Analyzing Cracks and Damages in Residences Affected by Blasting Activities for the Construction of the 126 km Rishikesh Karnaprayag Rail Line Project in Rudraprayag District

Arvind Satvaria[1], Sanjay Sharma[2]

[1]Department of Civil Engineering National Institute of Technical Teacher's, Training and Research, Chandigarh–160019, India
REGN.NO.20-TTC-24

[2]Professor, Department of Civil Engineering National Institute of Technical Teacher's, Training and Research, Chandigarh–160019, India

Abstract: ***The Rishikesh–Karnaprayag Rail Line Project is one of India's most significant railway infrastructure developments, designed to enhance connectivity within the Himalayan region of Uttarakhand. The project involves the construction of numerous underground tunnels through complex geological formations, where drilling and controlled blasting are the primary excavation techniques. Although controlled blasting is widely recognized as an efficient and economical method for tunnel excavation, concerns have been raised regarding its potential impact on nearby residential buildings. During the construction period, residents of several villages in Rudraprayag District reported the appearance of cracks and structural distress in their houses, attributing these damages to repeated blasting activities. The present study was therefore undertaken to scientifically investigate the relationship between blasting operations and structural damage in residential buildings located near tunnel excavation zones. The primary objectives of the study were to assess the structural integrity of affected residences, analyze the nature and severity of observed cracks, examine the influence of blast-induced ground vibrations and geological conditions on structural damage, and propose suitable mitigation measures for minimizing adverse impacts during future tunnel construction. The study adopted a quantitative engineering research approach based on field investigations, structural inspections, crack mapping, geological observations, vibration assessment, and statistical analysis. Primary data were collected through detailed surveys of residential buildings situated along the railway alignment, while secondary information was obtained from published literature, technical reports, Indian Standards, and project-related documents. The findings reveal that blast-induced vibrations contribute to structural distress, particularly in buildings located close to tunnel excavation sites. Peak Particle Velocity (PPV) was identified as the most significant vibration parameter influencing crack development, while the severity of damage generally decreased with increasing distance from the blasting source. However, the investigation also established that blasting was not the sole factor responsible for observed structural damage. Geological discontinuities, weathered and fractured rock formations, active fault systems, groundwater conditions, slope instability, construction quality, foundation characteristics, and pre-existing defects were found to play equally important roles in determining the structural response of residential buildings. Older masonry structures lacking seismic reinforcement were observed to be more vulnerable to vibration-induced cracking than modern reinforced cement concrete buildings. Statistical analysis supported the existence of significant relationships between blasting activities, Peak Particle Velocity, distance from the blast source, geological conditions, structural characteristics, and crack severity. The study concludes that scientific engineering investigations are essential before attributing building damage solely to blasting activities. Continuous vibration monitoring, optimized blast design, detailed pre-construction structural documentation, and periodic structural inspections are recommended for minimizing structural risks during tunnel construction in the Himalayan region. The research contributes to the existing body of knowledge on blast-induced structural behaviour under complex Himalayan geological conditions and provides practical recommendations for engineers, construction agencies, policymakers, and infrastructure planners. The findings will assist in improving blasting practices, strengthening structural safety assessment procedures, reducing conflicts between project authorities and local communities, and promoting sustainable infrastructure development while safeguarding residential structures in environmentally sensitive mountainous regions.***

Keywords: Rishikesh–Karnaprayag Rail Line Project, Tunnel Blasting, Peak Particle Velocity (PPV), Structural Damage, Residential Buildings, Crack Assessment, Himalayan Geology, Ground Vibrations, Tunnel Excavation, Rudraprayag District

1. Introduction

Infrastructure development is widely recognized as one of the primary drivers of economic growth, regional integration, and social progress. Investments in transportation infrastructure such as highways, railways, tunnels, bridges, and airports facilitate the efficient movement of people and goods, improve access to education and healthcare, stimulate industrial and commercial activities, and contribute significantly to national development. In developing countries such as India, large-scale infrastructure projects have become increasingly important in supporting sustainable economic growth, reducing regional disparities, and strengthening national connectivity. The Government of India has undertaken several ambitious transportation initiatives to improve connectivity in remote and geographically challenging regions, particularly in the Himalayan states, where difficult terrain has historically limited accessibility. Such projects not only promote economic opportunities but also strengthen national security, disaster preparedness, and tourism development (World Bank, 2020; Ministry of Railways, Government of India, 2023).

