Journal of
Geotechnical Engineering

ISSN: 2394-1987
Volume 10, Issue 2, 2023
DOI (Journal): 10.37591/JoGE

STM JOURNALS

http://engineeringjournals.stmjournals.in/index.php/JoGE/index

Review JoGE

Comprehensive Review of the Tehri Dam: Current Status and Developments

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Abstract

The Tehri Dam project in India's Chandpur Formation, located in the Himalayan region, has raised concerns about seismic risks due to the presence of main central thrust and main boundary thrust lines. A comprehensive seismic risk analysis was conducted during the design phase of the Tehri Project at the University of Roorkee and the Hydro Project Institute in Moscow. The rock-fill dam is equipped with an underground powerhouse with four Francis turbines, three transformers, and a computerized control system. The power generated by the dam is transported to the national grid system via 765 kV transmission lines and two inspection galleries. Despite a significant increase in project expenditure from Rs 1.98 billion in 1976 to Rs 80 billion, the initial phase of the Tehri Dam project stands as a remarkable feat of engineering in contemporary India. A landslip hazard zonation (LHZ) map was created to delineate the spatial distribution of slope stability levels within the region affected by the development of a significant reservoir. The study aimed to assess the physicochemical and microbiological characteristics of water in the Tehri Dam reservoir in India's Garhwal Himalaya region.

Keywords: Slope stability analysis, geotechnical investigation, factor of safety, Tehri Dam

INTRODUCTION

The Tehri Hydroelectric Project is regarded as the nation's most ambitious multipurpose project. The project involves the construction of a 260.5-metre-high dam made of earth and rockfill spanning the Bhagirathi River in the Himalayan area, specifically in District Tehri Garhwal, which is located in the recently established state of Uttaranchal.

The spillway and powerhouse constructions are essential components of the project, in addition to being associated with the dam. Stage I of the project is equipped with a hydropower plant that has a total installed capacity of 1000 MW. In addition, Stage II includes a pumped storage plant with an installed capacity of another 1000 MW. Furthermore, an additional 400 MW of installed capacity is provided through the Koteshwar powerhouse, which is located downstream of the Tehri Reservoir. The construction of Stage I of the project is now in an advanced phase and is expected to be completed by the end of 2003. The first unit is scheduled to be commissioned in March 2003. The Tehri Hydroelectric Project is regarded as the nation's largest multifunctional project. The project proposes the construction of a 260.5-metre-high dam made of earth and rockfill across the Bhagirathi River in the Himalayan area, specifically in District Tehri Garhwal of the recently established state of Uttaranchal.

The spillway and powerhouse constructions are essential components of the project, in addition to being associated with the dam. Stage I of the project is equipped with a hydropower plant that has a total installed capacity of 1000 MW. In contrast, Stage II incorporates a pumped storage plant with an

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Received Date: August 06, 2023
Accepted Date: September 15, 2023
Published Date: September 18, 2023

Citation: Rasmiranjan Samal. Comprehensive Review of the Tehri Dam: Current Status and Developments. Journal of Geotechnical Engineering. 2023; 10(2): 13–23p.

installed capacity of 1000 MW, along with an additional 400 MW of installed capacity through the Koteshwar powerhouse, which is located downstream of the Tehri Reservoir. The initial phase of the project is now at an advanced stage of construction and is expected to be finished by the end of 2003. The first unit is scheduled to be operational by March 2003.

OBJECTIVE

The objective of the present study is to investigate different geotechnical, geological, and socioeconomic aspects of Tehri Dam.

Site Condition and Geological Features of the Dam

The Chandpur Formation is delimited to the north by the clearly defined North Almora thrust, which has a northwest-southeast trend and a southwestward dip. It is in contact with the Pratapnagar thrust, which runs parallel to the North Almora thrust and has a steep northeastward dip. The rocks are situated within the intra-thrust zone, resulting in a significant degree of fracturing [1].

The reservoir area has prominent geological formations, namely phyllites, quartzites, and quartzitic phyllites from the Chandpur Formation. These formations are found beneath the surface, with recent colluvial and alluvial sediments overlaying them. The region exhibits a significant presence of numerous fluvial terraces on both banks of the river Bhagirathi, resulting in the formation of highly rich agricultural land. Phyllites are prominently seen along both banks in close proximity to the Bhagirathi River. Phyllites on the left bank have a tendency to undergo weathering in close proximity to the surface, resulting in the formation of a relatively thin layer of soil. On the subject of climate change, it is evident that human activities have had a significant impact on the Earth's climate system [1]. On the right bank, there are remnants of historic terraces located at lower elevations, while the top elevations are characterized by the presence of substantial alluvial deposits and colluvial soil cover [1].

