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GEOLOGICAL CHARACTERIZATION OF POTENTIAL DAM SITES

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Abstract
The paper covers various aspects of geological site exploration, including the exploration techniques, methodology, stages, data collection, analysis, and presentation. The review also includes a case study of a dam site failure to illustrate the importance of thorough exploration and accurate data analysis. The study emphasizes the significance of proper geological exploration practices to prevent potential failures. Properly characterizing the site's geological conditions ensures the safety, stability, and success of the dam, serving as the basis for informed engineering decisions.

Keywords: congestion charging, cordon area, risks mitigation, traffic volume survey, questionnaire survey.

1. INTRODUCTION

The complexity and variability of subsurface conditions hinder the establishment of a standard geological investigation method. The planning and selection of specific investigation methods depend on the site variability and purpose of the investigation. However, fundamental data acquisition steps are essential for engineering projects. Collected field data underpin subsequent decisions, project completion, and implementation. Standardizing procedures aids in reducing time and expenses.

Dam sites possess distinct geological and geotechnical features, and design requirements vary based on dam types, sizes, purposes, and hazards. Comprehensive site understanding is crucial for relevant dam construction and operation inquiries. Objectives of investigations should align with design requirements, covering essential parameters and design assumptions. Investigation plans allow for revisits and supplementary exploration to accommodate evolving design modifications. Comprehensive investigations encompassing reservoir rim, terrain changes, drainage patterns, landslide potential, and peripheral issues are vital. Remote sensing aids regional geologic interpretation and needs to be considered for identifying potential hazards (NDOT 2005). Site geology influences the dam design through the nature of subsurface formations and construction material availability. Project specifics, criteria, constraints, and design requirements inform the extent of investigations. Systematic data collection supports alternative analysis, concept selection, and detailed design considerations. Data-driven approaches align with potential design alternatives, guiding field geotechnical investigation methods, process and data collection tools (Rogers G. D., et al., 2012).

Integration of geological understanding and engineering design is essential for successful economical dam projects. Geologic data must answer engineering questions and address potential failure hazards. Synthesizing geologic data based on dam vulnerabilities and failure modes is crucial. Understanding vulnerabilities guides data collection priorities (Shaffner Peter, 2011).

Foundation requirements and geomechanical properties of subsurface material play vital roles in foundation decisions. Dam foundation assessment involves embankment and spillway foundation conditions, materials confirmation, and engineering properties. Geological aspects impact the dam reservoir environment, slope stability, erosion potential, and siltation risk. Geomechanical properties of rocks impacting dam structures should be determined to address weathering, discontinuities, strength, and hydraulic conductivities (Kocbay A., et al., 2006. A).

The paper emphasizes the importance of systematic geological exploration for dam site characterization. Tailoring investigations to specific dam types, sizes, and purposes ensures accurate data collection. Integrating geology and engineering considerations, understanding vulnerabilities, and assessing foundation conditions contribute to successful dam design and construction while minimizing potential risks.

2. GEOTECHNICAL MAPPING AND FOUNDATION CONSIDERATIONS

Geological investigations are crucial across the dam footprint, valley floor, potential borrow sites, and access roads of the proposed dam. Moreover, thorough assessments are required along abutment slopes, reservoir rim, and

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suspected landslide-prone zones within the reservoir area. Detailed stratigraphic mapping aids in determining the transition between reinforced cement concrete and embankment dam sections (Mike Marley, et. al., 2007).

Detailed geologic sections and maps are essential for understanding and communicating foundation conditions. Geologic mapping of the foundation and downstream abutments is needed for defining discontinuities and potential sliding areas. In steep terrain, specific evaluations for sliding hazards, like the Vaiont Dam Failure, can be conducted using maps and aerial photographs. Comprehensive geological investigations must extend beyond the dam's immediate footprint (Shaffner Peter, 2011).