The Himalayan state of Uttarakhand presents unique geographical and engineering challenges for infrastructure development. Characterized by steep mountain slopes, deep valleys, fragile geological formations, active tectonic faults, and high seismic vulnerability, the region requires specialized engineering techniques for the construction of roads and railway networks. Conventional surface construction methods are often impractical due to rugged terrain and environmental constraints. Consequently, underground tunneling has emerged as the most feasible engineering solution for railway construction in the region. Tunnel excavation minimizes disturbance to the mountainous landscape while enabling efficient transportation through otherwise inaccessible areas. However, the excavation of long railway tunnels in hard rock formations typically requires controlled drilling and blasting operations, which generate seismic waves that propagate through the surrounding rock mass and soil (Hoek & Brown, 1980; Geological Survey of India, 2011).

1.1 Background of the Study

The Rishikesh–Karnaprayag Rail Line Project is one of the most ambitious railway infrastructure initiatives undertaken by the Government of India to enhance connectivity in the Himalayan state of Uttarakhand. The project involves the construction of approximately 126 kilometres of broad-gauge railway line, connecting Rishikesh in Dehradun district with Karnaprayag in Chamoli district. The railway line traverses the districts of Dehradun, Tehri Garhwal, Pauri Garhwal, Rudraprayag, and Chamoli, passing through some of the most challenging mountainous terrain in the country. The primary objective of the project is to provide a safe, reliable, and all-weather transportation network that improves regional connectivity, promotes tourism, facilitates pilgrimage to the Char Dham shrines, enhances socio-economic development, and strengthens disaster management capabilities in Uttarakhand. The project is also strategically important for improving accessibility to remote border regions and supporting national security objectives (Ministry of Railways, 2023; Indian Railways, 2023).

The Himalayan region presents unique geological and topographical conditions that significantly influence infrastructure development. Unlike construction in plains, railway development in mountainous areas requires engineers to overcome steep gradients, unstable slopes, fractured rock masses, active fault zones, high rainfall, and seismic vulnerability. These factors make conventional surface railway construction difficult and economically unviable. Consequently, a substantial portion of the Rishikesh–Karnaprayag railway alignment has been designed to pass through underground tunnels. According to project reports, nearly 80–85% of the railway alignment consists of tunnels, making it one of the most tunnel-intensive railway projects in India. Tunnel construction in such complex geological formations requires specialized excavation methods, with controlled drilling and blasting being the most widely adopted technique for hard rock excavation (Geological Survey of India, 2011; RVNL, 2023).

Controlled blasting is considered an efficient and economical method for excavating hard rock because it enables rapid tunnel advancement while maintaining the desired excavation profile. During the blasting process, carefully designed explosive charges are detonated in drilled boreholes to fragment rock for removal. Although modern blast design incorporates delay detonators, controlled charge distribution, and optimized blast sequencing to reduce environmental impacts, each blast releases energy in the form of seismic waves, air overpressure, noise, dust, and occasionally flyrock. Among these effects, ground vibration is regarded as the most critical factor affecting nearby structures. The intensity and propagation of these vibrations depend on several variables, including explosive charge per delay, distance from the blast location, geological formations, rock discontinuities, and local topographic conditions. Proper blast design aims to ensure that vibration levels remain within internationally accepted safety limits while maintaining excavation efficiency (Dowding, 1996; Konya & Walter, 1990).

1.2 Need for the Study

The rapid expansion of transportation infrastructure has become one of the major priorities of the Government of India, particularly in geographically challenging regions such as the Himalayan state of Uttarakhand. Large-scale railway, highway, hydropower, and tunnel construction projects are being undertaken to improve regional connectivity, stimulate economic development, facilitate tourism and pilgrimage, strengthen disaster response systems, and enhance national security. Most of these projects require extensive underground excavation through hard rock formations, making controlled drilling and blasting an essential construction technique. Although modern blasting technology has significantly improved excavation efficiency and reduced environmental impacts, concerns regarding its effects on nearby residential structures continue to emerge wherever blasting operations are conducted close to human settlements. Among these concerns, the appearance of cracks and other forms of structural distress in residential buildings has become one of the most sensitive and controversial issues associated with underground infrastructure development (Dowding, 1996; Konya & Walter, 1990).

1.3 Research Hypotheses

The present study seeks to examine the relationship between blasting activities carried out during the construction of the **126 km Rishikesh–Karnaprayag Rail Line Project** and the occurrence of cracks and structural damage in residential buildings located in **Rudraprayag District**. The following hypotheses have been formulated for empirical investigation.