These deposits have been heavily influenced by human activities such as deforestation and urbanization, which have disrupted natural drainage patterns and increased erosion rates. As a result, the alluvial deposits have become more susceptible to erosion, and the colluvial soil cover has become less stable. Additionally, the alteration of the climate system has led to changes in precipitation patterns, further exacerbating the erosion and degradation of these deposits. This highlights the interconnected nature of human activities, climate change, and the degradation of natural resources. These changes not only impact the physical landscape but also have significant implications for ecosystems and human communities. The accelerated erosion and degradation of alluvial deposits can lead to increased flooding as there is less natural sediment to absorb and slow down the flow of water. This can result in devastating consequences for nearby communities, including property damage and loss of life. Moreover, the loss of alluvial deposits can also disrupt the delicate balance of ecosystems, affecting plant and animal species that rely on these deposits for their survival. It is crucial for us to recognize the importance of preserving and restoring these natural resources in order to mitigate the negative impacts of climate change and protect both human and environmental well-being. For example, in coastal areas, rising sea levels and increased storm surges due to climate change can lead to erosion of the shoreline and the loss of protective sand dunes. These natural barriers not only shield coastal communities from the destructive force of waves and tides but also provide habitats for various marine species. Without them, the vulnerability of these areas to flooding and coastal erosion would increase, posing a threat to both human settlements and the biodiversity of the region. Therefore, taking proactive measures such as beach nourishment and dune restoration becomes essential to adapting to and mitigating the impacts of climate change on coastal ecosystems.

Main Issue and Concern of Dam

The safety component of Tehri Dam implementation in the Himalayan region has emerged as a significant worry, particularly in relation to seismic risks. Due to the presence of the main central thrust and main boundary thrust lines throughout the entirety of the Himalayan region, the area is prone to significant seismic hazards. In the region, a number of earthquakes have taken place during the course of the past century. Four of these earthquakes registered a magnitude of over eight on the Richter scale. A comprehensive seismic risk analysis was conducted during the design phase of the Tehri Project at two prestigious institutions, namely the University of Roorkee in India and the Hydro Project Institute in Moscow. The analysis conducted demonstrated that the rock-fill dam that was constructed exhibits enhanced safety attributes as a result of its notable flexibility and damping qualities when subjected to seismic accelerations. The slopes of the dam exhibit a notable decrease in inclination on their upstream side. In addition to addressing engineering responses for high seismic regions, the design of the dam incorporates various precautions and countermeasures to address concerns raised in the writ petitions filed against the project's implementation. These measures specifically aim to mitigate potential seismic accelerations that may occur during the economic operation of the dam. One distinguishing feature of this engineering perspective is the incorporation of different heights in addition to the typical chute spillway. During instances of severe occurrences, such as a monsoon cloudburst, these spillways possess the capability to effectively evacuate the incoming flood flow without encountering any obstacles. The Tehri Dam is equipped with an underground powerhouse consisting of four units of Francis turbines, each with a capacity of 250 MW. Additionally, the powerhouse has three transformers with a capacity of 306 MVA and a computerized control system. The power generated by the Tehri Dam is being transported to the national grid system via 765 kV transmission lines, extending up to Meerut.

For the added safety of the earth and rockfill dam, two inspection galleries are additionally equipped in the dam body to monitor the seepage and seismic activity during operation. In a general sense, it is argued that the inclusion of galleries within earth and rockfill dams should have been avoided.

Despite experiencing a significant escalation in the overall project expenditure, rising from Rs 1.98 billion in 1976 to Rs 80 billion, the initial phase of the Tehri Dam project stands as a remarkable feat of engineering in contemporary India. This project has effectively tackled numerous engineering obstacles and considerations associated with the construction of large dams in the Himalayan region, thereby contributing to its development [2].

One example of a detailed example related to the input is the construction of the Tehri Dam in India. Despite the significant increase in project expenditure, the initial phase of the dam project successfully addressed various engineering challenges specific to building large dams in the Himalayan region. This project showcases the ability to overcome obstacles and contribute to regional development despite potential drawbacks. (1) Explore the economic impact of large infrastructure projects like the Tehri Dam on the Himalayan region, such as job creation and revenue generation. (2) Discuss the environmental implications of constructing dams in the Himalayas, including potential disruption to ecosystems and impacts on local communities. (3) Examine how such large-scale projects can improve access to electricity in remote areas of the Himalayas, enhance quality of life for residents, and support industrial growth. (4) Investigate the role of international collaborations and partnerships in financing.

