hz	10 – 25 Hz	> 25 Hz
Industrial buildings, RCC & Framed structures	20	35	50
Domestic Houses/ structures (brick & cement construction with RCC roof, brick & mud plastered with cement and wooden ceiling, mud with thatched roof)	10	15	25
Objects of historical importance and sensitive structure	2	5	10

Table: DGMS Criteria for Different Types of Structures in Mining Areas

Type of Structure	Safe Particle Velocity, mm/s		
	< 8 Hz	8 – 25 Hz	> 25 Hz
A) Buildings/ Structures not belonging to owner			
1. Domestic houses/structures (Kuchha, brick & cement)	5	10	15
2. Industrial buildings (RCC & framed structures)	10	20	25
3. Objects of historical importance and sensitive structures	2	5	10
B) Buildings/ Structures belonging to Owner			
1. Domestic Houses/structures (kuchha, brick & cement)	10	15	25
2. Industrial buildings (RCC & frames structures)	15	25	50

After Australian Standard(AsA-2183)(JustandChitombo,1987)

Type of structures	Ground PPV (mm/s)
Historical building and monuments and buildings of special value	2
Houses and low rise residential buildings, commercial buildings not Included below	10
Commercial buildings and industrial buildings or structures of reinforced Concrete or steel construction	25

After Australian Standard (Ca-23-2183)(JustandChitombo,1987)

Types of structures	Ground PPV (mm/s)
Historical buildings and monuments and buildings of Special value	0.2mm displacement for Frequencies less than15Hz
Houses and low rise residential buildings, commercial Buildings not included below	19mm/s resultant PPV for Frequencies greater than15Hz
Commercial buildings and industrial buildings or structures of reinforced concrete or steel construction	0.2mm maximum displacement correspond to 12.5 mm/s PPV at 10 Hz and 6.25 mm/s at 5 Hz

After Hungarian Standard

Type of structures	Permissible limit (mm/s)
Construction demanding special protection, military, telephones, airport, dams, bridges which have length of more than20m	Extra opinion from expert
Statistically not solid damaged construction, temples, monuments, Oil and gas wells and upto 0.17 MPa and below 0.7 MPa pressure in pipes(oil and gas)	2
Panel houses and statistically not fully determined structures	5
Statistically good condition structures, towers, electrical apparatus, water plant	10
RCC and structures concrete, tunnels, canals and other pipelines beneath the soil surface greater than0.7m,opening the sublevel	20
Public road, railway and electrical lines, telephone lines ropeway	50

After USSR Standard

Type of structures	Allowable PPV(mm/s)	
	Repeated	One fold
Hospitals	8	30
Large panel residential buildings and children's institution	15	30
Residential and public buildings of all type except large panels, office and industrial buildings having deformations, boiler rooms and high brick chimneys	30	60
Office and industrial buildings, high reinforced concrete pipes, Railway and water tunnels, traffic flyovers, saturated and slopes	60	120
Single storage skeleton type industrial buildings, metal and block Reinforced concrete structures, soil slopes which are part primary Structures, primary mine openings(service life upto 10 years) pit bottom, main entries, drifts	120	240
Secondary mine openings(service life upto 3 years)haulages and drifts	240	480

Selection of a most appropriate safety criterion for a particular situation is a very difficult task. An extra conservative criterion may paralyze the blasting work, whereas a liberal criterion could damage the surrounding structures. In many cases, particularly for excavation in urban areas, even the cosmetic cracks in the houses are not acceptable. The safety criteria are also governed by the response of human beings to ground vibrations and noise produced due to blasting. Therefore, several trial blasts must be carried out for optimization of the blast design parameters which will help to select appropriate safety criteria.

CHAPTER 4

QUALITATIVE ASSESSMENT OF CIVIL STRUCTURES: CASE STUDIES

CWPRS, Pune has successfully carried out qualitative assessment of various types of civil structures by using combination of different non-destructive testing methods and also through vibration monitoring for ensuring safety of structures against induced vibrations. In this chapter, selected case studies are being illustrated along with its significant impact.

4.1 Bhatghar Hydro Electric Project, Maharashtra

The Bhatgar Hydro Power station, Maharashtra (1 x 16 MW) was commissioned in 1977 on Yelwandi river. Vertical Kaplan turbine machine with 214.3 rpm was installed at Bhatghar Hydro Power station. The ultimate strength of concrete used in construction of the barrel concrete structure is of 15-20 MPa. The barrel concrete structure has served for more than 36 long years for power generation. Subsequently, during operation of the Unit, excessive vibrations were felt in the generator portion. The vibrations of machines were transferred to Lower Bracket supporting foundations which resulted in loosening of anchors in the foundations. With a view to ascertain the extent of damage caused to barrel concrete structure, the Bhatgar Hydro Power station authorities have entrusted the task of testing the quality of in-situ concrete of barrel concrete structure of Bhatgar Hydro Power station to CWPRS, Pune. Accordingly, the non-destructive testing for assessing the quality of barrel concrete structure was carried out by employing rebound hammer test and ultrasonic pulse transmission technique. Schmidt hammer and Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) instruments were used for estimating hardness of layer and the travel time of elastic compressional wave through the barrel concrete wall consisting of four pedestals, eight L-shaped portion near to pedestals, eight heater pedestal portion and inner and outer wall. The present studies were undertaken with the selected portions of the barrel concrete wall. Photographs are showing the ultrasonic testing of pedestal at power house, Bhatghar HEP, Maharashtra.

Photograph showing the NDT of pedestal

A Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) equipment with suitable transducers has been used for this purpose. Elastic compressional wave velocity was estimated at more than 200 grid points covering maximum portion of the concrete of the barrel concrete structure. In-situ quality of concrete was evaluated by comparing the observed rebound number and velocities with adopted velocity criteria and correlating compressional wave velocity with the quality of concrete. The studies have revealed that the in-situ quality of concrete for most part of the barrel concrete structure is of good to very good quality. However, four pedestals may be graded as questionable to poor quality. Based on the studies, remedial measures for repair/ rehabilitation have been suggested of four pedestals. Accordingly, the weak portions were removed by concrete breakers. Four concrete pedestals with M-30 micro concrete were re-casted. The development of concrete strength with time and its in-situ quality was tested by conducting field and laboratory studies.

(a)

(b

(c)

Laboratory testing of concrete cubes using (a) PUNDIT, (b) Schmidt hammer and (c) Universal testing machine

From the results of field and laboratory studies carried out, it has been concluded that the concrete of four pedestal blocks are of very good quality and it is recommended to initiate further steps for installation and commissioning of necessary power generating unit of Bhatghar Hydro Electric Power Project.

Major Impact of the Study

Based on the results of the NDT tests, it was suggested to dismantle the existing distressed pedestal blocks and recast the same with fibre reinforced concrete by providing proper anchoring at the base in vertical direction as well as in transverse direction with the parent barrel concrete. Steel fibre approximately 1% by volume may be added to the at least M_{30} design mix concrete. It was further advised to increase volume of the pedestal blocks to 1.5 to 2 times of the present volume of the blocks.

After implementation of the recommendation made by CWPRS, the foundation structure of the generation unit has been re-commissioned successfully. The generation units have been continuously in operation without facing any further difficulty for fulfilling the power demands of the nearby region of Maharashtra. The study ensured the safety of the powerhouse and enhanced the service life of the generation units.

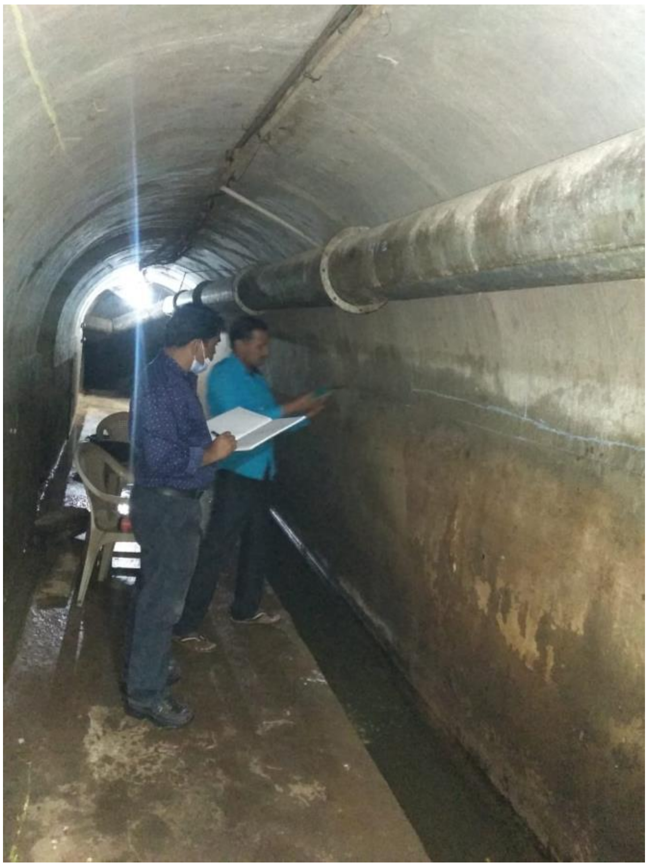
4.2 Rengali Hydroelectric Project, Odisha

Rengali Hydro Electric Project under Odisha Hydro Power Corporation (OHPC) Ltd., Odisha consists of a 1,040 m long and 70.5 m high masonry-cum-concrete gravity dam. The power house is located at the toe of the power blocks. The water discharge of power house is utilized for irrigation purpose and also leads to a barrage (under construction) with two canals at Samal, located about 45 km downstream of Rengali Dam.

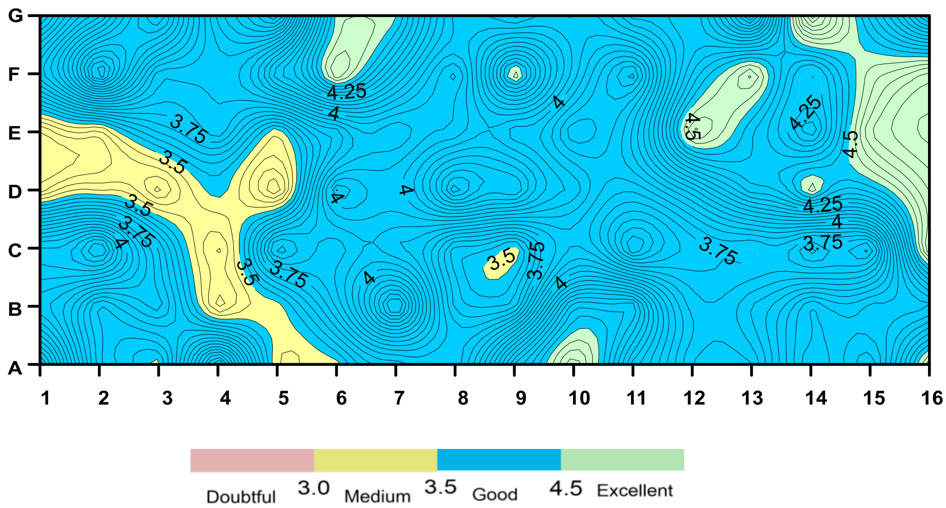
Aerial View of the Rengali Power House, Odisha

The Power house of Rengali has a 250 MW installed capacity. The power house accommodates the service bay and five unit bays for installation of 50 MW capacity generators in each unit. The construction of main dam had been completed in 1985. Due to aging effect various distresses in the form of leaching and seepage have been observed in the powerhouse. The visible distresses have raised apprehensions about the structural safety of the powerhouse. Accordingly, based on the request from OHPC Authority for assessment of in-situ quality of concrete of distressed structural member of Rengali Power House structure, qualitative assessment by Non-destructive testing has been carried out by CWPRS at various locations by using Ultrasonic Pulse Transmission Technique and Rebound Hammer method.