Comprehensive geological investigations are imperative for dam site characterization. These investigations should encompass a range of areas within and beyond the dam's footprint, considering factors such as foundation conditions, potential sliding risks, and geological mapping. This integrated approach ensures a thorough understanding of the site's geology, aiding in informed decision-making and effective dam design and construction. The design's completion is contingent upon the exposure, inspection, comprehension, and approval of the foundation.

3. STAGES OF GEOLOGICAL STUDY IN DAM PROJECTS

The geological study for dam projects unfolds in four sequential stages: pre-feasibility, feasibility, preconstruction/design support, and construction. These stages involve an array of activities such as surveying, exploration, data collection, analysis, and control measures. By systematically progressing through these stages, dam projects can achieve informed decision-making, safe construction practices, and effective problem-solving, all of which are crucial for successful dam implementation.

1. **Pre-feasibility Stage:** Initial stage involving surveying, geological, and geophysical exploration. Data collection includes existing geological information, technical publications, and terrain analysis through topographic maps and satellite imagery.
2. **Feasibility Stage:** Continuation of geological exploration and data collection through site reconnaissance and detailed geological surveys. Focus on reviewing and analyzing soil, rock types/depth, geological structures, drainage patterns, and conducting sampling and testing.
3. **Preconstruction or Design Support Stage:** Geological exploration persists, aiding design decisions and problem-solving. Comprehensive analysis of collected data to inform dam design and construction plans.
4. **Construction Stage:** Geological and geotechnical control is paramount during this phase. Addressing local problems encountered during excavation and ensuring safe construction.

4. EXTENT OF EXPLORATION

Determining appropriate levels of exploration is crucial for safe and cost-effective dam construction. Comprehensive investigations, focused data collection, geology-design integration, and lessons from past failures all contribute to a thorough understanding of potential failure modes. This iterative process, coupled with multidisciplinary assessment and clear communication of uncertainties, ensures that geological considerations are well-integrated into dam safety studies and design decisions. Sissakian, V.K.et al.(2020).

1. **Determining Appropriate Exploration:** Optimal exploration level is critical for timely, safe, and cost-effective project completion. Quantity and quality of geological exploration influence construction accuracy, budget, and safety. Guidelines from ICOLD (1989) suggest comprehensive investigations for accurate site knowledge, focused explorations in complex geological structures, and designs grounded in real information.
2. **Focused Data Collection:** After initial failure mode evaluation, additional work targeting significant failure modes is necessary. Risk analysis guides data collection for specific failure modes, aiding uncertainty reduction. Multi-disciplinary assessment enhances understanding of failure modes, directing foundation data collection and analysis. Clear documentation of uncertainty in subsurface data is crucial to prevent misuse.
3. **Incorporating Geology into Design:** Geologists play a vital role in understanding and communicating uncertainty. Geologic information must be integrated into design decisions, accounting for uncertainties. The mere existence of geologic reports doesn't ensure robust design; lessons from past failures like St. Francis Dam and Malpasset Dam underscore this.
4. **Iterative Process:** Investigation and data analysis involve evaluating failure modes, reducing uncertainty through further exploration, reevaluating potential failure modes, risk assessment, and iterative estimation.

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5. ITERATIVE APPROACH TO INVESTIGATIONS

The iterative approach to site investigation involves a series of well-defined activities, ranging from initial question formulation and data assessment to detailed geological modelling, property quantification, and engineering analyses. This approach allows for gaps to be identified and addressed progressively, leading to a comprehensive understanding of the site's geotechnical and geological conditions. The iterative nature ensures that investigations continue until the required level of confidence is attained in the project's safety and feasibility.

