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Advanced Real-Time Geotechnical and Deformation Monitoring Framework for the World's Tallest RCC Dam

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***Abstract*— *This research presents an integrated real-time geotechnical monitoring framework for the Diamer Basha Dam Project, combining UAV photogrammetry, GNSS networks, total station surveys, GIS-based deformation mapping, and geotechnical instrumentation (piezometers, inclinometers, extensometers, and crack meters). The research assesses excavation-induced deformation, blasting impacts, groundwater pressure fluctuations, and slope stability under complex geological conditions. Results show that the integrated approach enhances deformation prediction, improves slope safety evaluation, and supports effective risk management during the construction of large RCC dam projects.*

Keywords*— *Diamer Basha Dam; Geotechnical Monitoring; Deformation Analysis; UAV Photogrammetry; GNSS Monitoring; GIS-Based Deformation Mapping; Slope Stability; Roller Compacted Concrete (RCC) Dam; Geotechnical Instrumentation; Excavation-Induced Deformation; Groundwater Pressure Monitoring; Construction Risk Management; Real-Time Monitoring; Hydropower Infrastructure; Structural Health Monitoring.

I. INTRODUCTION

The Diamer Basha Dam Project (DBDP), being constructed on the Indus River approximately 40 km downstream of Chilas in northern Pakistan, is one of the largest hydropower and water-storage infrastructure projects currently under development worldwide. The project comprises a 272 m high Roller Compacted Concrete (RCC) gravity dam, making it the tallest RCC dam under construction in the world. Upon completion, the dam will provide approximately 4,500–4,800 MW of installed hydropower capacity and create a reservoir with a gross storage capacity of about 8.1 million acre-feet (MAF), significantly enhancing Pakistan's water security, flood mitigation capability, and energy generation potential. The project is also expected to generate nearly 18–19 billion kWh of clean electricity annually while extending the operational life of the downstream Tarbela Reservoir by reducing sedimentation impacts.

The dam is located within one of the most geologically complex and tectonically active regions of the world, near the convergence zone of the Himalaya, Karakoram, and Hindu Kush mountain ranges. The project area is characterized by steep valley walls, highly fractured rock masses, active fault systems, significant relief variation, and intense seasonal hydrological fluctuations. These conditions create substantial geotechnical challenges during excavation, foundation preparation, slope stabilization, tunnel construction, and dam abutment development. The rugged terrain, combined with seismic susceptibility and large-scale excavation activities, necessitates comprehensive monitoring programs to ensure construction safety and long-term structural stability.

Construction of the Diamer Basha Dam involves extensive rock excavation, deep foundation treatment, stabilization of high rock slopes, construction of diversion tunnels, underground powerhouses, access roads, and associated hydraulic structures. The project includes multiple diversion tunnels, underground powerhouses on both riverbanks, power tunnels, flushing tunnels, and massive RCC placements exceeding 16 million cubic meters of concrete. Such large-scale engineering operations inevitably induce deformation in surrounding rock masses and may alter the stress equilibrium of natural slopes and excavated faces. Consequently, continuous monitoring of ground movement, slope deformation, groundwater response, and structural displacement is essential for maintaining construction safety and mitigating geotechnical risks.

Traditionally, geotechnical and structural monitoring of dam projects has relied primarily on periodic surveying using total stations, precise leveling, and manual instrumentation observations. While these methods provide reliable point-based measurements, they are often insufficient for modern mega-infrastructure projects where rapid construction activities and large spatial coverage demand high-frequency and near real-time data acquisition. The limitations of conventional monitoring become particularly significant in mountainous environments where inaccessible terrain, blasting operations, and continuously changing excavation geometries can affect both measurement accuracy and operational efficiency.

Recent advances in geospatial technologies have transformed the field of engineering monitoring by enabling the integration of multiple observation systems into comprehensive deformation-monitoring frameworks. Unmanned Aerial Vehicle (UAV) photogrammetry, Global Navigation Satellite System (GNSS) monitoring networks, robotic total stations, Geographic Information Systems (GIS), and automated geotechnical instrumentation now provide continuous, high-resolution spatial and temporal information regarding structural and geotechnical behavior. These technologies facilitate early detection of instability, improve predictive assessment capabilities, and support data-driven decision-making during construction activities.

UAV-based photogrammetry has emerged as a powerful tool for generating high-resolution digital terrain models, orthophotos, and three-dimensional surface reconstructions of excavation zones and rock slopes. Repeated UAV surveys enable rapid identification of deformation patterns, rockfall-prone areas, and excavation-induced changes in slope geometry. Similarly, permanent GNSS monitoring stations provide continuous three-dimensional displacement measurements with millimeter-level precision, allowing engineers to detect subtle ground movements that may indicate developing instability. Robotic total stations further enhance monitoring by delivering automated prism observations and high-frequency deformation measurements for critical structural components.