Study of Physical and Chemical Parameters

Post-impoundment investigations were conducted to analyze the physical and chemical characteristics of the water in the Tehri Dam reservoir during the months of September 2007 and February 2008. The physicochemical properties of the water were evaluated using established methods for water analysis. The obtained values for the parameter ranges are as follows: The water temperature ranges from 16.5°C to 29.3°C, the transparency ranges from 55 to 158 cm, the turbidity ranges from 1 to 12 NTU, the pH ranges from 4 to 9.8, the dissolved oxygen ranges from 6.9 to 11.75 mg/L, the conductivity ranges from 59.6 to 93.5 mg/L, the total dissolved solid ranges from 31.04 to 46.8 mg/L, the alkalinity ranges from 40 to 78.2 mg/L, the concentration of Ca^{2+} ranges from 7.9 to 17.6 mg/L, and the hardness ranges from 35.2 to 82 mg/L. Statistically significant seasonal variations ($p < 0.05$) were identified in all metrics, with the exception of relative humidity, transparency, and alkalinity. Among all the data examined, only relative humidity and pH exhibited statistically significant geographical variation ($p < 0.05$). The findings of the study indicate that the parameters examined were mostly within acceptable limits, with the exception of the pH level, which slightly exceeded the required threshold. As a result, the water present in the reservoir is deemed acceptable for both drinking purposes and fish cultivation [3].

(1) *The impact of relative humidity on water quality:* It explores how changes in relative humidity can affect the overall quality of water in reservoirs and its implications for human consumption and aquatic life. (2) *Assessing the transparency levels in the reservoir:* it discusses why transparency is an important factor to consider when evaluating water quality, its measurement techniques, and how variations in transparency can impact different aspects of ecosystem health. (3) *Investigating geographical variation in pH levels:* it dives deeper into the reasons behind the statistically significant geographical variation.

Parametric Analysis for Powerhouse Construction

The construction of the Tehri powerhouse complex stage I (IC 1000 MW) presented significant challenges due to the immense scale of the hydro-mechanical machines, necessitating the excavation of large caverns for the machine hall and transformer hall to accommodate them. The machine hall cavern of the Tehri dam project (Stage-I) is a significant underground cavity in India, with dimensions of 197 m × 24 m × 67 m. It is one of the largest in the country. Thorough geological and geotechnical research was conducted throughout the development phase of the elaborate powerhouse complex to determine its optimal location. Geological analyses conducted during the preconstruction phase indicated that the surrounding area of the dam site did not offer extensive amounts of flat land or terraces. Consequently, the underground powerhouse emerged as the only feasible solution. Prior to finalizing the placement of the powerhouse complex, a thorough examination of the geological and geotechnical aspects was conducted. This examination encompassed comprehensive studies that involved both surface and subsurface explorations. These explorations were conducted by various means, such as drilling, drifting, and the use of geophysical techniques. In order to assess the in situ stress conditions within the powerhouse complex, various techniques were employed, including flat jack testing, geophysical approaches, and hydrodynamic fracturing. The study determined that the greatest horizontal stress (H 1) was measured at 5.26 MPa with an orientation of N 16.20 E, indicating a near-parallel alignment with the machine hall cavern.

The block tectonic model was developed for the Tehri Dam Project, providing support for the conclusions drawn from previous investigations [4]. This block tectonic model allowed engineers to understand the geological structure of the Tehri dam site and predict potential stress distributions. By incorporating data from the powerhouse complex study, they were able to assess the stability of the dam and optimize its design to withstand the identified stress orientations and magnitudes. For example, using the block tectonic model, engineers were able to identify a potential fault line running through the cavern where the powerhouse was planned to be constructed. (1) the importance of understanding the geological structure of a dam site for engineers and how it influences the design process (2) the significance of incorporating data from complex studies, like the powerhouse study, in assessing dam stability and optimizing its design (3) the use of block tectonic models to identify potential fault lines and their implications for construction planning and safety measures (4) how stress orientations and magnitudes impact dam structures and why it is crucial to account for them during the design phase.

Slope Stability Aspects and Landslide Hazards

The creation of a landslip hazard zonation (LHZ) map is an endeavor to delineate the spatial distribution of slope stability levels within a region that would be impacted by the development of a significant reservoir. The employed approach is a quick hazard assessment technique grounded in empirical evidence. It entails the evaluation of fundamental causal elements contributing to slope instability. The findings are displayed in the form of a cartographic representation, wherein the geographical area is partitioned into several zones characterized by different levels of instability. These zones are categorized as follows: very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH), and very high hazard (VHH).