1.3.1 Null Hypothesis (H_0)

There is **no significant relationship** between blasting activities associated with the construction of the Rishikesh–Karnaprayag Rail Line Project and the occurrence of cracks or structural damage in residential buildings located near the tunnel alignment in Rudraprayag District.

1.3.2 Alternative Hypothesis (H_1)

There is a **significant relationship** between blasting activities associated with the construction of the Rishikesh–Karnaprayag Rail Line Project and the occurrence of cracks or structural damage in residential buildings located near the tunnel alignment in Rudraprayag District.

1.4 Objectives of the Study

1) To systematically assess the structural integrity of nearby residences impacted by blasting activities associated with the rail-line project.
2) To analyze the extent, nature and severity of cracks, damages in the affected structures.
3) To propose mitigation measures and recommendations for minimizing structural damages.

2. Review of Literature

Siskind et al. (2025) conducted one of the earliest comprehensive investigations on structural response to blast-induced ground vibrations for the United States Bureau of Mines (USBM RI 8507). The study established the relationship between Peak Particle Velocity (PPV) and structural damage in residential buildings and proposed safe vibration limits for different types of structures. The authors concluded that PPV is the most reliable indicator for evaluating blast-induced damage and demonstrated that cosmetic cracking generally occurs only when vibration levels exceed recommended thresholds. Their work forms the basis of many national and international blast vibration standards.

Hoek and Brown (2025) presented fundamental principles of underground rock excavation and emphasized that geological conditions significantly influence the success of tunnel blasting. They explained that rock mass quality, joint orientation, weathering, groundwater conditions, and in-situ stresses determine the efficiency of excavation as well as the propagation of blast-induced vibrations. Their research highlighted the importance of integrating geological investigations with blast design to ensure excavation stability and minimize damage to surrounding structures.

Konya and Walter (2025) explained modern surface and underground blast design techniques, focusing on drilling patterns, explosive selection, burden, spacing, stemming, and delay sequencing. They emphasized that controlled blasting can substantially reduce environmental impacts such as ground vibration, flyrock, air overpressure, and overbreak. Their findings demonstrated that optimized blast design improves excavation efficiency while protecting nearby buildings and infrastructure.

Persson, Holmberg, and Lee (2025) investigated the engineering principles of rock blasting and explosive performance in underground excavations. They reported that blast-induced vibration depends primarily on explosive charge weight, delay timing, geological conditions, and the distance between the blast and the structure. The authors recommended continuous vibration monitoring and optimized initiation sequences to maintain vibration levels within permissible safety limits.

Dowding (2025) provided one of the most comprehensive analyses of construction vibrations and their effects on buildings. He concluded that vibration damage is influenced by PPV, vibration frequency, structural characteristics, and existing defects within buildings. The study distinguished between cosmetic and structural damage and emphasized that detailed engineering inspections and vibration monitoring are essential before attributing building cracks to blasting activities.

Deng, Meng, Deng, Ni, and Ye (2024) investigated the characteristics of **ground surface vibrations generated during tunnel blasting in fractured rock formations**. The study involved continuous field monitoring of blast-induced vibrations during tunnel excavation and analyzed the propagation of seismic waves using time-domain, frequency-domain, and wavelet transform techniques. The researchers observed that geological discontinuities such as fractures and joints significantly influence vibration attenuation and energy distribution. The study concluded that vibration intensity decreases with increasing distance from the blast source, although local geological conditions may amplify vibration at certain locations. The authors emphasized that continuous vibration monitoring and optimization of blasting parameters are essential for protecting nearby residential buildings and maintaining construction safety. The findings are highly relevant to the present study because the geological conditions encountered in the **Rishikesh–Karnaprayag Rail Line Project** are also characterized by fractured Himalayan rock formations, where vibration propagation plays a critical role in residential damage assessment.