In addition to geodetic monitoring systems, geotechnical instrumentation plays a fundamental role in evaluating subsurface conditions and understanding the mechanisms governing slope and foundation behavior. Piezometers are widely employed to monitor pore-water pressure variations within rock masses and foundation zones, while inclinometers provide detailed information regarding lateral ground movement and shear-zone development. Extensometers measure internal deformation within rock slopes and underground excavations, whereas crack meters monitor the progression of discontinuities and structural fractures. The integration of these instruments enables comprehensive assessment of both surface and subsurface responses to excavation, blasting, reservoir loading, and groundwater fluctuations.

Blasting activities associated with large-scale excavation represent another critical concern in the Diamer Basha Dam Project. Repeated blasting generates dynamic loading and vibration waves that may affect slope stability, induce cracking within rock masses, and accelerate deformation processes. Monitoring blast-induced vibrations and correlating them with displacement measurements provides valuable insight into excavation performance and assists in optimizing blasting parameters to minimize adverse geotechnical impacts. Likewise, seasonal and excavation-related changes in groundwater conditions can significantly influence slope stability by altering effective stress conditions and pore-water pressures. Therefore, continuous hydrogeological monitoring is essential for understanding deformation mechanisms and evaluating potential failure risks.

The integration of geodetic, photogrammetric, GIS-based, and geotechnical monitoring technologies offers a comprehensive approach for managing the complex geotechnical challenges associated with mega RCC dam construction. By combining multiple data sources within a unified monitoring framework, engineers can improve deformation prediction accuracy, enhance slope safety assessments, and establish effective early-warning systems for construction risk management. Such integrated monitoring approaches are increasingly recognized as best practice for large hydropower developments in mountainous environments where traditional surveying methods alone are no longer sufficient.

This research presents an advanced integrated monitoring framework implemented at the Diamer Basha Dam Project, combining UAV photogrammetry, GNSS control networks, total station observations, GIS-based deformation analysis, and automated geotechnical instrumentation. The research investigates excavation-induced deformation, blasting vibration effects, groundwater pressure variations, and slope stability behavior under complex geological conditions. The findings contribute to the development of modern monitoring strategies for large RCC dam projects and provide valuable guidance for improving safety, operational efficiency, and long-term infrastructure resilience in challenging mountainous terrains.

Background

The Diamer Basha Dam Project is situated on the Indus River in Gilgit-Baltistan, northern Pakistan, within one of the most tectonically active mountain belts of the world. The project lies near the junction of the Himalaya, Karakoram, and Hindu Kush mountain ranges, where the ongoing collision between the Indian and Eurasian tectonic plates has produced complex geological structures, active fault systems, intense rock deformation, and steep topographic relief. The region is characterized by high seismicity, rapid uplift rates, and deeply incised valleys, making it one of the most challenging environments for large-scale hydraulic infrastructure development.

The dam site is primarily founded on metamorphic and igneous rock formations comprising gneisses, schists, granitic intrusions, amphibolites, and highly jointed rock masses. Geological investigations conducted during the planning and construction phases revealed the presence of multiple discontinuity sets, shear zones, fault traces, fractured rock blocks, and weathered rock horizons. The orientation and spacing of these discontinuities significantly influence slope stability, excavation behavior, groundwater movement, and foundation performance. The structural complexity of the rock mass creates heterogeneous geotechnical conditions that require continuous monitoring throughout the construction period.

Construction of the Diamer Basha Dam involves one of the largest excavation programs ever undertaken for a hydropower project in South Asia. The development includes massive open-cut excavations for the dam foundation, spillway structures, diversion tunnels, underground powerhouses, access tunnels, intake structures, and associated infrastructure. These excavation activities alter the in-situ stress regime of the surrounding rock mass and cause stress redistribution within the abutments and valley slopes. Removal of large rock volumes can reduce confining pressures, resulting in stress concentration zones, crack initiation, joint dilation, rock relaxation, and localized instability.

Excavation-induced deformation is particularly critical in the steep valley slopes surrounding the dam site. The slopes are subjected to continuous changes in geometry as excavation progresses, which may trigger block movements, wedge failures, planar sliding, toppling mechanisms, and rockfall events. The presence of persistent discontinuities and tectonic fractures further increases the susceptibility of these slopes to instability. In addition, seasonal temperature variations, precipitation, snowmelt, and groundwater fluctuations contribute to progressive rock mass deterioration and deformation.