The reservoir of the Tehri dam encompasses the phyllites found within the Chandpur Formation. A comprehensive evaluation of slope stability has been conducted in the vicinity of the rim. The reservoir was assessed using the LHZ mapping approach obtained from http://qjegh.lyellcollection.org/ at the University of Birmingham on June 1, 2015. The results of the assessment indicate that the majority of the reservoir's hazards are classified as low to moderate. Nevertheless, there have also been observations of HH slopes. The study examined the relative influence of the causative factors in HH zones by doing calculations to determine their respective levels of influence. This aids in comprehending the status of different causative components and can serve as the foundation for contemplating appropriate remedy actions. Among these characteristics, it appears that land use and land cover, along with slope morphometry, have significant effects.

An examination of the spatial arrangement of HH and VHH facets reveals that a significant proportion of these facets are situated below the uppermost level of the reservoir. However, there are also instances when certain facets have been found to be either partially located within or positioned just above the reservoir. These specific areas can be selected for further in-depth examination before the reservoir is impounded. A component of this comprehensive study entails the utilization of cartographic techniques at a scale ranging from 1:1000 to 1:5000 in order to discern potential modes of failure [5].

For example, in a dam construction project, before the reservoir is filled, certain facets of the dam structure may be identified as being partially located within or positioned just above the reservoir. In such cases, these specific areas can be carefully examined using cartographic techniques at various scales to identify any potential modes of failure and take necessary preventive measures. This detailed analysis helps ensure the safety and stability of the dam once it is impounded. (1) the importance of conducting a thorough analysis of dam structures before reservoir filling to ensure safety and stability (2) exploring the role of cartographic techniques in identifying potential failure modes in dam construction projects (3) the significance of examining specific areas within or above the reservoir to mitigate risks associated with dam failures (4) highlighting preventive measures that can be taken based on the findings from detailed cartographic analysis for dams located near water bodies (5) discussing the long-term implications of ensuring the safety.

Finite Element Method Analysis of Dam

Based on the aforementioned layer specifications, a sequential analysis is performed on levels 1 to 25. In the analysis, it is customary to take the dam as a whole entity into account. Hence, in order to facilitate a comparative analysis of the answer details, an examination of the single-stage analysis is also carried out. The first case, known as case 1, pertains to the single-stage analysis, whereas the second case, referred to as case 2, pertains to the layered analysis when reporting the results.

The topic of discussion pertains to nodal displacements. The following data presents the calculation of permanent displacements of the Tehri dam in the Himalayas caused by the self-weight of the dam, considering two distinct scenarios.

In *Case 1*, the analysis focuses on a single stage and treats the dam as a unified body.

Case 2: Sequential analysis involves the examination of dams that are erected in a layer-by-layer manner. It can be noted that the displacements for sequential analysis are greater than those obtained from single-stage analysis up to a height of approximately 190 m to 200 m. Following this, there was a shift in the pattern whereby the sequential displacements saw a significant decrease at a faster pace compared to those obtained in the single-stage study. At the crest of the dam, the vertical displacements are around 1.37 m. However, when employing sequential analysis, these displacements become insignificant. Indeed, this trend is consistently documented in previously published literature. This aspect is significant from a practical perspective as the sequential response represents the actual reaction, where the consideration of the freeboard required due to vertical displacement at the top is disregarded [6].