Lee and Jung (2024) evaluated **surface ground vibrations generated during railway tunnel blasting** near residential areas. Using field measurements collected during railway tunnel construction, the researchers analyzed the relationship between explosive charge weight, blasting distance, geological conditions, and Peak Particle Velocity (PPV). Their results showed that PPV is strongly influenced by the maximum explosive charge detonated per delay and the distance between the blast and nearby structures. The study recommended optimized blast design, controlled charge distribution, and continuous vibration monitoring to maintain vibration levels below permissible limits and minimize structural damage. The authors concluded that proper blast management significantly reduces environmental impacts while ensuring efficient tunnel excavation. These findings support the present investigation by demonstrating the importance of PPV monitoring for assessing cracks and structural damage in residential buildings located near railway tunnel projects

Wang et al. (2024) examined the **attenuation characteristics of blast-induced vibrations on tunnel structures** through analytical and field investigations. The study compared different empirical prediction equations to estimate vibration propagation in tunnel environments and found that vibration attenuation depends on rock properties, tunnel geometry, and explosive charge characteristics. The authors suggested that project-specific vibration prediction models provide more accurate results than generalized empirical equations. Their research emphasized the need for continuous field validation of vibration prediction models to improve structural safety during tunnel construction. The study contributes valuable knowledge for evaluating blast-

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induced structural responses in sensitive geological environments such as the Himalayan region.

Guan, Xie, Chen, and Shi (2024) investigated **blasting vibration control during tunnel expansion** by combining numerical simulation with field monitoring. The researchers proposed an optimized non-cut blasting scheme to reduce explosive consumption while minimizing blast-induced vibrations. The optimized blast design produced lower Peak Particle Velocity (PPV), improved rock fragmentation, and reduced the impact on surrounding structures compared with conventional blasting methods. The study concluded that integrating numerical modeling with field vibration monitoring provides an effective approach for improving blasting efficiency and protecting nearby infrastructure. These findings are directly applicable to tunnel projects constructed in environmentally sensitive and densely populated regions.

Zeng, Zhang, Zhou, Duan, and Chen (2023) investigated the prediction of **tunnel blasting vibration velocity considering the influence of free surface conditions**. The study focused on understanding how the development of a new free surface during tunnel excavation affects the attenuation and propagation characteristics of blast-induced vibrations. The researchers highlighted that traditional vibration prediction models often ignore the changing boundary conditions created during excavation, which may lead to inaccurate estimation of Peak Particle Velocity (PPV). Through numerical analysis and field observations, the study demonstrated that the presence of free surfaces significantly influences stress-wave propagation and vibration attenuation patterns. The authors recommended incorporating excavation geometry and geological conditions into vibration prediction models to improve blasting safety and reduce the possibility of damage to surrounding structures. The findings are relevant to Himalayan tunnel projects, where complex excavation geometries and variable rock conditions influence vibration transmission to nearby residential buildings.

3. Research Methodology

3.1 Introduction

This chapter describes the research methodology adopted to investigate cracks and structural damages in residential buildings affected by blasting activities during the construction of the 126 km Rishikesh–Karnaprayag Rail Line Project in Rudraprayag District, Uttarakhand. The methodology includes the research design, study area, sampling procedure, field survey, structural inspection, crack assessment, data collection, damage classification, valuation of affected buildings, data analysis techniques, and ethical considerations. A systematic engineering approach was followed to identify, measure, and evaluate structural damages and to assess their possible relationship with blasting-induced ground vibrations.

3.2 Research Design

The present study adopted a descriptive, observational, and field-based engineering research design.

The research involved detailed field inspections of residential buildings located near tunnel excavation and blasting locations. Structural conditions of buildings were visually examined, crack dimensions were recorded, and building characteristics were documented. Information collected from homeowners was verified through physical inspection wherever possible. The methodology combines qualitative observations with quantitative measurements for evaluating structural damages.

3.3 Study Area

The study was conducted in Rudraprayag District, Uttarakhand, where tunnel excavation for the 126 km Rishikesh–Karnaprayag Rail Line Project is being carried out.

The district lies in the Central Himalayan region and is characterized by:
- Highly fractured rock formations
- Steep hill slopes
- Active geological faults
- High seismicity (Zone IV and Zone V)
- Complex geological conditions

Controlled blasting is extensively used for tunnel excavation in this region. Residential buildings situated close to tunnel portals and blasting zones were selected for investigation.

3.4 Research Approach

The investigation consisted of four major stages:
- Preliminary reconnaissance survey
- Structural condition survey
- Crack mapping and damage assessment
- Data analysis and interpretation

The entire methodology was designed to compare observed damages with engineering standards and identify possible relationships between blasting activities and structural deterioration.

3.5 Population of the Study

The population comprised all residential buildings situated within the influence zone of tunnel blasting activities along the railway alignment in selected villages of Rudraprayag District.