In-situ Ultrasonic tests in progress



Location Showing NDT Studies Conducted in Inspection Gallery



Velocity contours for Conference Room

In-situ Ultrasonic and Rebound Hammer testing in progress during the field study are shown above figures. In order to cover maximum portion of the concrete surfaces, test surfaces have been divided into several close grids. Grease has been applied at each grid points to have good coupling between transducers and test surface. Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) equipment and Schmidt Rebound Hammer have been used for evaluating the in-situ quality of the structural concrete. During the present study, about 860 velocities of elastic compressional waves and about 700 rebound numbers have been recorded. The distribution of computed velocity based on measured travel time is shown in the form of contours and colourful zones.

The results of the UPV test in the form of contours conducted for conference room is shown in contours. It is evident from the contour plot that major portion is covered with blue color indicating that quality of concrete in this location is good. However, at few locations the quality of concrete has been found to be of medium type which as shown in yellow color in the contour plot. Based on the analysis of the data collected at all the desired locations, it can be concluded that doubtful quality of concrete has been observed at various locations such as few sections in LTR, MCR, Battery Room and Turbine floor. Therefore, it is suggested to take remedial measures such as replacement of poor quality material by suitable epoxy mortar and suitable epoxy grouting of joints/cracks at these locations for improving quality of the structure.

Impacts of the Study

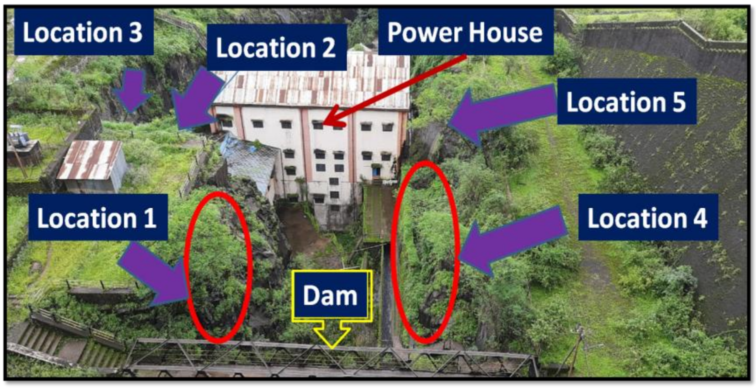
Based on the results of the study quality of the concrete at various locations of the powerhouse structure has been assessed by using combinations of various NDT methods.

Doubtful quality of concrete has been observed at various locations such as few sections in LTR, MCR, Battery Room and Turbine floor.

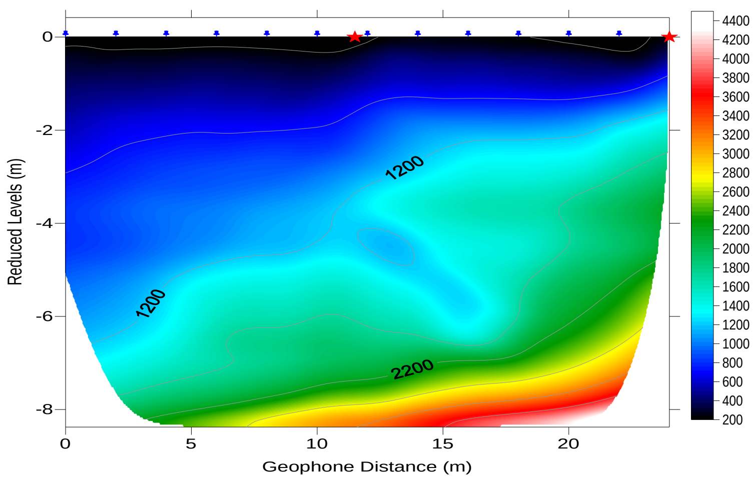
As the study identified the weak zones at different locations of the powerhouse, accordingly epoxy grouting and repairs have been suggested at these locations for strengthening of the structure which will improve the overall safety of the powerhouse structure.

4.3 Panshet Hydroelectric Project, Maharashtra

Panshet Dam constructed on Ambi River, is located at about 50 km southwest of the Pune city. The dam was constructed in the late 1950's and the water from the reservoir is mainly used for irrigation, drinking water and hydro power generation for fulfilling the requirement of Pune. The power house is located at the toe of the dam with an installed capacity of about 11 MW. The power house was constructed by excavating hard basalt rock about 20 to 25 m deep vertically near downstream toe of the dam.

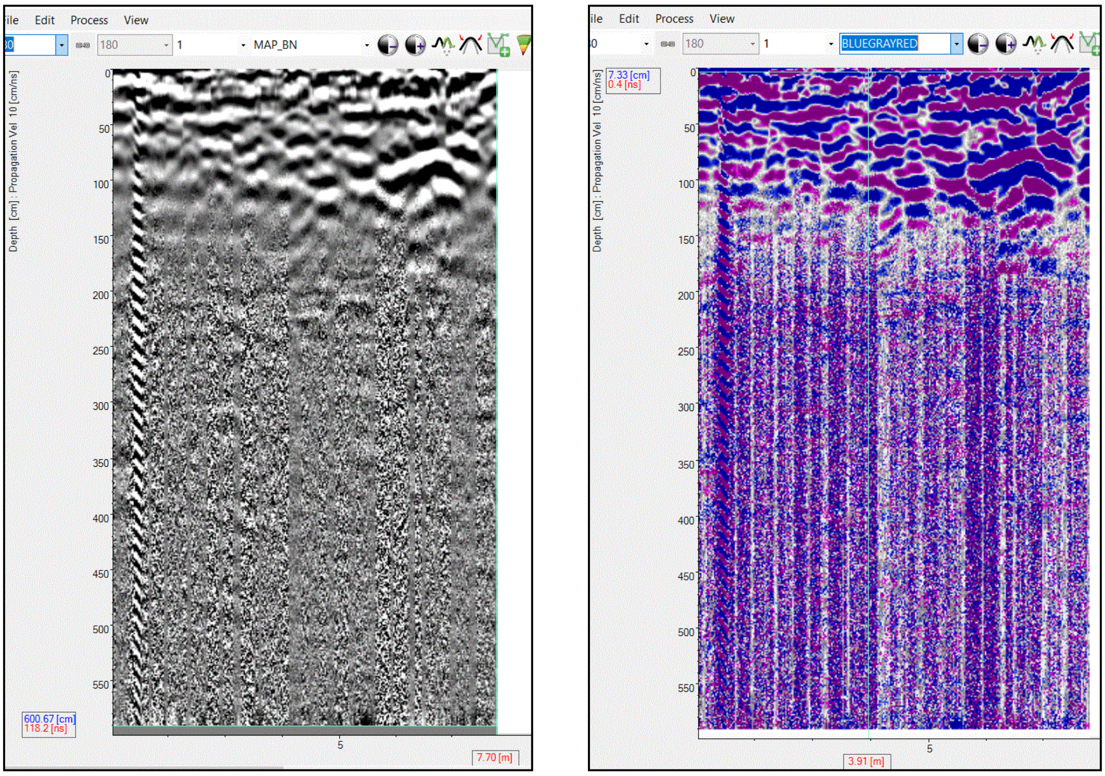


Locations around the powerhouse



Contour map showing the distribution of velocities with depth

The powerhouse building is located very close i.e. about 1 to 2 m from the vertical rock cliff as shown in above figure. Due to vertical cutting of the rock, frequent rock cliff falling has been observed during rainy season since 2003 putting the powerhouse structure in danger. Considering the importance of the powerhouse structure, it becomes very much essential to ensure the safety of the powerhouse from rock fall. In this connection, based on the request from the project authority, NDT study has been carried out by using different methods such as Ground Penetrating Radar, Seismic Refraction and Sonic wave transmission methods for in-situ quality assessment of the rockmass around the power house. The results of the NDT study identified the weak zones in the rockmass as shown in above contour map and based on the analysis of the results, necessary remedial measure were suggested for strengthening of the rockmass around the power house by grouting. It was recommended to carry out cementitious grouting at all the locations in order to improve the strength of the rockmass. Accordingly, cementitious grouting using grout mix design, has been carried out at site by following the suggestions made by CWPRS. Further in order to assess the efficacy of the grouting at site, GPR study has been carried out at one location. GPR study results revealed that grouting materials have travelled into the voids located in the rockmass and which in turn significantly improved the quality of the rock mass after grouting. Hence, it is suggested to continue with the same procedure of grouting at other locations at the site to further improve the quality and strength of rockmass at other distressed locations.



GPR Image Obtained at about 3 m from the Rock Face

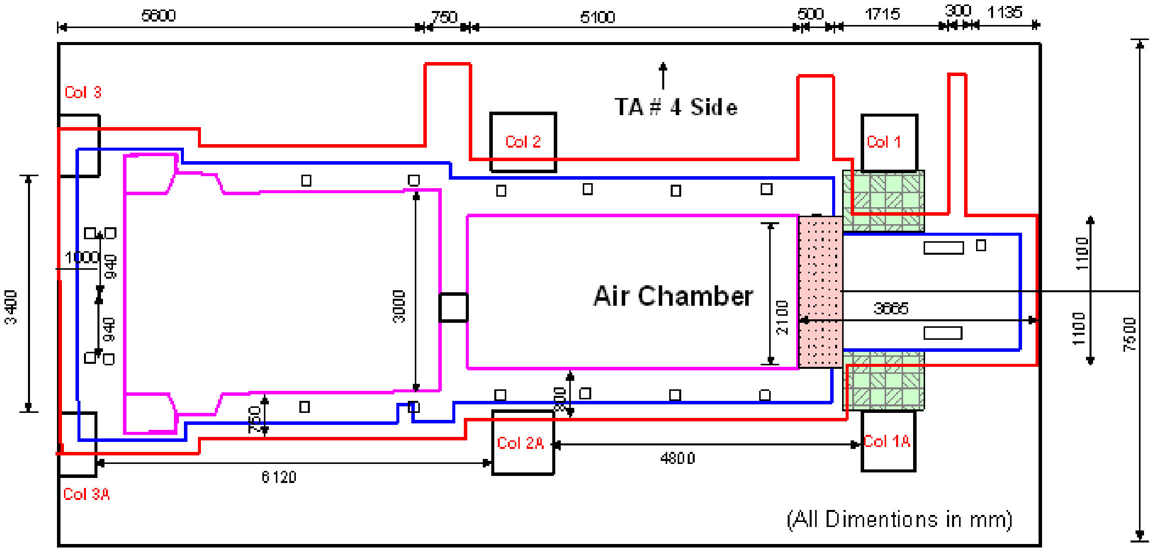
Impact of the Study

The study identified the weak zones in the rockmass and accordingly remedial measures were suggested for strengthening. The strengthening of the rock cliff ensured the safety of the powerhouse structure by arresting the rock fall which further paved the way for continuous operation of the generation units for power generation to full fill the power demands of Pune.