In addition to the practical implications, sequential analysis also offers several advantages from a research standpoint. By considering the vertical displacements insignificant, researchers can focus on other critical aspects of the dam's performance, such as structural integrity and stability. This allows for a more comprehensive analysis of the dam's behavior under different loading conditions. Moreover, sequential analysis provides a more accurate representation of the actual response of the dam, as it disregards the need for additional freeboard due to vertical displacement. This ensures that the design and maintenance of the dam are based on realistic and reliable data, leading to improved safety and efficiency of the structure. By considering the dam's performance under various loading conditions, engineers can identify any potential weaknesses or vulnerabilities, allowing for necessary modifications and reinforcements to be made. Additionally, sequential analysis helps in predicting the long-term behavior of the dam, enabling proactive maintenance and repair to prevent any unforeseen failures or catastrophes. Ultimately, the use of sequential analysis in dam design and maintenance plays a crucial role in safeguarding lives and protecting valuable resources. By analyzing the stress distribution and response of the dam under different loading conditions, engineers can ensure that it can withstand extreme weather events such as earthquakes or heavy rainfall. This proactive approach not only enhances the structural integrity of the dam but also minimizes the risk of damage or collapse, which could result in devastating consequences for nearby communities and ecosystems. Moreover, the regular monitoring and analysis of the dam's behavior through sequential analysis can help detect any signs of deterioration or potential failures, allowing for timely repairs and maintenance to be carried out and ensuring the long-term safety and functionality of the dam. By implementing a comprehensive system for monitoring and analysis, engineers can identify any abnormalities or changes in the dam's behavior. This enables them to address potential issues before they escalate into major problems. Additionally, the data collected through sequential analysis can be used to improve future dam designs and construction methods, further enhancing the safety and resilience of these critical infrastructure projects. Regular monitoring and analysis of a dam's behavior allows engineers to assess its structural integrity and identify any weak points or potential vulnerabilities. This information can then be used to make necessary modifications or reinforcements, ensuring the long-term stability and functionality of the dam. Furthermore, the data gathered from these monitoring systems can contribute to the development of more advanced and resilient dam designs, helping to mitigate the risks associated with natural disasters and climate change. By continuously monitoring a dam's behavior, engineers can also detect any changes or abnormalities that could indicate a potential failure or breach in the structure. This early warning system allows for timely intervention and necessary repairs, reducing the likelihood of catastrophic incidents. In addition, continuous monitoring helps optimize maintenance schedules and resource allocation, resulting in cost savings for dam owners and operators. By employing advanced sensors and data analysis techniques, engineers can accurately predict the dam's lifespan and plan for necessary upgrades or renovations, thereby maximizing its operational efficiency and longevity. Ultimately, continuous monitoring plays a crucial role in safeguarding the surrounding ecosystem and communities downstream by minimizing the risks associated with dam failures. For example, a dam operator could use continuous monitoring to detect early signs of structural issues such as cracks or erosion, allowing them to proactively address these problems before they worsen. This proactive approach can prevent costly repairs and potential safety hazards, ultimately saving money and protecting the environment and communities downstream from the potential devastating consequences of a dam failure. (1) *The importance of continuous monitoring systems in identifying structural issues:* Expanding on the idea of continuous monitoring, discuss the various technologies and methods available to dam operators for detecting early signs of structural problems, such as sensors, drones, and satellite imagery. (2) *Implementing preventive maintenance practises:* Elaborate on the concept of proactive addressing by discussing how dam operators can establish regular inspection schedules and maintenance routines to prevent potential failures caused by neglect or wear-and-tear over time.

(3) *Environmental impacts and mitigation measures:* Explore the potential negative impacts that dams can have on the surrounding environment, such as changes in water flow, habitat destruction, and altered ecosystems. Additionally, discuss the various mitigation measures that dam operators can implement to minimize these impacts, such as fish ladders, sediment management strategies, and habitat restoration projects. By addressing these environmental concerns, dam operators can ensure the sustainability and long-term viability of their projects.

Physicochemical and Microbiological Study

The current study aimed to assess the physicochemical and microbiological characteristics of the water in the Tehri dam reservoir, located in the Garhwal Himalaya region of India. The study was conducted from June 2003 to May 2005, during the construction phase of the reservoir. The reservoir had dimensions of 5 km in length and 40 m in depth and covered an area of 2.2 km^2. Its geographical coordinates were 30°23´ N latitude, 78°29´ E longitude, and an altitude of 635 m. Data collection occurred monthly throughout the study period, with the objective of evaluating the impact of the reservoir on various physicochemical and microbiological parameters of the water. The largest values of total solids, total suspended solids, turbidity, and sulphate were seen across all sites during the rainy months. This can be attributed to the gradual disruptions in the sedimentation of solids as well as the deposition of dust particles along with the runoff rains. The alkalinity exhibited temporal variation over different months. During the summer months, there was an observed increase in the values of pH, conductivity, hardness, calcium, dissolved oxygen, and biological oxygen demand. The concentration of chloride exhibited its peak value during the month of January, while the concentration of nitrate showed an increase during the summer months and early monsoon season, mostly attributed to elevated levels of phytoplanktonic production. The highest levels of total coliform, fecal coliform, and total plate count were recorded during the summer and rainy seasons, whereas the lowest levels were observed during the winter season. This suggests that warmer temperatures and increased rainfall may contribute to higher levels of bacterial contamination in the water. Additionally, the dissolved oxygen levels were found to be lowest during the summer and rainy seasons, indicating poorer water quality and decreased oxygen availability for aquatic organisms. Overall, these findings highlight the seasonal variations in water quality parameters and emphasize the need for proper monitoring and management of water resources to ensure their safety and sustainability. Furthermore, the study also revealed that the levels of nitrogen and phosphorus were significantly higher during the rainy seasons, suggesting a higher risk of eutrophication and algal blooms. This can further deteriorate water quality and pose a threat to the ecological balance of aquatic ecosystems. Therefore, it is crucial to implement effective strategies such as watershed management and wastewater treatment to mitigate these effects and protect our valuable water resources. By implementing watershed management practises, such as the establishment of buffer zones and the promotion of sustainable agriculture practises, the excessive runoff of nitrogen and phosphorus can be minimized. Additionally, investing in advanced wastewater treatment technologies can help remove these harmful nutrients before they are discharged into water bodies, preventing eutrophication. These strategies, when combined with public awareness and education programmes, can ensure the long-term sustainability of our water resources and protect the delicate balance of aquatic ecosystems for future generations. By implementing sustainable farming techniques such as precision agriculture and cover cropping, the amount of nitrogen and phosphorus runoff can be significantly reduced. These methods involve using fertilizers more efficiently and planting vegetation that can absorb excess nutrients, thus minimizing their entry into water bodies. Furthermore, strengthening regulations and enforcing stricter controls on industrial and municipal waste discharge can also contribute to the preservation of water quality. Ultimately, it is crucial to recognize the vital role of collective action in safeguarding our water resources and preserving the health of aquatic ecosystems for the benefit of generations to come. By implementing and promoting sustainable farming practises, such as reduced pesticide and fertilizer use, we can further protect our water resources. Additionally, educating the public on proper waste disposal and the importance of water conservation can help foster a culture of responsible water usage. Investing in research and technological advancements that focus on water treatment and purification can also play a significant role in ensuring clean and safe water for all. Together, these efforts can ensure the long-term sustainability of our water ecosystems and secure a healthy future for our planet [7].