Blasting operations constitute another major geotechnical concern during construction. Controlled blasting is extensively employed to excavate hard rock for foundations, diversion tunnels, and underground structures. However, blasting generates dynamic stresses and vibration waves that propagate through the surrounding rock mass. Repeated blasting cycles can induce micro-cracking, reduce rock mass strength, increase joint aperture, and accelerate deformation processes. Monitoring blast-induced vibrations and associated ground displacement is therefore essential to ensure that excavation activities do not adversely affect slope stability, foundation integrity, or nearby structures.

Groundwater conditions represent an additional challenge for the project. The fractured nature of the rock mass facilitates groundwater seepage through joints, fractures, and fault zones. Excavation activities often intercept groundwater-bearing structures, resulting in changes in pore-water pressure distribution and groundwater flow patterns. Elevated pore-water pressures can significantly reduce effective stress and shear strength along discontinuities, thereby increasing the likelihood of slope instability and foundation settlement. Consequently, continuous monitoring of groundwater levels and pore-water pressure variations is necessary to evaluate hydrogeological responses to excavation and support the design of drainage and stabilization measures.

The construction of diversion tunnels and underground powerhouse caverns introduces further geotechnical complexities. Large underground openings create stress concentrations around tunnel peripheries and cavern walls, potentially leading to convergence, deformation, spalling, and instability. Continuous monitoring of tunnel deformation and rock mass response is therefore required to validate design assumptions, assess support system performance, and ensure worker safety during excavation.

Given the scale and complexity of the project, traditional periodic surveying methods alone cannot adequately capture the spatial and temporal variability of ground movements. Modern geotechnical practice increasingly relies on integrated monitoring systems that combine geodetic, photogrammetric, and geotechnical observations to provide near real-time assessment of structural and geological behavior. Such systems enable early detection of abnormal deformation trends, facilitate risk-based decision-making, and improve overall construction safety.

For the Diamer Basha Dam Project, continuous monitoring is particularly important during the construction of cofferdams, spillways, diversion tunnels, dam abutments, and RCC foundations. These structures form the critical components of the hydraulic system and are directly influenced by excavation-induced stress changes, blasting effects, groundwater fluctuations, and geological discontinuities. Reliable monitoring data are therefore essential for ensuring structural integrity, optimizing construction operations, and maintaining long-term project stability.

Problem Statement

The Diamer Basha Dam Project faces significant geotechnical challenges due to steep slopes, deep excavations, fractured rock masses, blasting vibrations, groundwater pressure variations, and excavation-induced deformation in a tectonically active Himalayan setting. Conventional monitoring methods provide limited, periodic, and disconnected data, making real-time risk assessment and early detection of instability difficult. Therefore, this research addresses the need for an integrated deformation monitoring system combining UAV photogrammetry, GNSS, total station observations, GIS analysis, and automated geotechnical instrumentation to improve deformation prediction, slope safety assessment, excavation control, and construction risk management.

Research Objectives

1. To evaluate integrated real-time deformation monitoring techniques employed at the Diamer Basha Dam Project.
2. To investigate the relationship between excavation activities, blasting effects, groundwater conditions, and slope deformation.
3. To assess the reliability of UAV, GNSS, and total station data for geotechnical monitoring.
4. To develop a risk-based monitoring framework for improving slope stability assessment and construction safety in mega RCC dam projects.

II. LITERATURE REVIEW

Evolution of Geotechnical Monitoring in Large Civil Engineering Projects

Deformation monitoring has long been recognized as a fundamental component of geotechnical engineering, particularly in large infrastructure projects involving deep excavations, underground openings, high rock slopes, and dam foundations. The primary objective of monitoring is to evaluate the response of geological materials and engineered structures to construction activities and environmental loading conditions. Deformation measurements provide essential information for validating design assumptions, assessing stability, and implementing timely corrective measures to mitigate geotechnical risks.

One of the earliest and most influential contributions to rock engineering was made by Hoek and Bray (1981) in Rock Slope Engineering, where the authors emphasized that monitoring is an indispensable component of slope stability management. Their work demonstrated that excavation-induced stress redistribution can significantly alter the behavior of rock masses, causing joint opening, rock relaxation, displacement, and progressive failure mechanisms. The research highlighted that observational methods combined with continuous deformation measurements provide a more reliable basis for stability assessment than design calculations alone.

Similarly, Dunnicliff (1993) established the importance of geotechnical instrumentation in engineering practice through his seminal work Geotechnical Instrumentation for Monitoring Field Performance. Dunnicliff argued that instrumentation should not merely be used for data collection but as a decision-support tool for evaluating field performance and reducing uncertainties in design assumptions. According to Dunnicliff, monitoring programs should be integrated into project planning from the outset and should provide timely information regarding deformation, pore-water pressure, stress changes, and structural behavior. His work remains a cornerstone for modern geotechnical monitoring systems.