4.4 Rourkela Steel Plant, Odisha

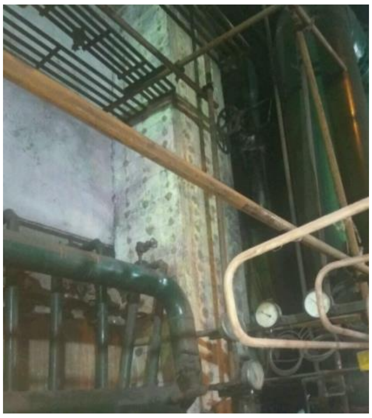
The Turbo Alternator Unit No. 6 (TA # 6), a part of the Captive Power Plant No.1 (CPP-1) is used to meet the power requirement of Rourkela Steel Plant (RSP), Rourkela, Odisha. The unit was commissioned in the year 1965-66. The ultimate strength of the concrete used in construction of the foundation was 22.5 MPa. In the past, the RSP authorities have renovated the CPP-1 by replacing the old turbines by new ones, retaining their old frame type R.C.C. foundations and alternators. Subsequently, during operation of the TA # 6, excessive vibrations were felt in the generator portion. It was suspected that the excessive vibrations may be due to deterioration in quality of the foundation concrete. With a view to ascertain the in-situ quality of foundation concrete, non-destructive testing was carried out by Central Water and Power Research Station (CWPRS), Pune. The non-destructive testing of different parts of the concrete foundation was carried out by using ultrasonic pulse transmission technique. The studies identified a portion of about 2.1 m long and 1m thick concrete in deck slab / transverse beam between the columns 1 and 1A is of poor quality. Based on these recommendations, the transverse beam was repaired by the Project Authorities.

Inside view of Captive Power Plant, Rourkela Steel Plant, Odisha



Schematic Diagram Showing Deck Plan of the 25 MW TA Foundations for RSP

To ascertain the efficacy of the repairing measures, the RSP authorities have entrusted the task of testing the quality of in-situ concrete of the repaired transverse beam to CWPRS Pune. Ultrasonic pulse transmission technique was deployed for evaluating the in-situ quality of the concrete of the repaired transverse beam. Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) instrument with suitable transducers was used for testing of the concrete. The transverse beam was marked with 250 mm × 250 mm grid points and travel times of elastic compressional waves were measured at each grid point. Knowing the distance of travel path and corresponding travel time of elastic waves, compressional wave velocity was estimated at each grid point.



Column Structure where opposite faces are not accessible (Indirect

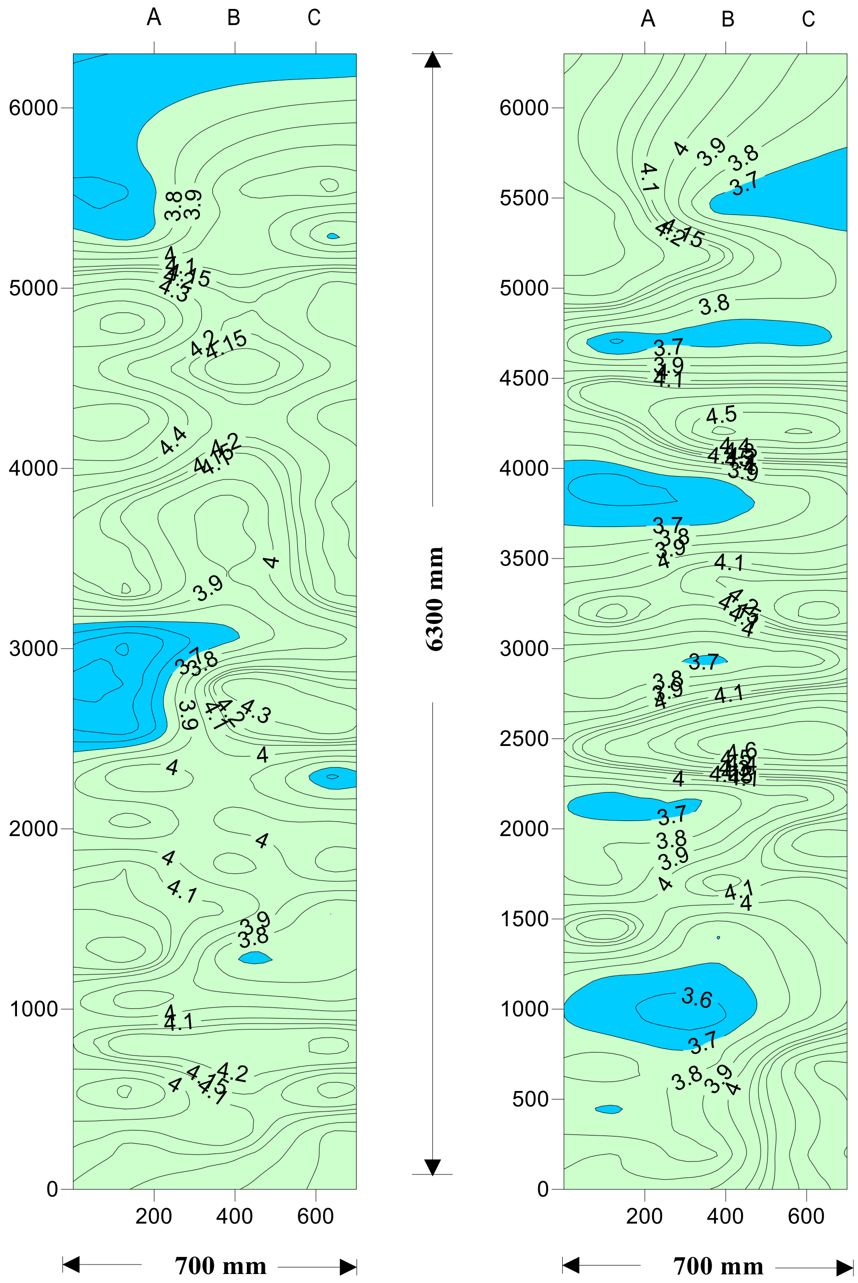
Pedestal Structure where opposite faces are accessible (Direct

Beam Structure where opposite faces are not accessible (Indirect

Column/Pedestal Structure

Beam Structure

A velocity criterion based on CWPRS experiences gained from testing of large number of concrete foundations over last several decades has been adopted to correlate the observed velocity with in-situ quality of foundation concrete of TA # 6. Considering the velocity of elastic compressional waves obtained and the velocity criteria adopted the in-situ quality of concrete of the transverse beam between columns 1 and 1 A has been inferred as of good to very good quality. The repairing measures undertaken by the project authorities have helped to improve the in-situ quality of the transverse beam between column 1 and 1A of TA # 6.



Column -1 **Column -1A**

Contour map showing the distribution of P-wave velocities

- Both Ultrasonic pulse transmission and Rebound Hammer test techniques have been deployed at designated grid points for complete in-situ evaluation of quality of structural concrete of T.A. foundation of RSP unit No. 6.
- In-situ studies have been conducted while the turbines, alternator and condenser including all other ancillary equipment of the Unit have been in their respective designated fixed places.
- In order to classify the quality of the concrete, velocity and rebound number criteria as specified in IS 13311: 1992 have been used.
- Based on test results, the structural concrete of the test locations can be designated as good to very good quality.

Impact of the Study

The study successfully identified weak zone at beam 2A and suggested for repairing. Accordingly, Project Authority has repaired beam and assessed the in-situ quality of concrete present in the beam 2A. After repair, the quality of concrete was found to be of good to very good category. It has enabled the project authority for continuous operation of the thermal power generation unit.

4.5 Vihar Dam, Maharashtra

Vihar dam was constructed in 1859 for full filing the water requirements of Mumbai city. Due to aging and other environmental factors various distresses were developed in the dam structure; hence it was required to be strengthened after qualitative assessment.

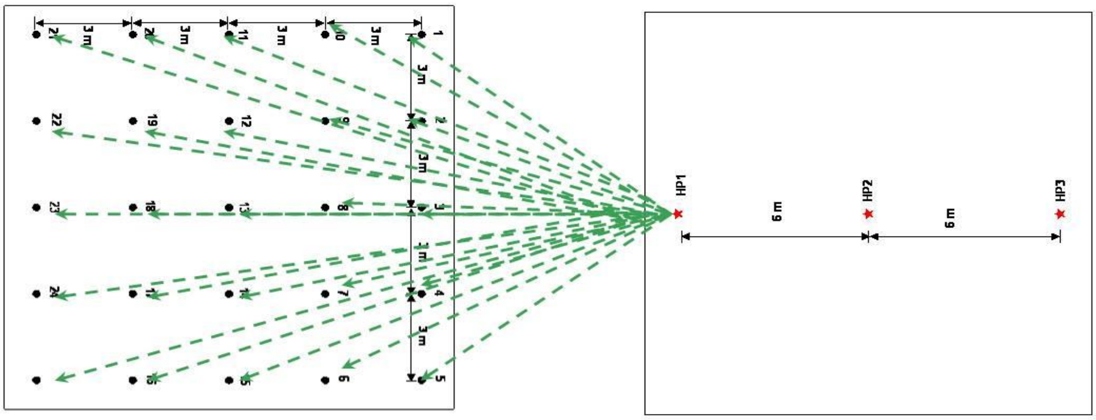
Salient features of these dams are given below.

Salient Features		
S.No.	**Description**	**Vihar Lake**
1.	Commissioning Year	1859
2.	Type of dam	Earthen (3 sections)
3.	Catchment area, sq.km.	18.96
4.	Total length of dam,m	711.20
5.	Top Width of the dam,m	a)7.31, b)6.09, c)6.09
6.	Maximum height of dam, m	a)25.60, b)12.80, c)14.90
7.	Length of waste weir, m	107.90

Non-destructive testing for the masonry sections of these dams have been carried out by using sonic wave transmission methods to ascertain the in-situ strengths and quality of the masonry.