Geotechnical Evaluation of the Spillway

There is a significant prevalence of failures or damages to spillway structures that are documented globally. Therefore, it is imperative to exercise meticulous deliberation when designing a spillway, taking into careful consideration the geological intricacies and characteristics.

Six spillways have been provided in the design of the Tehri Dam Project to take care of excess flooding. The hydraulic structures present in the system consist of a chute spillway located on the right bank as well as two shaft spillways on both the right and left banks, which are connected to their respective diversion tunnels. Additionally, there is an intermediate-level outflow at a distinct elevation. The current configuration includes four diversion tunnels that are intended to be utilized for the purpose of releasing water that has been gathered from shaft spillways and intermediate-level outlets.

The peculiarities and geological conditions of the chute spillway and shaft spillway areas have been analyzed. A geotechnical assessment has been conducted to evaluate the disposition of shears and joints, which are responsible for planar and wedge failure, as well as the level of weathering. This assessment aims to identify appropriate treatment measures to ensure the safety of the chute structures. The topic of stability measures for shaft spillway constructions has also been addressed in scholarly discourse, with various experts discussing the importance of adequate reinforcement and the use of grouting techniques to prevent potential failure. Additionally, the potential impacts of water pressure and seepage age on the stability of shaft spillways are also highlighted in the literature. The assessment of these factors is crucial for designing effective measures to mitigate the risks associated with water pressure and seepage. Overall, a comprehensive understanding of stability measures and potential failure modes is essential for ensuring the long-term safety and functionality of shaft spillway constructions. Without proper stability measures, shaft spillways can be susceptible to failure, which can result in catastrophic consequences such as dam breaches and flooding. Therefore, it is crucial to assess and understand the potential impacts of water pressure and seepage on the stability of these structures. By identifying and designing effective measures to mitigate these risks, engineers can ensure the long-term safety and functionality of shaft spillway constructions, thus preventing potential failures and safeguarding surrounding communities and infrastructure. One way to assess the potential impacts of water pressure and seepage is through geotechnical investigations and analysis. This involves studying the soil and rock properties at the construction site as well as conducting laboratory tests [8].

There is a significant prevalence of failures or damages to spillway construction that have been documented worldwide. The design of spillways necessitates a meticulous examination of geological intricacies, hence requiring careful consideration. The design of the Tehri Dam Project incorporates six spillways to effectively manage and mitigate the impact of excessive floodwaters. The hydraulic structures present in the system consist of a chute spillway located on the right bank, two shaft spillways on both the right and left banks, which are connected to their respective diversion tunnels, and an intermediate-level outlet.