Traditional monitoring techniques have primarily relied on geodetic surveys, precise leveling, total station observations, extensometers, inclinometers, piezometers, and crack meters. These instruments have proven effective for measuring localized deformation and subsurface responses. However, their application in large-scale projects is often constrained by limited spatial coverage, labor-intensive data collection, and the inability to provide continuous real-time information. As infrastructure projects have become increasingly complex, the limitations of conventional monitoring systems have become more apparent, driving the development of advanced geospatial and automated monitoring technologies.

Geodetic Monitoring for Deformation Assessment

Geodetic monitoring techniques have been widely employed in dams, tunnels, bridges, open-pit mines, and high rock slopes due to their ability to provide accurate displacement measurements. Total stations and precise leveling systems have historically served as the primary tools for monitoring structural and ground deformation. These methods are capable of achieving millimeter-level accuracy and have been extensively applied in dam safety monitoring programs worldwide.

The development of Global Navigation Satellite Systems (GNSS) has significantly enhanced the capability of deformation monitoring. GNSS technology provides continuous three-dimensional positioning and allows real-time detection of displacement over large areas. Modern GNSS monitoring networks are capable of achieving subcentimeter accuracy and are increasingly integrated with conventional surveying systems to improve monitoring reliability. Research has demonstrated that GNSS monitoring is particularly effective in large infrastructure projects where deformation occurs over extensive spatial scales and where access to monitoring locations may be difficult.

Deformation monitoring is now recognized as an essential component of structural health monitoring systems. Modern approaches combine geodetic observations with automated data processing and early-warning mechanisms to improve predictive assessment and risk management. Such integrated systems enable engineers to identify abnormal displacement trends before critical instability develops and provide a quantitative basis for decision-making during construction and operation.

Geotechnical Instrumentation and Slope Stability Monitoring

Geotechnical instrumentation remains the foundation of subsurface monitoring in major engineering projects. Instruments such as piezometers, inclinometers, extensometers, tiltmeters, strain gauges, and crack meters provide valuable information regarding internal deformation mechanisms that cannot be observed through surface measurements alone.

Piezometers are commonly used to monitor groundwater conditions and pore-water pressure variations, which directly influence slope stability and foundation performance. Elevated pore-water pressures reduce effective stress and can trigger slope failures, particularly in fractured rock masses and highly jointed geological formations. Inclinometers provide measurements of lateral ground movement and are widely employed for identifying shear zones and monitoring progressive slope deformation. Extensometers are used to evaluate displacement within rock masses and underground excavations, while crack meters measure changes in the width of fractures and discontinuities.

Recent studies on landslide and slope monitoring have shown that automated instrumentation systems provide continuous time-series data capable of detecting subtle deformation patterns before failure occurs. Modern monitoring programs increasingly integrate multiple sensors to improve reliability and establish relationships between groundwater conditions, deformation rates, and environmental triggers. Such integrated instrumentation frameworks have significantly improved the understanding of failure mechanisms in both natural and engineered slopes.

UAV Photogrammetry in Geotechnical Engineering

The emergence of Unmanned Aerial Vehicles (UAVs) has transformed geotechnical monitoring by enabling rapid, cost-effective, and high-resolution data acquisition. UAV photogrammetry combines aerial imagery with Structure-from-Motion (SfM) techniques to generate detailed orthophotos, digital terrain models, and three-dimensional point clouds. These datasets facilitate comprehensive analysis of terrain morphology, excavation progress, slope deformation, and structural behavior.

Recent reviews indicate that UAVs have become one of the most significant technological advances in geotechnical engineering. UAV-based monitoring provides extensive spatial coverage while reducing field exposure in hazardous environments. Studies have shown that UAV systems can effectively detect terrain changes, monitor slope failures, evaluate excavation performance, and assess infrastructure condition with high accuracy. UAV monitoring is particularly advantageous in mountainous regions and inaccessible areas where conventional surveying methods face operational limitations.

Vishweshwaran and Sujatha (2024) reported that UAV systems significantly improve monitoring efficiency by enhancing data quality, reducing operational risks, and lowering project costs. Their review demonstrated that repeated UAV surveys enable engineers to quantify terrain changes and assess geotechnical hazards over large areas while maintaining high spatial resolution.

Recent dam-monitoring studies further demonstrate the effectiveness of UAV photogrammetry. Yang and Yin (2025) reported that drone-based close-range photogrammetry achieved crack detection accuracy of approximately ±0.1 mm and deformation monitoring accuracy of ±1.2 mm, while improving inspection efficiency by five to eight times compared with conventional methods. Their findings indicate that UAV photogrammetry is becoming a viable alternative for intelligent dam safety monitoring.

Similarly, studies on structural health monitoring have shown that UAV photogrammetry can provide deformation measurements comparable to conventional surveying techniques. High-resolution UAV imagery integrated with GNSS control networks has been reported to achieve deformation accuracies within millimeter ranges, demonstrating the suitability of UAV systems for engineering-scale monitoring applications.