NDT tests in progress at site

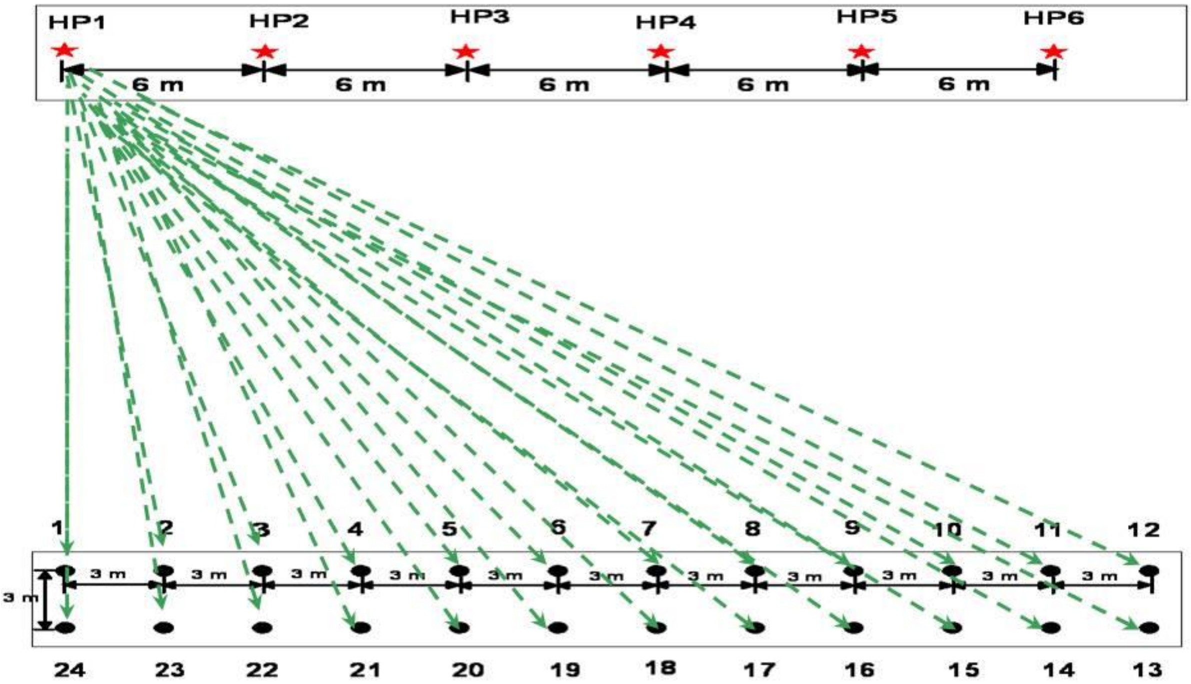
Pattern A (5 points x 5 lines): To cover selected portion, 24 geophones were fixed in a square type pattern on downstream side. The Locations of geophones were marked as 1 to 24. Pattern A is used for testing of all earthen dams.



Marking of Geophones and Location of Hammer Points in Pattern A

Three hammer points for generating seismic waves were marked in vertical line on the upstream face of the dam; Hammer Point 1 (HP1) opposite to geophone location 3, HP2 opposite to geophone location 13 and HP3 opposite to geophone location 23. Above figure shows the location of three hammer points HP1, HP2 and HP3 located on the upstream face.

Pattern B (12 points x 2 lines): To cover selected portion 24 geophones were fixed in a linear type pattern on downstream side. The Locations of geophones were marked as 1 to 24. Pattern B is used for testing of all masonry dams.



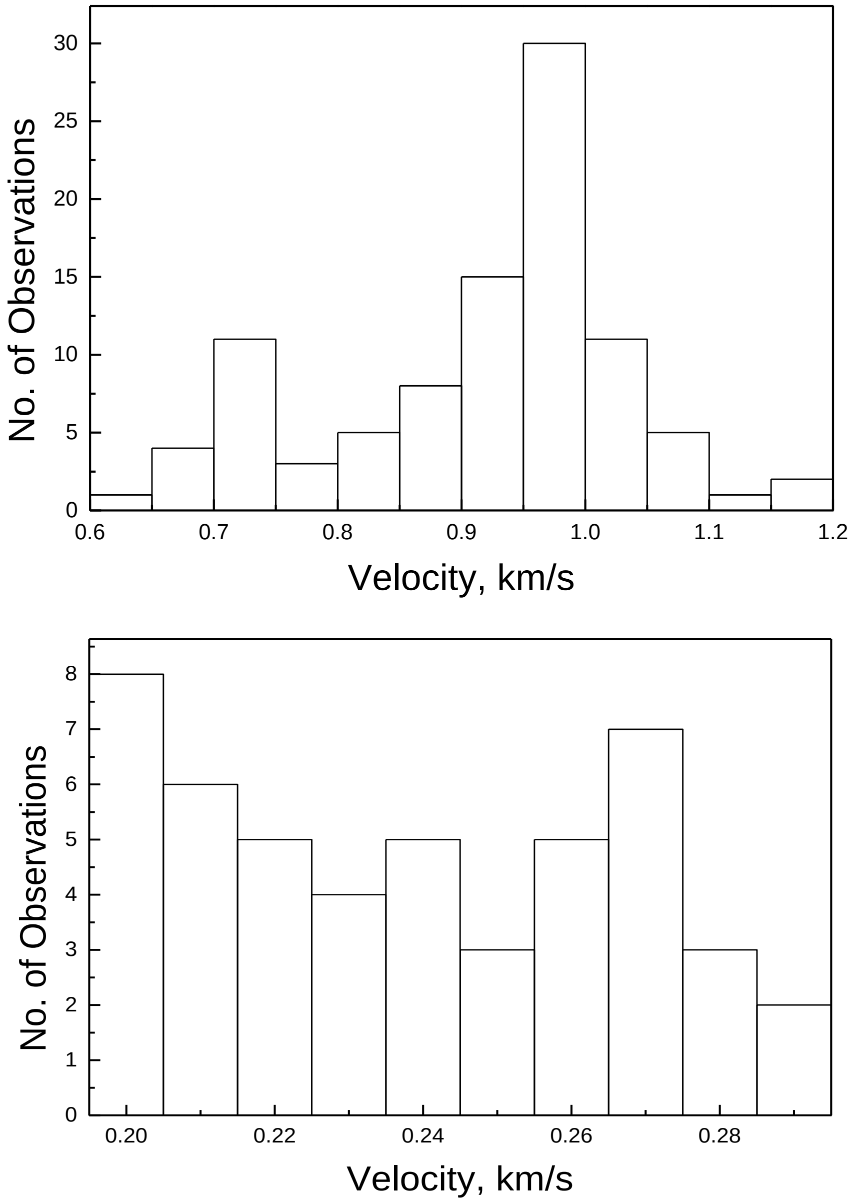
Marking of Geophones and Location of Hammer Points in Pattern B

Six hammer points for generating seismic waves were marked in horizontal line on the upstream face of the dam; Hammer Point 1 (HP1) - opposite to geophone location 1, HP2 - opposite to geophone location 3, like that HP3 to HP6, opposite to geophone location 3, 5, 7 and 11. Below Figure shows the photograph of six hammer points HP1 to HP6 located on the upstream face.

The elastic waves generated at each of the hammer points on the upstream face of the dam were detected simultaneously at twenty-four locations (profile) by geophones on the downstream face of the dam.

In the study compression wave velocity passing through earthen portion in the range of 0.2 to 2.0 km/s is considered as good to very good quality and less than 0.2 km/s is considered as questionable to poor quality.

From the results, it has been observed that the velocities of elastic compressional waves in the earthen dams of Vihar dam No. 1, 2, 3 are in the range of 0.2 to 2 km/s which indicates the quality to be of good to very good type material.



Distribution of P-wave Velocities Observed at Vihar dam No. 1&2

Impact of the study

Qualitative assessment of 100 – 150 year old dams, have been assessed successfully by NDT methods which enabled the Project Authority to make full use of the capacity of the reservoir to store water required for supplying to Mumbai, Maharashtra.

4.6 Indira Sagar Project, Madhya Pradesh

Indira Sagar Project (ISP) located in Khandwa district of Madhya Pradesh across River Narmada is a multipurpose project with an installed capacity of 1000 MW (8 × 125 MW). The project comprises of a 92 meters high and 653 meters long concrete gravity dam consisting of 158 m of non-overflow section and 495 m of overflow spillway portion. The Indira Sagar Power Station (ISPS), a part of the multipurpose project on river Narmada was developed by NHDC Limited (A joint venture of National Hydropower Corporation Ltd and Government of Madhya Pradesh), formerly known as Narmada Hydroelectric Development Corporation Ltd. The Power House with Machine hall (202 m long, 23 m wide and 53 m high), service bay (42 m long, 23 m wide and 24 m high) and transformer yard (202 m long, 20 m wide) to house eight Francis type turbines of 125 MW each is situated on the right bank of the river. The synchronous speed of the turbines is 115.4 RPM and number of poles of each turbine is 52. Below image shows the view of dam and power house of ISP. During power generation condition, structural vibrations were observed in the power house civil structures. It was apprehended that excessive vibrations may damage power house structure. Therefore, vibration study was undertaken for measuring the vibration levels on machine hall structures during different operating conditions of turbine units.

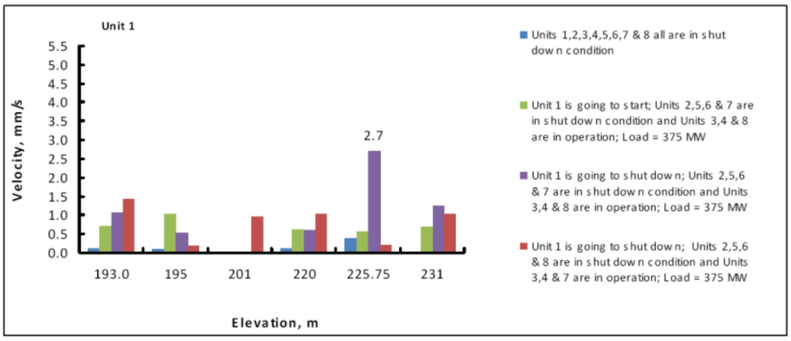
View of the Dam and Power House of Indira Sagar Project

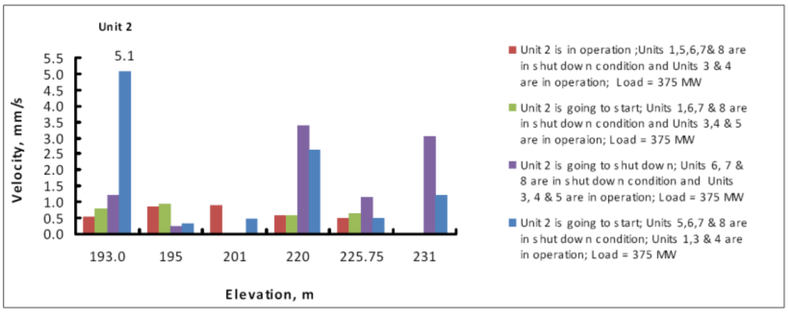
Vibration study has been carried out at different locations of various floor levels of the power house, such as near turbine shaft, pit liner wall, turbine floor, generator floor, machine hall floor and roof, and power house top. Tri-axial accelerometer with signal conditioners and PC based data acquisition system were used for measuring the vibration. At each location, vibration levels were measured in three mutually perpendicular directions; viz., longitudinal, vertical and transverse directions. The acceleration data were analyzed to obtain the peak velocity and its associated predominant frequency. The peak velocities obtained from three mutually perpendicular directions were used to estimate the resultant velocity, which was compared with the available standards to assess the possibility of the impact of vibrations on civil structures.