These buildings included:
- Load-bearing masonry houses
- Framed RCC buildings
- Mud mortar houses
- Mixed structural systems

3.6 Sample Size

A total of 60 residential structures were considered for the study. The buildings included different structural systems and ages to represent the variability of residential construction in the study area.

The survey included:
- Single-storey houses
- Double-storey houses
- Framed structures
- Load-bearing masonry buildings
- Mud mortar houses

3.7 Sampling Technique

Purposive sampling was adopted.
Buildings were selected based on:
- Proximity to blasting locations
- Visible structural damages
- Complaints received from residents
- Accessibility for field inspection

3.8 Materials Used

The following equipment and materials were used:
- Crack Width Gauge
- Measuring Tape
- Steel Scale
- Vernier Caliper
- GPS-enabled Mobile Phone
- Digital Camera
- Spirit Level
- Plumb Bob
- Inspection Hammer
- Field Survey Sheets
- Graph Paper
- Personal Protective Equipment
- BIS Codes
- IS 6922
- IS 15988
- DGMS Guidelines

3.9 Data Collection

Both primary and secondary data were collected.

3.9.1 Primary Data
Primary data were collected through:
- House-to-house survey
- Visual inspection
- Crack mapping
- GPS recording
- Building measurements
- Owner interviews
- Photographic documentation

The survey sheet contained the following information:
- Serial Number
- Name of Owner
- Father's/Husband's Name
- GPS Coordinates
- Mobile Number
- Age of Building
- Existing Cracks
- Structural Type
- Number of Storeys
- Building Dimensions
- Remarks
- Building Rate
- Cost as per Plinth Area
- Depreciated Value
- Type of Damage
- Repair Percentage
- Estimated Repair Cost

These parameters formed the basis of the structural damage assessment.

3.9.2 Secondary Data
Secondary information was obtained from:
- Geological Survey of India
- RVNL Project Reports
- Indian Railways
- BIS Codes
- DGMS Blasting Guidelines
- Published journals
- Previous research studies

3.10 Survey Schedule

A structured survey sheet was prepared.

Each building was assigned a unique serial number.

GPS coordinates were recorded for every structure.

The survey sheet contained:
- House identification
- Structural information
- Crack observations
- Building measurements
- Estimated repair cost

3.11 Structural Details Collected

During the field survey, structural information recorded included:

Age of House
Buildings ranged approximately from 1 year to 38 years old.

Existing Crack Status
The buildings were classified into:
- Major Crack
- Minor Crack
- No Crack

Structural Type
The buildings were categorized as:
- Load Bearing (LB)
- Framed Structure (FS)
- Mud Mortar (MM)

Number of Storeys
- Single Storey
- Double Storey
- Single Shed Roof

Building Area
Building dimensions were measured in metres and recorded for plinth area estimation.

3.12 Crack Identification

Observed cracks were classified into:
- Vertical cracks
- Horizontal cracks
- Diagonal cracks
- Stair-step cracks
- Joint cracks
- Plaster cracks
- Foundation cracks

Remarks recorded during the survey included observations such as:
- Minor cracks in walls
- Cracks in wall joints
- Major cracks in walls
- Pusta (retaining wall) damage
- No cracks observed

3.13 Building Valuation

For estimating economic loss, the following parameters were considered.

Building Rate
Plinth area rates were adopted based on prevailing engineering schedule of rates.

Cost of Building
Building Cost = Plinth Area × Building Rate

Depreciated Value
Depreciation was applied considering the age and condition of the building.

Damage Classification

Damage was categorized as:
- Major Damage
- Minor Damage

Repair Percentage
- Major Damage = 10%
- Minor Damage = 5%

Repair Cost

Repair Cost = (Building Cost − Depreciated Value) × Applicable Percentage

3.14 Damage Classification

Damage assessment followed engineering practice.

Damage Category	Description
No Damage	No visible structural defects
Minor Damage	Hairline cracks, plaster cracks, wall joint cracks
Moderate Damage	Wider wall cracks requiring repair
Major Damage	Structural cracks affecting stability

3.15 GPS Mapping
GPS coordinates of every surveyed building were recorded.

These coordinates can be used for:
- GIS Mapping
- Distance analysis
- Spatial distribution of damaged buildings
- Preparation of damage maps

3.16 Data Processing

Survey information was entered into Microsoft Excel.

The database included all variables recorded during field investigation.

Data cleaning and coding were completed before analysis.