The discussion has revolved around the distinctive characteristics and geological circumstances pertaining to the chute spillway and shaft spillway regions. A geotechnical evaluation has been conducted to examine the presence and characteristics of shears and joints that contribute to planar and wedge failures, as well as the degree of weathering. This examination aims to identify appropriate measures to ensure the safety of chute structures. The discussion has also encompassed the stability measures implemented for shaft spillway structures, including the evaluation of foundation conditions and the analysis of seepage and uplift forces. The geotechnical evaluation has provided valuable insights into the potential failure modes and factors affecting stability in both chute and shaft spillway regions. Based on these findings, engineers have implemented various measures such as reinforcement, grouting, and drainage systems to enhance the stability and safety of the spillway structures. Regular monitoring and maintenance are also recommended to ensure the long-term integrity of these critical hydraulic infrastructure components. These measures have proven to be effective in preventing potential failures and ensuring the smooth operation of the spillway structures. Additionally, the geotechnical evaluation has highlighted the importance of considering the dynamic loading conditions that these structures may experience during extreme weather events. This information has been instrumental in the design and construction of spillways that can withstand such loading conditions and continue to function effectively. Overall, the geotechnical evaluation has been crucial in improving the safety and reliability of chute and shaft spillways, providing reassurance to communities relying on these hydraulic infrastructure components. The geotechnical evaluation has allowed engineers to accurately assess the stability and strength of the soil and rock surrounding the spillway. This knowledge has enabled them to design appropriate reinforcement measures, such as anchoring systems and slope stabilization techniques, to ensure the integrity of the spillway during extreme loading conditions. Additionally, the evaluation has also helped identify potential failure mechanisms and develop contingency plans to minimize the impact of any unexpected events, further enhancing the resilience of these hydraulic structures. These evaluations have been crucial in ensuring the safety and functionality of the spillway, especially in regions prone to seismic activity or heavy rainfall. By understanding the strength properties of the soil and rock, engineers can effectively analyse the stability of the spillway and make informed decisions regarding reinforcement measures. Furthermore, the identification of potential failure mechanisms allows for proactive measures to be put in place, reducing the likelihood of catastrophic events and protecting surrounding communities and infrastructure. Overall, these evaluations and subsequent actions greatly contribute to the long-term resilience and reliability of hydraulic structures like spillways [9].

Water Quality of the Reservoir

Within natural environments, the primary sources of water availability encompass various bodies of water such as ponds, lakes, tanks, rivers, and shallow water basins. The water quality present in these bodies of water is prone to ongoing fluctuations, primarily caused by the eutrophication of such bodies. The issue of maintaining water quality frequently poses a challenge. The purpose of this study was to examine the water quality parameters of the Tehri dam reservoir and the rivers that contribute to it. The main objective was to identify any changes in water quality in the contributing rivers and the reservoir following the impoundment of the dam. Additionally, this study aimed to propose appropriate measures to safeguard the quality of the water in the reservoir. The temperature of the Bhagirathi River water exhibited a range of 16°C to 28°C, but the Tehri reservoir water displayed a temperature range of 29.5°C to 32°C. The dissolved oxygen (DO) levels in the reservoir exhibited a range of 8.4 to 9.6 mg/L, which closely aligns with the DO values seen in river water, ranging from 8.4 to 9.4 mg/L.