GIS-Based Deformation Analysis and Integrated Monitoring Systems

Geographic Information Systems (GIS) have emerged as powerful tools for integrating, visualizing, and analyzing large volumes of geospatial monitoring data. GIS platforms facilitate the integration of survey observations, UAV-derived terrain models, geotechnical instrumentation data, geological mapping, and construction records within a single analytical environment. Such integration enhances spatial interpretation of deformation patterns and supports informed decision-making.

Recent research has emphasized the value of combining surface and subsurface monitoring data through integrated frameworks. Advanced monitoring systems increasingly employ GIS-based platforms to establish relationships between excavation activities, groundwater conditions, geological structures, and observed deformation. These systems provide engineers with comprehensive situational awareness and support the development of predictive models for risk assessment.

A recent systematic review by Igwenagu et al. (2025) highlighted the growing trend toward integrating UAV monitoring with subsurface investigation techniques for earth infrastructure applications. The authors concluded that data fusion approaches significantly improve the capability of early-warning systems by linking surface deformation observations with subsurface geotechnical conditions. Such integrated methodologies have demonstrated considerable potential for monitoring slopes, embankments, dams, and other critical infrastructure systems.

Similarly, recent reviews of remote sensing technologies in geotechnical engineering have emphasized the benefits of integrating UAV photogrammetry, LiDAR, satellite imagery, InSAR, and GIS for infrastructure monitoring. These technologies provide high-resolution spatial data that support improved risk assessment, design validation, and long-term infrastructure resilience.

Monitoring of Mega Dam Projects

The construction of mega dams presents unique geotechnical challenges due to large excavation volumes, high slopes, extensive underground works, and complex hydrogeological conditions. Consequently, dam safety monitoring has evolved from conventional surveying practices toward integrated systems that combine geodetic measurements, geotechnical instrumentation, remote sensing, and automated data processing.

International experience from major dam projects demonstrates that integrated monitoring systems provide significant improvements in deformation prediction and safety assessment. Recent research indicates that UAV-assisted inspections enhance failure detection, reduce personnel exposure to hazardous environments, and support informed decision-making in dam safety management. Furthermore, automated monitoring networks incorporating GNSS, total stations, piezometers, inclinometers, and GIS platforms enable continuous assessment of structural and geotechnical performance.

Despite substantial advances in monitoring technologies, limited research has focused on developing integrated deformation-monitoring frameworks specifically for mega RCC dams constructed in highly tectonic and mountainous environments such as the Himalayas. Most existing studies address individual monitoring technologies rather than comprehensive systems capable of simultaneously evaluating excavation-induced deformation, blasting impacts, groundwater variations, and slope stability. This gap highlights the need for research on integrated monitoring approaches tailored to projects such as the Diamer Basha Dam.

Research Gap

The literature demonstrates significant progress in geotechnical instrumentation, geodetic surveying, UAV photogrammetry, remote sensing, and GIS-based deformation analysis. However, most studies focus on individual monitoring technologies or isolated applications. Limited research has been conducted on the integration of UAV photogrammetry, GNSS monitoring, total station observations, GIS-based deformation mapping, and geotechnical instrumentation within a unified framework for mega RCC dam construction in tectonically active mountainous regions. Furthermore, there is insufficient understanding of the combined effects of excavation, blasting, groundwater fluctuations, and geological discontinuities on deformation behavior during large dam construction. Therefore, an integrated real-time monitoring framework is required to improve deformation prediction, enhance slope stability assessment, and strengthen construction risk management for projects such as the Diamer Basha Dam.

Theoretical Framework

Conceptual Basis

The theoretical foundation of this research is based on the principle that large-scale excavation and construction activities alter the natural equilibrium of geological systems, resulting in deformation, stress redistribution, groundwater variations, and potential slope instability. According to Hoek and Bray (1981), excavation-induced stress changes can trigger rock mass relaxation, joint opening, displacement, and progressive failure mechanisms. Dunnicliff (1993) further emphasized that continuous monitoring of geotechnical parameters is essential for understanding field performance and reducing uncertainty in engineering decisions.

In mega RCC dam projects such as the Diamer Basha Dam, excavation works, blasting operations, tunnel construction, and foundation preparation act as primary disturbance factors that influence the behavior of rock masses and slopes. These activities generate measurable geotechnical responses including surface displacement, subsurface deformation, pore-water pressure changes, crack propagation, and vibration-induced instability. Effective monitoring of these responses enables engineers to evaluate structural performance, identify emerging hazards, and implement corrective measures before critical failures occur.