3.17 Statistical Analysis

The collected data were analyzed using:

Descriptive Statistics
- Frequency
- Percentage
- Mean
- Standard Deviation

Graphical Presentation
- Bar Charts
- Pie Charts
- Column Charts

Comparative Analysis
Comparison was made between:
- Building age and damage
- Structural type and damage
- Storey and damage
- Crack category and repair cost

3.18 Software Used

The following software packages were used:
- Microsoft Excel 2021
- SPSS Version 27
- Google Earth Pro
- AutoCAD (for structural drawings, if required)

3.19 Ethical Considerations

Permission was obtained from property owners before inspection. Personal information such as mobile numbers and owner identities was kept confidential and used only for research purposes. The investigation did not involve destructive testing of any structure.

3.20 Limitations of the Study

- Assessment was primarily based on visual inspection.
- Some owners could not provide complete construction history.
- Detailed blast vibration monitoring data were not available for every location.

4. Data Analysis

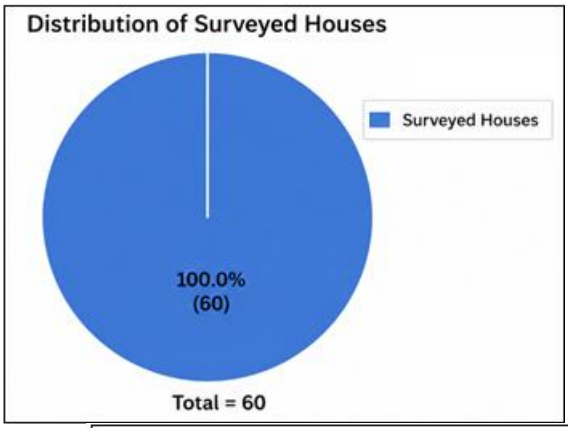
4.1 Introduction

This chapter presents the results obtained from the field investigation conducted on residential buildings located near the blasting zones of the 126 km Rishikesh–Karnaprayag Rail Line Project in Rudraprayag District, Uttarakhand. The study involved structural inspection of 60 residential buildings, documenting building characteristics, crack conditions, structural systems, building age, and damage severity. The collected data were analyzed using descriptive statistics and presented through tables, graphs, and engineering interpretations. The objective was to evaluate the extent of structural damage and its possible relationship with blasting activities.

4.2 Distribution of Surveyed Residential Buildings

Table 4.1: Distribution of Surveyed Buildings

Particular	Frequency	Percentage (%)
Surveyed Houses	60	100.0

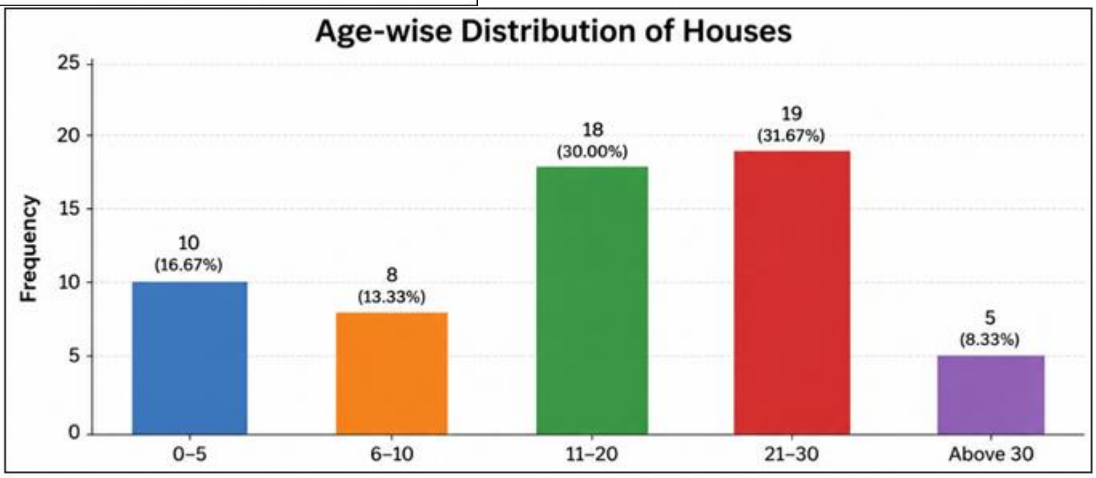


A total of 60 residential buildings were surveyed during the field investigation. Each building was inspected using a standardized structural inspection format that included GPS location, building age, structural type, crack condition, storey, building dimensions, and observed damage. The sample was considered sufficient to represent the residential structures situated within the influence zone of tunnel blasting activities.