During the present field studies, velocity and acceleration data were measured at different levels of the machine hall structure. Vibrations were measured in three mutually perpendicular directions (transverse T, vertical V and longitudinal L) for each unit running under the following conditions:

i. When all the eight units are in shut down conditions
ii. Particular unit is in running condition
iii. Particular unit is going to start
iv. Particular unit is going to shut down

The vibration levels recorded at different elevations of the machine hall structure for all the eight units running in different generation conditions are illustrated in the form of histograms.





Vibration recorded at different load conditions

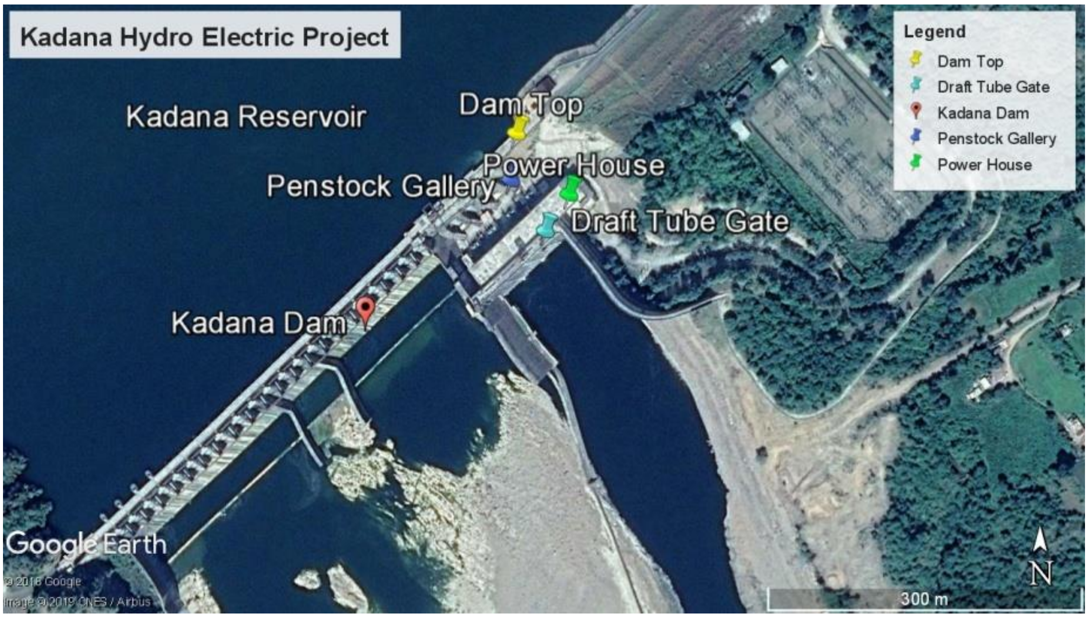
From comparison of the observed vibration levels with the adopted safe vibration level, it has been found that the observed vibration levels are well below the recommended safe limit for the powerhouse structure and not capable of inducing any structural damage.

Impact of the Study

The study assessed the safety of the powerhouse structure due to generation induced vibrations. As the observed vibration levels were found to be far lower than the safe vibration limit of the structure, hence the powerhouse was recommended to be operated continuously based on the requirement of the project for power generation.

4.7 Kadana Hydroelectric Project, Gujarat

66m high and 1.551km long earthen and masonry type composite Kadana Dam has been built during the period 1968 to 1979 after an agreement in the year 1966 between the Gujarat and Rajasthan States for development and utilization of water from Mahi River. The Dam is situated accross river Mahi near village Kadana in Kadana Taluka of Mahisagar District of Gujarat State under Gujarat State Electricity Corporation Limited (GSECL), an undertaking of the Government of Gujarat. Main purpose of the Dam is irrigation, hydropower generation and flood protection.The photograph below presents a panoramic view of Kadana Dam, including a portion of the reservoir.



Google Earth View of Kadana Dam and Power House

Downstream View of Kadana Dam

The Dam is a masonry dam flanked at both sides by earthen sections. Length of the masonry section including spillway is (621m+113m) whereas that of the earth Dam section is (762m+168m).Total length of the spillway is (406m+113m). There are a total of 27 (21+6) nos. Ogee type spillways having radial gates of size 15.5×14m. Above figure shows the downstream view of the Kadana Dam.The Dam is having a total power generation capacity of 240 MW having 4 generating units of 60 MW each. View of the Power House from the top of the Dam, featuring four transformer units, is illustrated in the figure.

View of Power House from Dam Top

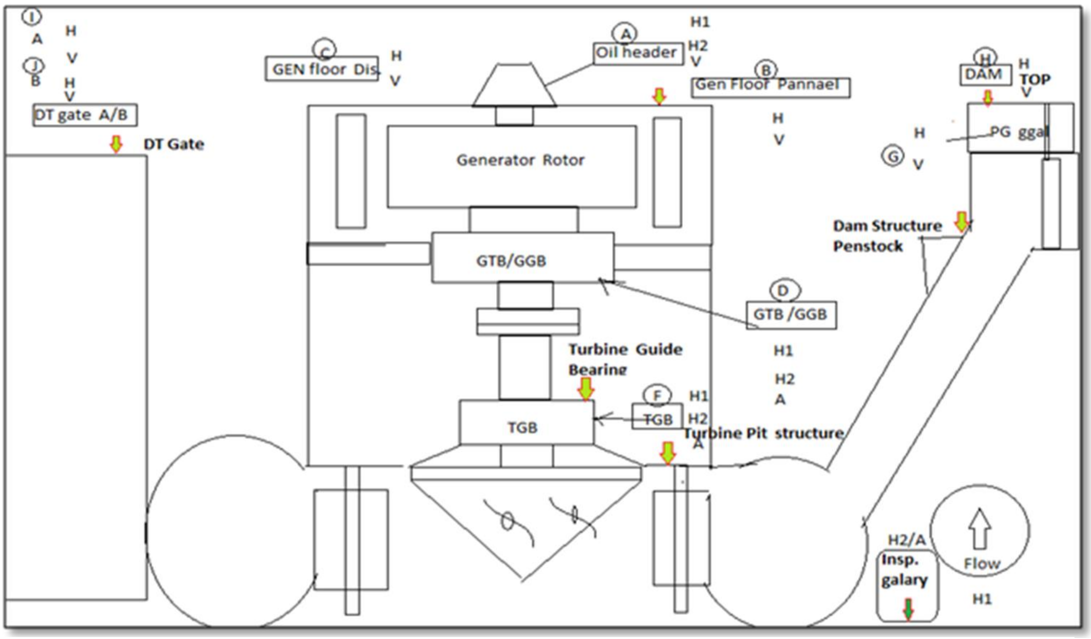
Each of these power units are equipped with Reversible Hydro Turbine and are thus capable of running in Generation mode and Pump mode, as well. Distance between each generating unit is 24 m. An internal view of the Power House featuring four generating units, each with a capacity of 60MW, is illustrated in the figures below.

Inside view of Power House with 4 ×60 MW units

Cross sectional model of Kadana Dam Power House (Photo courtesy: Kadana Dam Authority)

Vibration monitoring has been carried under the different load conditions, such as Generation Mode, Pump Mode at different locations such as Dam top near penstock gate of Unit No. 3, penstock gallery, Generator floor Upstream and Downstream , turbine floor and turbine pit, Inspection gallery (Draft tube manhole), draft tube gate etc.

Vibration measurements have been carried out at different locations which have been marked during initial inspection of the Dam and power house and as shown in the schematic diagram using instruments known as "Engineering Seismographs".



Locations selected for vibration monitoring

It has been observed that the RMS vibration level observed at turbine guide bearing during pump mode and generation mode operation except full load (pump mode) condition is found to be well below the recommended safe vibration level. However, during pump mode operation at full load condition, the vertical component of the RMS velocity is found to be 13.08 mm/s which is much higher than the safe vibration level. Therefore, it was suggested to take necessary preventive measures to restrict the vibration level under safe limit during the pump mode operation at full load condition.

Impact of the Study

The study assessed the safety of the powerhouse, dam as well as the turbine unit due to generation as well as pump mode operation of the turbine units. The pump mode operation of the Unit was attempted for the first time and it was found that the observed vibration levels under pump mode are quite higher than the generation mode. This enabled the project authority to take further necessary remedial measures for restricting the vibration within the safe limit.

4.8 Farakka Barrage, West Bengal

Farakka Barrage is located in Murshidabad and Malda districts of West Bengal at about 300 km North of Kolkata. It is one of the largest Barrage of its kind in the country. It was commissioned in the year 1975 with the main purpose of diverting the water of River Ganga through a feeder canal into the River Hoogly for the maintenance and survival of Kolkata Port. Farakka Barrage Project is facilitating implementation of agreement on sharing of Ganga water between India and Bangladesh.

Arial View of Farakka Barrage, Kolkata

FBP also ensures water supply for use of Thermal Power Plant operated by NTPC Ltd. at Farakka (2100 MW) and West Bengal State Power Distribution Company at Sagardighi (600 MW). This is a 2.245 km long concrete structure with 109 bays of 18.3 m span each. There are two road cum rail bridges over the barrage, providing the shortest link from Kolkata to Northern part of West Bengal and north east states. Therefore, heavy traffic is running on the road bridge, due to which vibrations are felt on the Beams and Piers. Vibrations are also observed due to the movement of train on the two rail tracks located on the barrage.

As per recommendations of Farakka Barrage Technical Advisory Committee, study has been carried out to assess the vibration levels in the rail cum Road Bridge, Piers and beams due to the existing road and rail traffic conditions.