1. **Defining Objectives:** Begin by defining the objectives of the work and the engineering /geological questions to be addressed.
2. **Initial Data Collection and Assessment:** Collect and assess existing geological data to form a preliminary site geological/geotechnical model. Attempt to answer questions from earlier steps. New questions may arise at this stage based on the geological understanding gained.
3. **Gap Filling Planning:** Plan activities to fill gaps in the geological and engineering understanding that emerged during the assessment of existing data.
4. **Cost Estimation and Approval:** Prepare a cost estimate and report to management, seeking approval to proceed with further investigations.
5. **Semi-Quantitative Model:** Develop a semi-quantitative engineering-geological model that encompasses regional geology, geological history, and site-specific geology. Focus on achieving geological sub-objectives.
6. **Quantification of Engineering Properties:** Perform field and laboratory tests to quantify engineering properties. Align test results with the geological model and incorporate realistic values or ranges into the geotechnical model.
7. **Analysis and Answers:** Conduct engineering analyses involving the structure and geotechnical model to answer the defined questions. Consider the probability of failure and the factor of safety. If all questions are confidently answered, the investigation is complete. If not, repeat the cycle of investigation until the desired level of confidence is achieved.

6. METHODS OF EXPLORATION

A variety of exploration methods are employed in dam site investigations. These methods encompass geophysical techniques, geological mapping, geotechnical drilling and testing, discontinuity surveying, downhole testing, and hydraulic conductivity assessment. Together, these methods provide a comprehensive understanding of subsurface conditions, enabling informed engineering decisions and ensuring the safety and effectiveness of dam construction projects

1. **Geophysical Methods:** Geophysical techniques like seismic refraction, electrical resistivity, self-potential, and seismic tomography provide spatial and depth-wise data. They assist in identifying bedrock, groundwater conditions, faults, and shear zones (Mike Marley, et. al., 2007). Jayanath MGS, et al. (2017), Adewoye, A. O et al. (2015)
2. **Geotechnical Drilling and Testing:** Includes water pressure testing, excavation, and geological mapping. Techniques like seismic refraction profiling, downhole geophysical logging, and hydrogeological investigation with drilling and pumping tests are employed (Mike Marley, et. al., 2007).
3. **Downhole Testing and Draft Logs:** Packer permeability testing, televiewer surveys, and seismic velocity testing are used. These provide insights into in-situ fracture orientation and rock mass features (Schug David L., et.al. 2011., Mike Marley, et. al., 2007). Logging soil and rock samples and drilling information in the field creates draft logs. These logs aid in developing geologic cross-sections and profiles, assisting in data evaluation and project deliverables (Rogers G. D., et al., 2012).
4. **Discontinuity Surveying, Stereonets and Rock Fracture Analysis:** Surface discontinuity surveys assess rock fractures, joints, and other features. Mapping aims to understand the rock mass character and identify potentially unstable sections (Mike Marley, et. al., 2007). Stereonets analyze the spatial distribution of sheared zones. Rock fracture data are compiled and plotted for evaluation of the proposed excavations' stability (Schug David L., et.al. 2011.).

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5. **Packer Test for Hydraulic Conductivity:** Packer test estimates in-situ hydraulic conductivity. It involves increasing and decreasing test pressures to monitor water loss. Packer tests are performed at geologic contact intervals to assess hydraulic conductivity contribution (Schug David L., et.al. 2011.).
   To assess water seepage potential, the joint systems of rock units are studied along with in-situ tests to estimate permeability values. If uncontrollable seepage is identified, corrective measures like grouting can be recommended. Grouting is employed to enhance foundation geomechanical quality and impermeability. The design of a grouting system, such as a grout curtain or consolidation grouting, is based on data from probe drillings, permeability tests, and test grouting.

7. LABORATORY TESTING

Laboratory testing forms a critical component of dam site investigations, enabling a comprehensive understanding of rock mass properties, foundation characteristics, soil engineering properties, and construction material suitability. These tests follow recognized standards and methodologies, contributing valuable insights that inform engineering decisions and ensure the successful and safe construction of dams. The following key aspects are considered:

1. **Soil Engineering Properties:** Soil properties are assessed for use in earthen embankment dams. Determination of cohesion, internal friction angle, deformation parameters (in-situ jacking tests), dry unit weights, saturated unit weights, porosity, permeability, specific gravities, and more is based on ASTM and ISRM standards (ASTM 1980, 1996, ISRM 1978, 1981, 1985).
2. **Characterizing Rock Mass Properties:** Laboratory testing quantifies the physical and geomechanical properties of intact rocks using methods like direct shear, unconfined compression, triaxial tests, tensile strength, and point load tests. ASTM International standards are often followed (Schug David L., et.al. 2011., Kaveh M. T.et al., 2011.).
3. **Foundation and Soil Testing:** Tests include bearing capacity (cone penetrometer and standard penetration, etc.), classification, grain size distribution, compaction, consolidation, and compressive strength. Pressure meter tests provide in-situ values of undrained shear strength and elastic properties of site soils.
4. **Material Evaluation for Construction:** Potential borrow areas for dam construction can be identified based on material properties. Recovered test pit materials can be crushed and tested for trial roller-compacted concrete (RCC) mixes. Aggregate quality testing is performed on on-site test quarry materials for suitability as RCC aggregate.

8. INVESTIGATING POTENTIAL FAILURE MODES IN DAMS

Investigations into potential failure modes in dams are crucial for ensuring their safety. From overtopping to foundation defects and geological challenges, thorough assessments and understanding of various failure mechanisms guide dam design, construction, and ongoing monitoring efforts. This holistic approach contributes to the resilience and stability of dams, preventing catastrophic failures. The primary objective of dam investigations is to ensure dam safety by assessing all identifiable and foreseeable failure mechanisms. This includes monitoring changes that could indicate the development of hazardous conditions. Gangopadhyay S. (1993)

1. **Common Failure Modes:** a. **Overtopping:** About 1/3 of dam failures globally result from overtopping. Poor geological conditions, settlement of dam crest due to foundation defects, or reservoir landslides can lead to overtopping. b. **Foundation Defects:** Roughly 1/3 of dam failures are attributed to foundation defects. Unequal settlement, instability, landslides, or events like earthquakes can compromise dam foundations. c. **Concrete Dam Failures:** Foundation problems are a common cause of concrete dam failures. Uplift pressures, uncontrolled seepage, and piping can also compromise foundations.
2. **Earthen Dam Failures:** Nearly 80% of earthen dam failures are linked to overtopping and quality issues. Quality problems often involve piping in the dam body or foundation due to cracks caused by various factors like settlement, shrinkage, and foundation defects.
3. **Factors in Rock Foundation Stability:** Most dams on rock foundations exhibit good performance. However, certain challenges arise due to uncertainties surrounding high transmissibility, erosion, deformability, inelasticity, interaction with landslides, weathering, and contiguous bedrock faults.

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4. **Common Issues with Rock Foundations:** a. **Sheet Joints:** The presence of sheet joints in rock can impact stability. b. **Rapid Erosion:** Erodibility of jointed rock can lead to instability. c. **Instability of Rock Blocks:** Potential instability of removable rock blocks is a concern. d. **Leakage through Joints:** Unsustainable leakage through open joints can compromise dam integrity.

9. ENGINEERING CLASSIFICATION OF ROCK MASS

Rock mass classification methods are invaluable in dam construction design. Numerical rock mass classification techniques are commonly used during preliminary design, aiding in estimating required rock support and groundwater control measures. Engineering geological investigations and rock mechanics studies contribute to rock mass characterization, involving discontinuity surveying, core drilling, in-situ, and laboratory testing. Engineering classification of rock mass involves various methods like RMR and Q systems, which are crucial for understanding rock mass quality, strength, and behaviour. These classifications serve as indispensable tools for preliminary design, site characterization, and support design in dam construction, contributing to safe and effective project implementation Fraser WA (2001)

1. **Core Recovery and Rock Quality Designation:** Total core recovery (TCR) and Rock Quality Designation (RQD) are determined for critical areas such as dam axis, spillway, and diversion tunnel alignment. These values aid in assessing basic rock mass quality.
2. **Empirical Failure Criteria and Classification Systems:** Empirical rock mass quality, strength, and constants are expressed using various methods such as Hoek-Brown empirical failure criteria, Rock Mass Rating (RMR), Geological Strength Index (GSI), and Rock mass quality (Q) values.