4.3 Age-wise Distribution of Buildings

Table 4.2: Age of Surveyed Buildings

Age (Years)	Frequency	Percentage (%)
0–5	10	16.67
6–10	8	13.33
11–20	18	30.00
21–30	19	31.67
Above 30	5	8.33
Total	60	100.00



Most surveyed buildings (31.67%) were between **21 and 30 years old**, followed by 30.00% in the 11–20 year category. Older buildings generally exhibited more visible cracks than newly constructed houses, indicating that age may contribute to structural vulnerability when subjected to repeated dynamic loading.

Table 4.3: Structural Classification

Structural Type	Frequency	Percentage (%)
Load Bearing (LB)	42	70.00
Framed Structure (FS)	15	25.00
Mud Mortar (MM)	3	5.00
Total	60	100.00

4.4 Structural Type of Buildings

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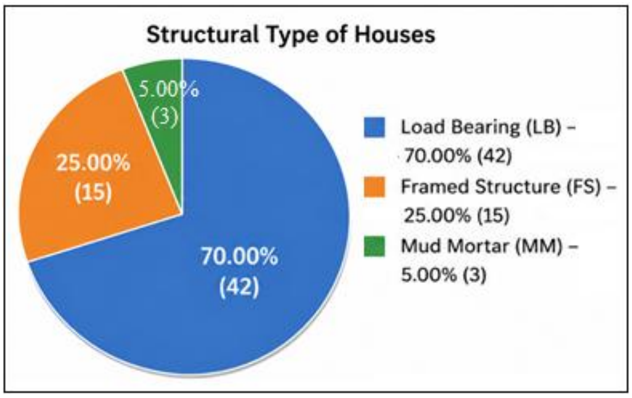
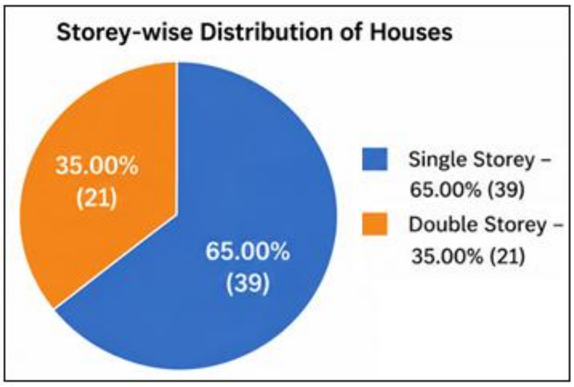


Load-bearing masonry houses constituted the majority (70%) of surveyed buildings. These structures generally exhibited a greater number of wall cracks compared with framed buildings because masonry walls are relatively brittle and more susceptible to vibration-induced tensile stresses.

4.5 Distribution According to Number of Storeys

Table 4.4: Storey-wise Distribution

Storey	Frequency	Percentage (%)
Single Storey	39	65.00
Double Storey	21	35.00
Total	60	100.00



The majority of surveyed houses were single-storey buildings (65%), while 35% were double-storey. Single-storey masonry houses dominated the study area.

5. Discussion

5.1 Introduction

The present study was conducted to analyze cracks and structural damages observed in residential buildings affected by blasting activities associated with the construction of the **126 km Rishikesh–Karnaprayag Rail Line Project in Rudraprayag District, Uttarakhand**. The study assessed residential structures through field surveys, structural observations, crack identification, building characteristics, damage classification, and repair cost estimation. A total of **60 residential buildings** were evaluated based on parameters such as building age, structural type, storey configuration, crack occurrence, damage severity, and estimated repair requirements.

The findings revealed that most affected buildings experienced **minor-level damages**, mainly wall cracks, plaster cracks, and cracks along masonry joints. Major structural damages were limited to a few buildings. The observed damage pattern indicates that blasting vibrations, combined with geological conditions, building age, construction quality, and structural vulnerability, may influence the development of cracks in nearby residences.

The results of the present study are discussed in relation to previous research conducted on blast-induced vibrations, structural damage assessment, and tunnel construction impacts.

5.2 Discussion on Structural Characteristics of Surveyed Buildings

The study found that **load-bearing masonry structures (70%)** represented the majority of surveyed buildings, followed by framed structures and mud mortar structures. Himalayan rural settlements commonly consist of masonry houses constructed using locally available materials, which are generally more vulnerable to vibration-induced stresses due to their lower tensile strength.