It has been observed that heavy to very heavy vehicles are running over the road bridge due to which significant continuous vibrations are felt on the different parts of the barrage such as beams and piers. As per notice board on road bridge of the barrage, speed of the vehicles on road bridge has been restricted to 20 km/hr in order to safe guard the barrage from any kind of damage. Based on the site inspection and discussion with Project officials, monitoring of real time vibration has been carried out on the footpath of Road Bridge (center of beam) near Bay No. 41 using velocity sensor as well as strong motion accelerographs.

Maximum vibration level of 23.1 mm/s and corresponding acceleration level of 0.101g have been recorded at this location, which is quite high and under continuous vibration may endanger the safety of the road bridge. Therefore, it is suggested to carry out long term real time vibration measurement at few critical locations of the Barrage by employing sufficient number of sensors.

There are two rail bridges over the barrage one for upcoming trains and another for down going trains. Different types of trains such as passenger and goods trains are running over the bridge. Speed limit of the trains has been restricted to 40 km/h in order to ensure utmost safety of the Barrage. Railway Authority has been insisting the project authority about the feasibility of increasing the speed of the trains above existing 40 km/h limit in the near future without endangering safety of the barrage. During inspection of the Piers and Beams, cracks have been observed in few Piers near the top.

To study the integral behaviour of the Pier having cracks and comparison with sound pier, Bay No. 3 and Bay No. 65were selected for vibration monitoring and location of sensors are shown in the above figures.After analysis of the vibration data, it has been observed that maximum vibration level of 1.16 mm/s and acceleration level of 0.063g have been recorded for the pier at Bay No 65 whereas maximum vibration level of 1.61 mm/s has been observed for the pier at Bay No. 3. The observed vibration levels are well within the acceptable limit. The level of vibration in pier having surface cracks is also very low and well within allowable limit and is almost same as in sound pier of bay no.65 but frequency of vibration is quite high indicating deep penetration of cracks into the pier which should be further investigated by NDT. Therefore, the vibration levels observed in the piers due to movement of road traffic and trains with speed restrictions remain well within acceptable limits.

Impact of the Study

Based on the observations made during the site inspection visit and after analysis of the vibration data at different locations following suggestions are made:

a) The vibration levels observed during the period of investigation is found to be very high in the mid portion of Road Bridge. Hence, considering the national importance of the Barrage, it was suggested to carry out long term real-time vibration measurement by installing sufficient number of sensors on the barrage.

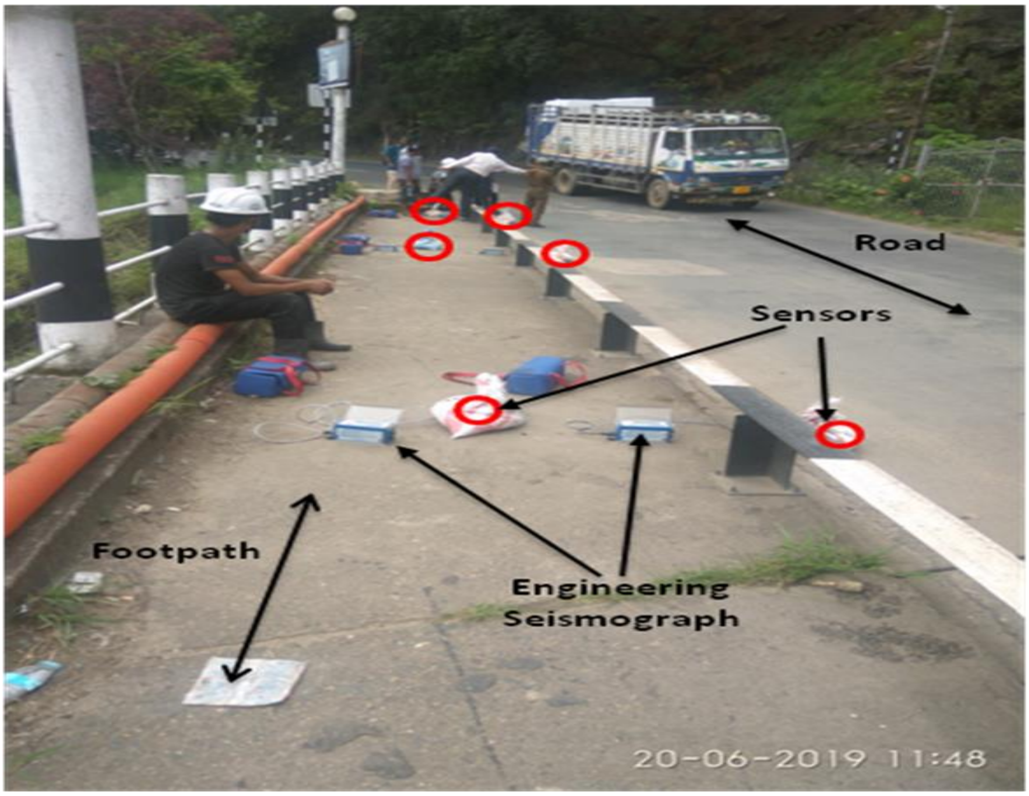
b) At present vibration levels in the pier during train movement at restricted speed of 40 Km/h are well within acceptable limits. For increasing the train speed limit as required by the Railway department, vibration measurement at different speed of the train (step wise increment with different type train and running speed condition as well as with simultaneously train running on both the rail tracks) needs to be carried out in order to ensure the safety of the barrage. Based on the observation and analysis of the data, optimum speed of the train may be finalized.

4.9 Umiam Hydroelectric Project, Meghalaya

The Umiam Stage-I, Hydro Electric Project of Meghalaya Power Generation Corporation Limited (Me.P.G.C.L.) is located in the East Khasi Hills District of Meghalaya at a distance of about 87 km from Guwahati & 16 km from Shillong. The project was commissioned in the year 1965, which comprises of 73.2 m high Concrete Gravity Dam across the Umiam River consisting of 11 blocks with two overflow spillway bays (12.2 m ×12.2 m each), two radial gates, a 2.05 km HRT, two penstock lines of 1.98 m dia having 530 m length each with a Power House of installed generating capacity of 36 MW electricity from four generating units of 9 MW capacity each. A 7.32 m wide two-lane road on top of the dam forms the part of National Highway (NH-40) linking the states of Mizoram, Tripura, Assam and Meghalaya and heavy traffic is passing over it. In view of above, Project Authorities are concerned about the safety of the dam due to traffic induced vibrations in the dam body. In this connection, based on request from Project Authority, the traffic vibration measurement studies have been carried out by Central Water & Power Research Station

(CWPRS), Pune at various locations on the Umiam Dam. Before commencement of vibration measurements, detailed site inspection has been conducted to figure out suitable locations for vibration monitoring at different locations of the dam and road bridge. Vibration measurements have been carried out at several locations viz. footpath, adjoining road, road railings, downstream face, spillway piers and drainage gallery of block no. 7 at Umiam dam. From the analysis and interpretation of vibration data, it has been observed that the vibration levels induced by traffic on Umiam dam is very low and is far below the recommended safe vibration level. Vibration level has been found to be in range from 0.064 mm/s to 2.585 mm/s in the entire portion of the dam which is much lower than the safe vibration level. Distribution of vibration levels observed at Foot path and on the Road for all the blocks of Umiam dam is shown below figure. Though the vibration levels are found to be low and within the safe limits, it is not advisable to have continuous vibrations due to heavy traffic on such important structure like a dam. Continuous vibrations due to heavy traffic on top of the dam in the long run, may induce internal cracking or increase the extent of cracking thus endangering structural safety of the dam. Moreover, vibrations may also induce opening up of lift and block joints thus resulting in seepage through joints. Considering the importance of the Umiam dam, it is suggested to carry out long term vibration monitoring by installing vibration monitoring system at the dam body.

Downstream View of the UmiamDam



Schematic Diagram Showing Vibration Monitoring Points at Different Locations on Top of Umiam Dam, Meghalaya

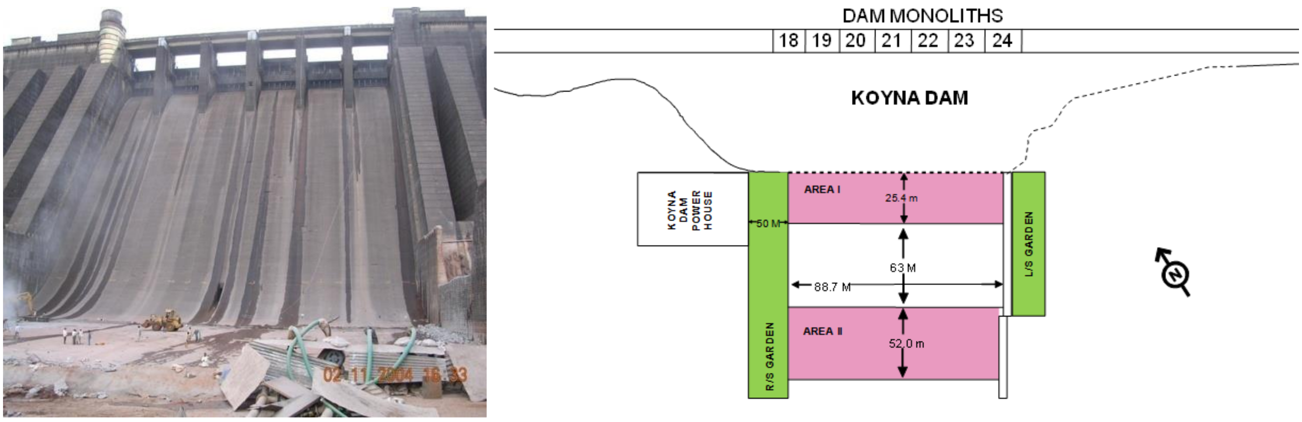
Impact of the Study

Based on the results of the vibration study carried out in different phases, it was suggested to divert the heavy vehicles by constructing parallel bridge for enhancing the service life of the existing Dam Bridge. Accordingly, the traffic was diverted by constructing parallel bridge and the dam was safe guarded as the observed vibration levels were well within the acceptable limit.