The research adopts an integrated monitoring approach in which multiple observation technologies are combined to provide comprehensive assessment of geotechnical behavior. UAV photogrammetry, GNSS networks, total station observations, GIS-based spatial analysis, and geotechnical instrumentation collectively serve as tools for capturing both surface and subsurface deformation processes. The integration of these technologies improves data reliability, enhances deformation prediction capability, and supports real-time risk assessment.

Theoretical Relationship Between Variables

The framework assumes that construction-related activities constitute the independent variables influencing geotechnical behavior within the dam site. These activities include:

1. Excavation depth and volume
2. Blasting intensity and vibration levels
3. Groundwater fluctuations
4. Tunnel excavation and underground works
5. Geological discontinuities and fault structures

These factors directly affect the dependent variables represented by geotechnical responses, including:

1. Slope displacement
2. Surface deformation
3. Rock mass movement
4. Pore-water pressure variation
5. Crack development
6. Foundation settlement
7. Tunnel convergence

The relationship between construction activities and geotechnical responses is measured through monitoring technologies that function as observation and assessment mechanisms.

These include:

1. UAV photogrammetry for terrain and slope deformation mapping
2. GNSS monitoring for continuous three-dimensional displacement measurement
3. Total station surveys for precise structural deformation monitoring
4. Piezometers for groundwater pressure monitoring
5. Inclinometers for lateral displacement assessment
6. Extensometers for internal rock mass deformation measurement
7. Crack meters for discontinuity monitoring
8. GIS platforms for spatial integration and visualization of monitoring data

The integrated monitoring system provides real-time information that supports geotechnical risk assessment, early-warning generation, and decision-making during construction.

Integrated Monitoring Framework

The theoretical model proposes that the effectiveness of construction risk management depends on the quality, frequency, and integration of monitoring information. As excavation and blasting activities increase, deformation behavior becomes more complex and dynamic. Conventional monitoring systems often provide isolated datasets that limit understanding of overall geotechnical performance.

The integrated framework overcomes these limitations by linking geodetic observations, photogrammetric measurements, geotechnical instrumentation, and GIS-based analysis within a unified monitoring environment. This integration facilitates:

1. Continuous deformation detection
2. Early identification of instability trends
3. Correlation between groundwater conditions and displacement behavior
4. Assessment of blasting impacts on slope stability
5. Improved prediction of failure mechanisms
6. Enhanced construction safety and operational efficiency

Consequently, the framework assumes that higher levels of monitoring integration lead to more accurate deformation prediction, improved slope stability assessment, and reduced geotechnical risk.

Theoretical Model

Independent Variables

Excavation activities

Blasting vibrations

Groundwater fluctuations

Geological discontinuities

Underground construction works

Geotechnical Responses

Surface deformation

Slope displacement

Rock mass movement

Pore-water pressure changes

Crack propagation

Foundation settlement

Monitoring Technologies

UAV Photogrammetry

GNSS Networks

Total Station Surveys

Piezometers

Inclinometers

Extensometers

Crack Meters

GIS-Based Analysis

Outputs

Real-Time Deformation Monitoring

Early Warning of Instability

Improved Deformation Prediction

Slope Stability Assessment

Construction Risk Management

Outcome

Enhanced Safety and Sustainable Construction of Mega RCC Dam Projects

Research Proposition

This research is based on the proposition that an integrated monitoring framework combining UAV photogrammetry, GNSS, total station observations, GIS analysis, and geotechnical instrumentation provides more accurate and reliable assessment of deformation behavior than conventional monitoring methods alone. The integration of multiple monitoring technologies is expected to improve early-warning capability, strengthen slope stability evaluation, and enhance construction risk management for the Diamer Basha Dam Project.

Research Area

The research area includes RCC foundation zones, cofferdam areas, diversion tunnels, excavation slopes, and monitoring networks surrounding the Diamer Basha Dam Project. The region is characterized by steep mountainous terrain, fractured rock masses, and high excavation intensity.

III. RESEARCH METHODOLOGY

Periodic observations were collected using Leica total stations, GNSS receivers, UAV surveys, and geotechnical instrumentation systems. Orthomosaic generation and terrain analysis were performed using drone photogrammetry. Deformation data were processed and compared with excavation progress and blasting activities for stability assessment.

Data Analysis and Interpretation

Monitoring results identified increasing displacement trends in excavation zones with greater blasting intensity. Groundwater pressure variation was directly related to localized instability. UAV surveys enabled rapid identification of unstable slopes and deformation zones. Integrated monitoring improved the reliability of geotechnical risk prediction.