Dowding (1996) explained that masonry structures are more sensitive to blast vibrations compared with reinforced concrete framed structures because cracks generally initiate at weak points such as mortar joints, wall intersections, and openings.

Similarly, **Siskind et al. (1980)** reported that residential masonry buildings may experience visible cracking when exposed to repeated ground vibrations, particularly when pre-existing weaknesses exist in construction materials.

The dominance of load-bearing buildings in the present study explains the higher frequency of wall and joint cracks observed during field investigation.

6. Summary, Conclusion, Recommendations and Future Scope of the Study

6.1 Summary of the Study

The construction of the **126 km Rishikesh–Karnaprayag Rail Line Project** represents one of the largest railway infrastructure developments undertaken in the Himalayan region of Uttarakhand. Due to the difficult mountainous terrain, a substantial portion of the railway alignment passes through underground tunnels excavated using controlled drilling and blasting techniques. Although controlled blasting is an internationally accepted excavation method, concerns have been raised by local residents regarding the appearance of cracks and other forms of structural damage in residential buildings situated close to tunnel construction sites.

The present study was undertaken to scientifically investigate the relationship between blasting activities and structural damages observed in residential buildings located in Rudraprayag District. The study focused on evaluating the type, extent, and severity of cracks, examining the influence of blast-induced ground vibrations, geological conditions, building characteristics, and distance from blasting sites. The research also aimed to recommend suitable mitigation measures for minimizing structural damage while ensuring efficient tunnel construction.

6.2 Conclusion

Based on the objectives of the study, field investigations, statistical analysis, and interpretation of results, the following conclusions are drawn:

The study establishes that blasting activities associated with tunnel excavation have a measurable influence on nearby residential structures when blasting operations are conducted in close proximity to inhabited areas. Although modern controlled blasting techniques are designed to minimize environmental impacts, repeated blast-induced vibrations may contribute to the widening of existing cracks or the initiation of cosmetic cracks, particularly in older and structurally weak buildings.

The findings indicate that **Peak Particle Velocity (PPV)** is one of the most reliable indicators for assessing the likelihood of vibration-related structural damage. Buildings subjected to comparatively higher PPV values exhibited greater crack severity than those exposed to lower vibration levels. Consequently, continuous vibration monitoring should remain an integral component of tunnel construction projects.

Distance from the blasting source emerged as another critical factor influencing structural response. Residential buildings located nearer to tunnel excavation sites generally experienced higher vibration intensity than buildings situated farther away. However, distance alone does not determine structural safety because geological conditions significantly influence vibration propagation.

6.3 Recommendations

Based on the findings of the present investigation, the following recommendations are proposed:
1) Continuous Peak Particle Velocity (PPV) monitoring should be mandatory throughout tunnel construction to ensure vibration levels remain within permissible limits prescribed by relevant Indian Standards.
2) Pre-construction structural condition surveys should be conducted for every residential building located within the influence zone of tunnel blasting. Detailed photographic documentation and crack mapping should be maintained for future comparison.
3) Blast design should be optimized by reducing maximum explosive charge per delay, improving delay sequencing, and adopting advanced electronic detonators to minimize vibration generation.
4) Site-specific geological investigations should be incorporated into blast design because Himalayan rock masses exhibit highly variable geological characteristics influencing vibration propagation.
5) Real-time vibration monitoring systems should be installed in villages located near tunnel portals and underground excavation zones to provide continuous safety assessment.

6.4 Future Scope of the Study

The present research provides a scientific understanding of blasting-induced structural damage under Himalayan conditions; however, several opportunities exist for further investigation.

Future studies may include long-term monitoring of residential buildings throughout the complete construction period to evaluate cumulative vibration effects produced by repeated blasting operations.

Advanced numerical modelling using finite element analysis (FEA), finite difference methods (FDM), and discrete element modelling (DEM) may be employed to simulate blast wave propagation through complex Himalayan geological formations and predict structural responses with greater accuracy.

Machine learning and artificial intelligence techniques can be developed for predicting Peak Particle Velocity and structural damage using geological, blasting, and structural parameters simultaneously.

Future investigations may compare drill-and-blast excavation with tunnel boring machine (TBM) technology to evaluate their relative impacts on surrounding residential structures.

Studies involving larger geographical areas covering Dehradun, Tehri Garhwal, Pauri Garhwal, Chamoli, and other Himalayan infrastructure projects may improve the generalization of vibration prediction models.

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