4.10 Koyna Dam, Maharashtra

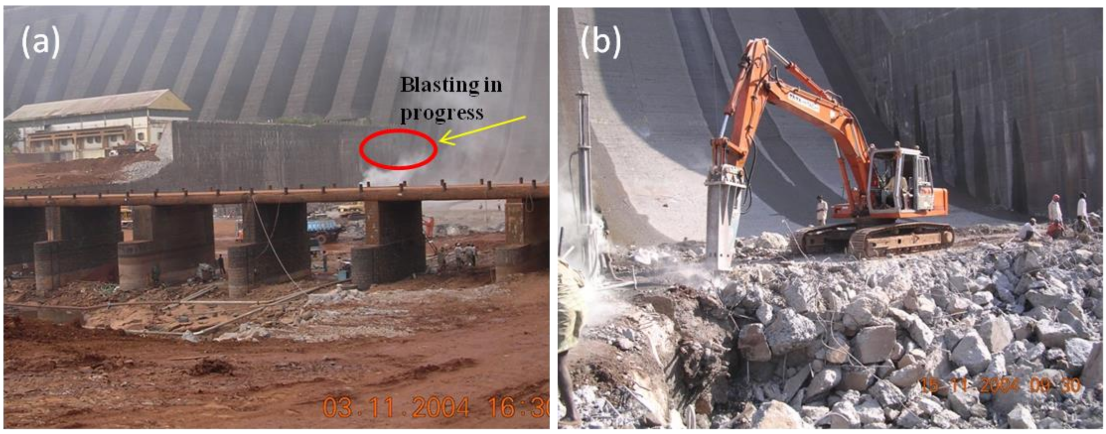
Koyna Dam is one of the largest Dams in Maharashtra, India. It is a rubble concrete gravity type of Dam with a length of about 807.2 m and maximum height above deepest foundation level as 103.2 m. Post Killari earthquake in 1967, as a safety measure towards improvement of safety of the Dam, Non-Overflow section of the Dam has been strengthened by providing concrete buttresses during 1973. Post Killari earthquake, for further safety improvement measures, it was decided by the Project Authority to strengthen Overflow portion of the Dam extending from half of monolith No. 18 to half of monolith No. 24 by providing full concrete backing.

Rock mass just downstream of spillway in close proximity of the Dam and the Koyna Dam Power House (KDPH), has been excavated to the extent of about 50,000 m^3 of hard rock and 21,000 m^3 of the overlying R.C. concrete by traditional method of drilling and blasting. Schematically diagram shows the excavation area and various structures located nearby Koyna Dam.



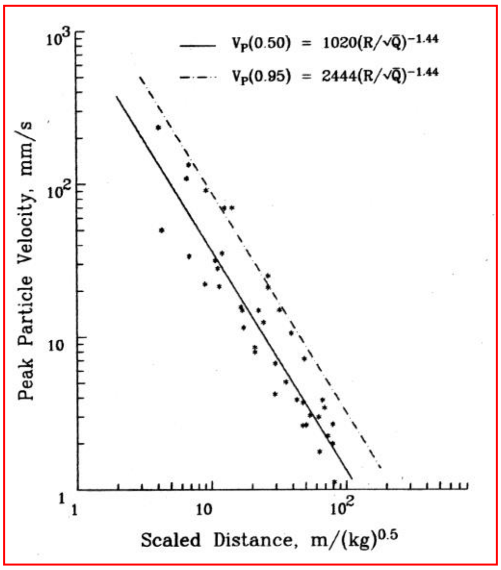
Koyna Dam Excavation Area

Several trail blasts were carried out for optimization of blast design parameters. The vibrations generated from the trial blasts were measured on the bedrock at several different distances. These data were used for developing the site specific attenuation relation.



Photographs Showing (a) Blasting and (b) Excavation Work in Progress at Koyna Dam Site

These attenuation equations are plotted in the graph along with the observed data. 95% confidence level relation has been used for estimating the safe charge weight per delay. The safe charges thus obtained for excavation in different zones of Area - I located in front of the various monoliths of Koyna Dam are given in table below.



The site specific attenuation relations with mean and 95% confidence levels developed

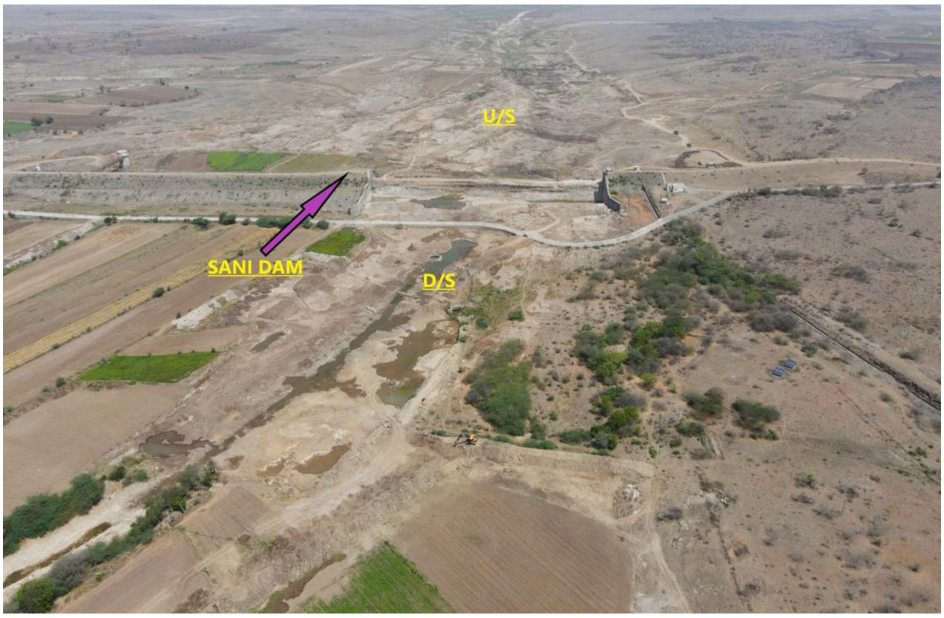
Impact of the study

Excavation of the desired quantity of rock mass has been successfully carried out by ensuring safety of the Koyna Dam. Accordingly, strengthening of the OF portion was carried out by providing additional concrete cover. Strengthening of the dam enabled project authority to store water up to its highest reservoir capacity and also for uninterrupted power generation through the hydropower unit.

4.11 Sani Dam, Gujarat

Sani Reservoir Project situated near village Jepur, Tal. Kalyanpur, District Devbhoomi Dwarka of Gujarat is located across river Sani. The project was commissioned in the year 1979 and completed with the canal system in the year 1992. The project is meant for Irrigation and drinking water supply to about 89 villages and 3 Nagarpalika of Okha-Mandal Region of Gujarat. However, due to aging, piping and other environmental effects various distresses were observed at the spillway portions of the dam. In view of the above and considering the importance of the dam for these regions, review committee recommended for reconstruction of the spillway portion of the dam after dismantling of the entire existing spillway portion (194.59 m) of the dam. The foundation strata below spillway portion consistsof very hard rock mass (Basalt). The excavation work was required to be carried out over a length of 194.59 m and with average depth of 3 – 4 m in spillway portion amounting to a rock mass volume of 25,000 cum.

Dismantling of Old Spillway in Progress



Aerial View of Sani Dam after Dismantling of the Old Spillway

Vibration Monitoring on Top of Left Side Embankment during Actual Blasting

Vibration Levels Observed at Base of the Embankment

In this connection, based on the request from Project Authority, CWPRS Scientists visited the site and conducted several trial blasts to recommend the safe charge weight per delay to be used during actual blasting operations by ensuring the safety of the earthen embankment and other nearby major structures. A maximum charge weight per delay in the range of 4.17 kg - 11.12 kg has been used for carrying out the rock excavation during actual blasting operations. Continuous monitoring of peak particle velocity (PPV) as well peak ground acceleration (PGA) has been carried out on top and base of the earthen embankment of the dam. Maximum PPV level observed on top of the earthen embankment has been found to be about 8.5 mm/s as shown in Fig.1 which is lower than the recommended safe vibration level. Maximum PGA level observed on top of the embankment from all the blasts is about 0.018 g which is also lower than the computed site specific PGA level of 0.14 g. No visible damage has been observed in the embankment as well as other nearby structures during the critical inspections after the completion of rock mass excavation. Hence, it can be concluded that the present rockmass excavation work by controlled blasting operation has been successfully completed by ensuring the safety of the earthen embankment as well as other nearby major structures.

Impacts of the Study

The study enabled the project authority for accelerating the reconstruction work of the dam which will ensure water availability for about 90 villages of Gujarat.

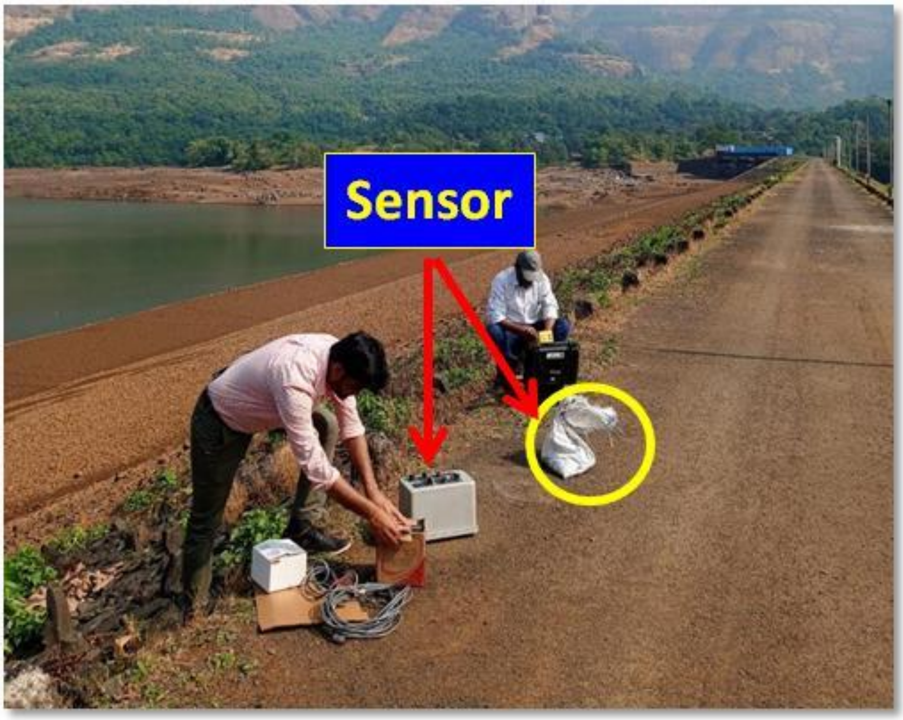
4.12 Bhira HEP, Maharashtra

Bhira Hydroelectric Project (HEP) located in the Raigad district of Maharashtra, consists of Tailrace Dam of 28 meter high earthen dam constructed across Kundalika River during the year 1927 and a 300 MW capacity Power house. It was considered as one of the major hydroelectric projects in India at that time having installed capacity of 300 MW. The water from this dam is mainly utilized for irrigation purposes by the nearby villages as well as for power generation by Tata Power Company Ltd., Maharashtra to fulfill the power demand of Mumbai and Pune regions. Presently, it is not possible to operate the Bhira Hydropower station in pump mode condition due to the unavailability of the required quantity of water in the pickup pond. To overcome this problem, Tata Power Company Ltd. decided to construct an open channel in hard rock for regulation of water flow.