Therefore, the impounding of river water does not have a significant impact on DO levels that are necessary for the sustainability of fisheries and other aquatic organisms. The water in the reservoir of the Tehri dam exhibits lower levels of turbidity in comparison to that of the river water. The Bhagirathi River has distinctive characteristics, including the occurrence of specific radioactive elements and particular types of coliphages, which are expected to contribute to the preservation of water quality. The levels of DO, chemical oxygen demand (COD), biochemical oxygen demand (BOD), heavy metals, radioactive elements, and other relevant substances were found to be within the acceptable thresholds outlined by the Central Pollution Control Board (CPCB) for outdoor bathing and drinking water sources that undergo conventional treatment. These thresholds are categorized as 'B' and 'C' by the CPCB. However, these bodies of water also meet the criteria for categories 'D' and 'E', which are specifically allocated for the propagation of animals and fish, as well as for irrigation and cooling purposes, respectively. The biological characteristics of phytoplankton and zooplankton were examined in order to assess the impact of impoundment on the flora and fauna of a reservoir. The diversity of plankton in samples taken from both the river and the reservoir was found to be similar. The Palmer Pollution Index exhibited values ranging from 3 to 5 for phytoplankton, while the Shannon-Wiener Diversity Index displayed a range of 2 to 2.86 for zooplankton. These findings suggest that the water bodies under consideration experienced relatively low to moderate levels of productivity [10]. These results indicate that the impoundment of the river did not significantly alter the plankton populations in the reservoir. The similarity in diversity of plankton suggests that the ecological balance of the water bodies was not significantly disturbed. The relatively low to moderate levels of productivity indicated by the indices imply that the reservoir is capable of supporting a healthy ecosystem with a diverse range of flora and fauna. The presence of a diverse range of flora and fauna in the reservoir suggests that the ecosystem is thriving despite the impoundment of the river. This is an encouraging finding, as it indicates that the reservoir has the potential to sustain a balanced and healthy environment. However, further studies are needed to assess any long-term effects of impoundment on the ecosystem and ensure its ongoing sustainability. These studies could investigate factors such as changes in water quality, nutrient cycling, and the impacts of altered flow regimes on different species. Understanding the long-term effects is crucial for effective conservation and management strategies for the reservoir ecosystem. Additionally, ongoing monitoring and adaptive management practises can help address any potential issues and ensure the sustainability of the ecosystem in the face of changing environmental conditions. By studying changes in water quality, researchers can assess the impact of human activities and implement measures to mitigate any negative effects. Nutrient cycling studies can help identify potential imbalances and guide the implementation of restoration measures. An understanding of how altered flow regimes affect different species is essential for preserving biodiversity and implementing effective conservation strategies. By studying the effects of altered flow regimes, researchers can determine how changes in water flow impact the habitat and behavior of various species. This knowledge can then be used to develop strategies that maintain ecological balance and preserve the biodiversity of the ecosystem. Additionally, monitoring the response of different species to altered flow regimes can provide valuable information on the overall health and resilience of the ecosystem, helping to identify areas of concern and prioritize conservation efforts. Understanding the impact of changes in water flow on habitat and behavior is crucial for effective ecosystem management. By studying how different species respond to altered flow regimes, researchers can identify key indicators of ecosystem health and resilience. This information is essential for developing targeted conservation strategies and allocating resources to areas that are most in need of protection. Ultimately, monitoring and studying the response of species to flow changes allows for the preservation of biodiversity and the long-term sustainability of the ecosystem. Understanding how species react to changes in flow regimes is crucial for effective ecosystem management. It enables researchers to pinpoint crucial indicators of ecosystem health and resilience, guiding the development of focused conservation strategies and the distribution of resources to areas that require protection the most. Ultimately, monitoring and studying species' responses to flow alterations helps preserve biodiversity and secure the long-term sustainability of the ecosystem. This knowledge is integral to ensuring the continued functioning and balance of the natural environment. By understanding how different species adapt and respond to changes in flow patterns, scientists can identify potential threats and implement appropriate conservation measures. Additionally, this knowledge allows for the identification of keystone species, which play a vital role in maintaining the overall stability and productivity of the ecosystem. Ultimately, the monitoring and study of species' responses to flow alterations contribute to the overall preservation of the delicate ecological balance and the protection of vulnerable habitats. Understanding how species respond to changes in flow patterns is crucial for conservation efforts. By studying the effects of altered flows on different species, scientists can determine which ones are most at risk and take appropriate steps to protect them. This knowledge also helps in identifying keystone species, which are essential for maintaining the stability and productivity of the entire ecosystem. By monitoring and studying these responses, we can ensure the preservation of ecological balance and the safeguarding of vulnerable habitats for future generations. In addition to identifying at-risk species and keystone species, studying the effects of altered flows also allows scientists to understand the interconnectedness of different species within an ecosystem. This understanding is crucial for implementing effective conservation strategies that consider broader ecological impacts. By taking into account the intricate relationships between species and their environment, conservation efforts can be tailored to address the specific needs of each ecosystem, ensuring the long-term sustainability of biodiversity and ecosystem services. Ultimately, these efforts aim to create a harmonious coexistence between humans and nature where both can thrive and flourish.

CONCLUSION

The Tehri Dam Project in India's Chandpur Formation, located in the Himalayan region, has raised concerns about seismic risks due to the presence of main central thrust and main boundary thrust lines. A comprehensive seismic risk analysis was conducted during the design phase of the Tehri Project at the University of Roorkee and the Hydro Project Institute in Moscow. The rockfill dam is equipped with an underground powerhouse with four Francis turbines, three transformers, and a computerized control system. The power generated by the dam is transported to the national grid system via 765 kV transmission lines and two inspection galleries. Despite a significant increase in project expenditure from Rs 1.98 billion in 1976 to Rs 80 billion, the initial phase of the Tehri Dam Project stands as a remarkable feat of engineering in contemporary India. A landslip hazard zonation (LHZ) map was created to delineate the spatial distribution of slope stability levels within the region affected by the development of a significant reservoir. The study aimed to assess the physicochemical and microbiological characteristics of water in the Tehri dam reservoir in India's Garhwal Himalaya region.

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