IV. DISCUSSION

Based on the findings presented in the research, the results demonstrate that excavation activities, blasting operations, and groundwater fluctuations are the primary factors influencing deformation behavior within the Diamer Basha Dam Project. Increased displacement trends observed in highly excavated zones indicate a strong relationship between excavation depth and slope response, confirming the theoretical principles proposed by Hoek and Bray regarding stress redistribution in rock masses. The observed correlation between groundwater pressure variations and localized instability further highlights the critical role of hydrogeological conditions in controlling slope performance. These findings suggest that relying solely on conventional surveying methods may not provide sufficient temporal and spatial coverage to detect rapid geotechnical changes in a complex Himalayan environment. Instead, the integration of GNSS observations, total station measurements, and geotechnical instrumentation offers a more comprehensive understanding of deformation mechanisms and enables continuous assessment of slope and foundation behavior.

Furthermore, the research demonstrates the effectiveness of integrating UAV photogrammetry with geodetic and geotechnical monitoring systems for real-time risk assessment and construction management. UAV surveys provided rapid, high-resolution visualization of excavation progress, unstable slopes, and deformation zones, significantly improving situational awareness in inaccessible mountainous terrain. When combined with GIS-based spatial analysis and automated instrumentation data, the integrated framework enhanced the accuracy of deformation prediction and strengthened early-warning capabilities. These findings are consistent with recent international studies that advocate multi-sensor monitoring approaches for large infrastructure projects. The results indicate that integrated monitoring systems not only improve slope stability assessment and excavation control but also contribute to safer and more efficient construction practices. Consequently, the proposed framework offers a practical and scalable solution for geotechnical risk management in mega RCC dam projects operating under complex geological and tectonic conditions.

V. CONCLUSIONS

This research demonstrates that integrated real-time deformation monitoring provides a highly effective solution for managing the complex geotechnical challenges associated with mega RCC dam construction. The findings indicate that excavation activities, blasting operations, groundwater pressure variations, and geological discontinuities Significantly influence slope stability and deformation behavior at the Diamer Basha Dam Project. By combining UAV photogrammetry, GNSS monitoring, total station observations, GIS-based analysis, and automated geotechnical instrumentation, the proposed framework enables comprehensive assessment of both surface and subsurface responses to construction activities. The integrated approach improves the accuracy of deformation detection, facilitates early identification of instability trends, and enhances understanding of the interaction between excavation processes and geotechnical conditions.

The research further confirms that conventional monitoring methods alone are insufficient for large-scale infrastructure projects operating in complex mountainous and tectonically active environments. UAV-based surveys proved particularly valuable for rapid terrain mapping and identification of unstable zones, while geotechnical instrumentation provided continuous information on groundwater behavior, rock mass movement, and slope performance. The integration of these datasets within a GIS-based monitoring environment significantly strengthened deformation prediction and risk assessment capabilities, enabling more informed decision-making during construction. The results demonstrate that multi-sensor monitoring systems can effectively reduce uncertainty, improve excavation control, and support proactive mitigation measures before critical failures occur.

Overall, the research establishes that integrated deformation monitoring frameworks are essential for ensuring construction safety, operational efficiency, and long-term structural stability in modern hydropower developments. The proposed framework offers a practical and scalable model for real-time geotechnical monitoring that can be applied not only to the Diamer Basha Dam Project but also to future RCC dams and other large civil engineering projects worldwide. Adoption of such integrated monitoring systems can significantly enhance slope stability analysis, strengthen early-warning mechanisms, improve risk management practices, and contribute to the sustainable and resilient development of critical infrastructure in challenging geological environments.

Graphical Analysis

Figure 1 illustrates the long-term deformation trend observed during excavation activities from 2020 to 2025. The graph indicates a continuous increase in displacement with the progression of excavation works. As excavation depth increased from 20 m in 2020 to 120 m in 2025, recorded displacement values rose from 1.4 mm to 15.3 mm. The deformation trend exhibits a nonlinear increase, particularly after 2022, suggesting that deeper excavations resulted in greater stress redistribution within the surrounding rock mass. This behavior is consistent with rock mechanics principles, where the removal of large rock volumes reduces confinement and promotes joint opening, rock relaxation, and slope movement. The graphical trend further demonstrates the importance of continuous monitoring in identifying accelerating deformation patterns before they reach critical levels.

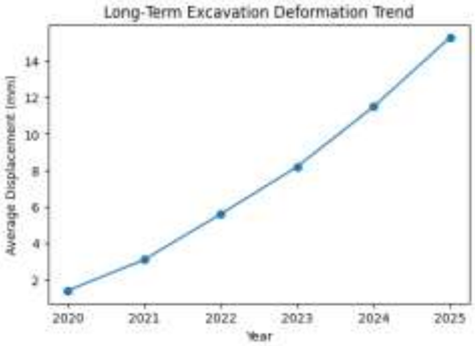


Fig.1: Long-term deformation trend observed during excavation operations.