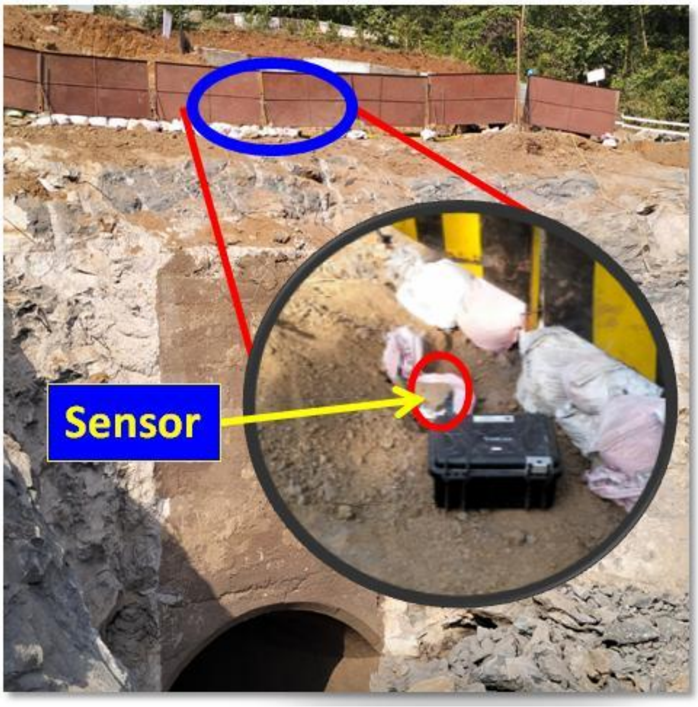
Aerial View of Bhira Tailrace Dam, Maharashtra

Map showing the monitoring and excavation locations
(Courtesy: Google LLC)

Some of the locations where blast vibrations have been monitored during the entire period of excavations are shown below.



Monitoring of Vibration on Dam Top



Monitoring of Vibration on Tunnel

In this connection, Project authority approached CWPRS, Pune to provide the necessary technical guidance for excavation of rock at site by using the methodology of controlled blasting in order to ensure the safety of the earthen dam and other important nearby structures. Accordingly, several trial blasts at site have been carried out to recommend the safe charge weight per delay and the blasting pattern to be used during actual rock excavation by ensuring the safety of the earthen dam and concrete lined tunnel. The recommended safe charge has been used for conducting actual blasting operations at site. Vibration level generated from all these blasts have been continuously monitored on rock bed close to dam, NOF section, top of the dam and tunnel by using tri-axial seismographs and strong motion accelerographs. Maximum Vibration level observed on top of earthen dam has been found to be about 0.8 mm/s whereas maximum vibration level recorded on top of tunnel has been found to be about 35 mm/s which are far lower than the recommended safe vibration level for ensuring safety. Maximum acceleration level of about 0.0035 g has been recorded at top of the dam which is also far lower than the PGA limit at this site. Post blast inspection of the dam and tunnel has been carried out to figure out any possible damage occurred in these structures due to controlled blasting operations. However, NO visible damage has been observed in these structures during the critical inspections after the completion of rock mass excavation using controlled blasting. Hence, it can be concluded that the present excavation work by blasting operation has been successfully completed using the methodology of controlled blasting by ensuring the safety of the dam as well as the tunnel.

Impact of the Study

The study enables the project authority to operate the 150 MW pumped storage unit successfully. The excess power generated due to the installation of control gate by rock excavation will be utilized for fulfilling the power demand of Mumbai and Pune region of Maharashtra.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

India has over 6000 dams and more than 3000 power plants including all the sources of power generation. Most of the existing dams and power houses are more than 40 years old. Due to ageing effect and old technologies employed in the construction of the structure during that period and exposures to frequent earthquakes, distress in various forms such as cracks, large deformations, seepages, bulging of faces of dams and galleries, loss of mortar in joints of masonry dams and dislodging of concrete from faces etc., have been observed. Due to these distresses, their conditions have become scary and have created apprehensions about their structural safety. Hence, evaluation and assessment of the present condition of the existing structures becomes more and more important.

In light of progressing deterioration in a structure, regular inspection and continuous monitoring form the basis to obtain reliable data about the present condition of the structures should be carried out. All these information enable to make decision for further maintenance and undertaking interventions. The portfolio of available non-destructive testing and monitoring methods for condition assessment is constantly growing. However, even though the methods are more and more elaborated the comprehensive evaluation of their reliability receive none or only minor attention. Major reason for this neglect is the lack of knowledge on how to assess and interpret the test results.

Non-destructive testing (NDT) methods have been extensively employed in qualitative assessment of various civil structures due to their reliability and effectiveness in assessing the overall quality of a material. NDT methods are regarded as potent instruments for assessing the strength and durability of existing concrete structures. It is frequently required to evaluate concrete structures once the concrete has fully solidified to ascertain whether the structure is appropriate for its intended purpose.

Non-destructive testing can be applicable on both existing as well as newly constructed structures. When constructing new buildings, the primary uses of NDT are for quality control and also for addressing uncertainties regarding the quality of materials. The evaluation of existing structures is typically associated with determining their structural integrity. In either scenario, if destructive testing is the sole method employed, such as by extracting cores for compression testing, the expenses associated with coring and testing may only permit a limited number of tests to be conducted on a massive structure like Dam, Aqueduct, powerhouse, barrage etc., the results obtained may be misleading. Under these circumstances, Non-destructive testing can be used as a preliminary step before proceeding with core sampling. This technical memorandum highlights the usefulness of non-destructive testing methods for qualitative assessment of massive civil structures with the help of several case studies.

In addition to the NDT methods, vibration based health monitoring of civil structures is extremely useful for assessing structural safety of the Dams, Powerhouses, barrages etc. During strengthening of old dams, barrages, etc. and expansion activities, deep excavations are required to be carried out in the close vicinity of existing hydraulic structures. During this process, excavation of hard rock is required to be carried out by using blasting operations as it is one of the most economical, efficient and time saving method for deep excavation of hard rock materials. In the process of blasting, the energy released due to the detonation of explosives is utilized for fragmentation of rock. However, during explosion ground vibrations are generated which has the potential to cause damage to the existing nearby structures. Therefore, for ensuring safety of these structures, the blasting pattern is required to be designed in such a way that the resulting vibration must be restricted within the safe limit. Qualitative assessment of the nearby structures before and after the blasting operation is also required to be carried out for assessing their structural integrity.

In several cases it has been observed that the structures are subjected to vibrations due to operation of generation units in a power house as well as the traffic induced vibration on barrages and bridges. If these vibration issues are not addressed before time, it may endanger the safety of the structures. Therefore, structural safety assessments of these structures are required carried out by continuously monitoring vibration levels under different conditions of traffic as well as generation. Based on the results obtained, remedial measures are taken towards strengthening of the structure.

In this technical memorandum, the applications of NDT and vibration monitoring methods have been discussed in detail with the help of successfully completed case studies. It has been observed that combination of one or more NDT methods for testing of civil structures are found to be more effective in assessing the in-situ quality of civil structures. Combined use of the testing methods, validate the results of one method with the other which in turn provides the confidence to the engineer to take decision about the structural integrity of the structure. Vibration based monitoring systems are found to be most suitable for assessing the structural safety of the civil structures.

5.2 Recommendations

In order to ensure the safety of the massive civil structures such as Dams, Powerhouses, Barrages, Aqueducts, etc. the following recommendations are made:

For Qualitative Assessment by NDT Methods

a) Non-destructive testing for qualitative assessment of the structures must be carried out by using ultrasonic and rebound hammer method for finding the weak zones if any.
b) Corrosion state of the reinforcement bars should be determined by using half-cell potential meter
c) Resistivity test of concrete for assessing the likelihood of corrosion in concrete be done
d) Combination of NDT methods must be used for validation of the test results
e) Based on the NDT results, suitable remedial measures shall be taken up for strengthening of the structure.
f) Post repairing of the structure, NDT tests must be carried out to further assess the efficacy of the methods used for repairing

For Structural Safety Assessment by Vibration Monitoring

a) Ambient vibration study initially be carried out
b) Vibration monitoring under different traffic on a barrage or under various load generation conditions in a powerhouse must be carried out.
c) Safety criteria must be adopted based on the nature of vibration and type of the structure
d) Time- velocity/acceleration spectra must be converted into frequency-velocity/acceleration spectra for finding the dominant frequency of vibration
e) Based on the magnitude and frequency of the vibration; structural safety will be assessed.

During blasting operation near civil structures following recommendations are to be followed:

a) Pre-blast survey of the nearby structures must be carried out.
b) Qualitative assessment of the structures before commencement of blasting activity should be done.
c) Adoption of safety criteria as per BIS and other international practices should be followed.
d) Conducting several trial blasts for optimization of blast charge and other associated parameters should be done.
e) Monitoring of blast vibrations near structures should be carried out.
f) Safe charge and suitable blasting pattern for excavation by blasting during actual blasting operations should be recommended.
g) Monitoring of vibration near structures during actual blasting at critical locations should be done.

h) Ensuring that the induced vibration levels are lying well below the adopted safe vibration level for safeguarding the nearby structures.

5.3 Future Directions

Monitoring structural damage is extremely important for sustaining and preserving the service life of civil structures. While successful monitoring provides resolute and staunch information on the health, serviceability, integrity and safety of structures; maintaining continuous performance of a structure depends highly on monitoring the occurrence, formation and propagation of damage. Damage may accumulate on structures due to different environmental and human-induced factors. Numerous monitoring and detection approaches have been developed to provide practical means for early warning against structural damage or any type of anomaly. Considerable effort has been put into vibration-based methods, which utilize the vibration response of the monitored structure to assess its condition and identify structural damage.

Meanwhile, with emerging computing power and sensing technology in the last decade, Machine Learning (ML) and especially Deep Learning (DL) algorithms have become more feasible and extensively used in vibration-based structural damage detection with elegant performance and often with high accuracy. Therefore, efforts must be taken to make use of the artificial intelligence techniques for structural health monitoring of civil structures.

VISION

To be a world-class centre of excellence in hydraulic engineering research and allied areas; which is responsive to changing global scenario, and need for sustaining and enhancing excellence in providing technological solutions for optimal and safe design of water resources structures.

MISSION

- To meet the country's need for basic and applied research in water resources, power sector and coastal engineering with world-class standards.
- To develop competence in deployment of latest technologies by networking with the top institution globally, to meet the future needs for development of water resources projects in the country effectively.
- To disseminate information, built skills and knowledge for capacity-building and mass awareness for optimisation of available water resources.

MAJOR FUNCTIONS

- Undertaking specific research studies relating to development of water resources, power and coastal projects.
- Consultancy and advisory services ton Central and State Governments, private sector and other countries.
- Disseminating research findings and promoting/assisting research activities in other organisations concerned with water resources projects.
- Contribution to Bureau of Indian Standards and International Standards Organization.
- Carrying out basic and applied research to support the specific studies.
- Contribution towards advancements in technology through participation in various committees at National and State Levels.

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