Figure 2 presents the relationship between excavation depth and geotechnical instability risk. The graph reveals a strong positive correlation between increasing excavation depth and risk level. At excavation depths of 20–40 m, displacement values remained relatively low and the risk level was categorized as low to moderate. However, as excavation depths exceeded 80 m, both displacement and groundwater pressure increased significantly, resulting in high-risk conditions. By 2025, at an excavation depth of 120 m, groundwater pressure reached 103 kPa and displacement increased to 15.3 mm, leading to a critical risk classification. The graphical analysis highlights that deeper excavations not only increase deformation but also intensify hydrogeological and geotechnical instability factors. These findings confirm the necessity of integrated monitoring systems capable of tracking excavation progress, displacement trends, and groundwater conditions simultaneously to support timely risk mitigation and ensure construction safety.

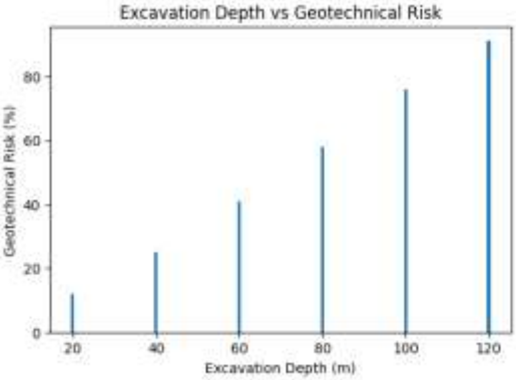
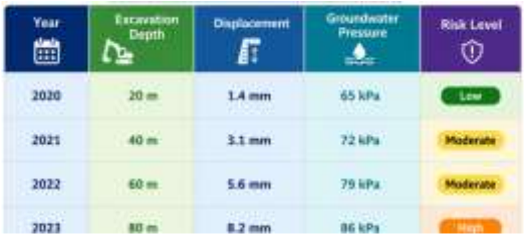


Fig.2: Relationship between excavation depth and geotechnical instability risk.

Table 1: Monitoring Data



Year	Excavation Depth	Displacement	Groundwater Pressure	Risk Level
2020	20 m	1.4 mm	65 kPa	Low
2021	40 m	3.1 mm	72 kPa	Moderate
2022	60 m	5.6 mm	79 kPa	Moderate
2023	80 m	8.2 mm	86 kPa	High

VI. FUTURE RECOMMENDATIONS

The findings of this research highlight the importance of integrated monitoring systems for managing geotechnical risks in large RCC dam projects. Future research should focus on increasing the frequency and automation of monitoring observations, particularly during critical construction stages such as deep excavation, tunnel development, and foundation preparation. Higher temporal resolution data would improve the detection of rapid deformation events and provide more reliable information for assessing excavation-induced instability in complex geological environments.

The application of Artificial Intelligence (AI) and Machine Learning (ML) techniques represents a promising direction for future studies. AI-based predictive models can be developed using historical monitoring datasets, excavation records, blasting parameters, and groundwater observations to forecast deformation trends and identify potential instability before critical thresholds are reached. Integration of predictive analytics with real-time monitoring networks would significantly enhance early-warning capabilities and support proactive geotechnical risk management.

Future investigations should also expand the use of UAV photogrammetry for continuous monitoring of high-risk and inaccessible slopes surrounding dam abutments, diversion tunnels, and reservoir margins. The integration of UAV-derived data with advanced remote sensing technologies such as LiDAR, InSAR, and terrestrial laser scanning could further improve the spatial resolution and accuracy of deformation mapping. Such multi-platform monitoring approaches would provide a more comprehensive understanding of slope behavior and geological hazards in mountainous terrain.

Given the significant influence of groundwater conditions on slope stability and foundation performance, future research should strengthen hydrogeological monitoring programs through the installation of additional piezometers and automated groundwater monitoring stations. Detailed investigation of the relationship between groundwater fluctuations, pore-water pressure changes, and deformation behavior would improve the understanding of failure mechanisms and support the design of more effective drainage and stabilization measures.

Furthermore, the development of cloud-based monitoring platforms is recommended to facilitate real-time data acquisition, storage, processing, and visualization. Cloud-integrated systems would enable seamless communication between geodetic instruments, geotechnical sensors, UAV platforms, and GIS databases while providing remote access to monitoring information for project managers and decision-makers. Such digital monitoring ecosystems could significantly improve response times, enhance data-driven decision-making, and support the implementation of smart infrastructure management practices.

Finally, future studies should validate the proposed integrated monitoring framework across different geological settings and dam types to assess its broader applicability. Comparative investigations involving RCC dams, concrete arch dams, embankment dams, and other large infrastructure projects would help establish standardized monitoring protocols and contribute to the development of international best practices for real-time geotechnical monitoring and construction risk management.

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