Bieniawski's RMR system involves assessing factors like uniaxial compressive strength, RQD, joint spacing, joint condition, joint orientation, and groundwater conditions for rock mass classification. Ratings are assigned to each factor, including groundwater, joint condition, and joint spacing. Several widely known methods are used for rock mass characterization: Rock Quality Designation (RQD, Deere D.U., 1968), Rock Mass Rating (RMR, Bieniawski 1973), and Geological Strength Index (GSI, Hoek & Brown 1997). **Geological Strength Index (GSI)** estimates the reduction in rock mass strength for varying geological conditions observed in the field. Modified versions of RMR (Bieniawski 1989) and GSI (Hoek et al. 1998, Sonmez & Ulusay, 1999, 2002) have emerged to enhance accuracy in rock mass characterization. **Q Rock Mass Quality System** developed by Barton (1974) et al., defines rock mass quality based on joint sets, discontinuity roughness, joint alteration, water pressure, stress reduction factor, and RQD. This classification aids in site characterization and support design for tunnels. Barton (2002) has further refined the Q system, offering a comprehensive framework for rock mass classification introducing changes in support recommendations and incorporating the rock material's strength factor (Dadkhah R., et al., 2010). **Dam Mass Rating (DMR)** by Romana in 2004 as an adaptation of RMR. It offers guidelines for dam engineering and foundation assessment in preliminary studies, considering rock mass anisotropy and water saturation effects (Kaveh M. T.et al., 2011).

Kinematic analysis of rock mass plays a crucial role in assessing potential failure modes, slope stability, and maximum safe slope angles in dam engineering. By considering slope orientations and discontinuity sets, this technique provides valuable information for making informed decisions about support measures and designing safe dam structures. The analysis provides preliminary insights into potential failure modes and their stability conditions. It guides initial assessments of support measures that can be undertaken to mitigate risks. Leulalem, S.B., et al. (2016)

1. **Identification of Dominant Discontinuity Sets:** Before conducting kinematic analysis, the dominant discontinuity sets on reservoir banks are identified. These sets play a crucial role in analyzing potential failure modes.
2. **Slope Orientation and Stability:** Kinematic analysis considers slope orientations to determine maximum safe slope angles (MSSA). The analysis aids in investigating rock mass failure modes and assessing slope stability. The kinematic analysis estimates MSSA for three fundamental failure modes: plane-sliding, wedge-sliding, and toppling. It reveals potential wedge, planar, and toppling failures in the study area.
3. **Stereographic Projection Technique:** A stereographic projection technique is often employed in slope failure mode studies. This technique helps in visualizing potential failure modes and their orientations.

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10. DATA REPRESENTATION IN DAM FOUNDATION INVESTIGATIONS:

Effective data representation is essential for conveying the outcomes of dam foundation investigations. Through standardized formats, detailed drawings, maps, test data, and other relevant information, engineers can communicate the geologic and geotechnical conditions accurately, facilitating informed decisions and designing strategies to ensure the safety and stability of dam structures.

1. **Standardized Formats:** Geological and geotechnical investigation results should be presented in specified standard formats. These formats ensure consistency and clarity in summarizing the findings of the investigations.
2. **Foundation Drawings:** Foundation drawings are crucial tools for understanding dam foundation performance and potential failure modes. These drawings assimilate geologic, geotechnical, and monitoring data, providing an unbiased presentation of factual information separate from interpretations.
3. **Detailed Plan Maps:** Various plan maps depict the location of exploration points, geologic sections, weak zones, problem materials, and potential failure planes. The continuity of important units and geological features is shown on these maps.
4. **Contour Maps and Drilling Notes:** Contour maps illustrate water loss, water pressure contours, and sample loss in drill holes. Drilling notes and other relevant data are essential to the depiction.
5. **Elevation and Structural Maps:** Elevation-related information includes the top of the rock, the thickness of liquefiable zones, and the top of significant soil units. Structural maps indicate dip angles of faults, shear zones, and key rock units relevant to failure planes.
6. **Test Data and Properties:** Test data, such as Standard Penetration Test (SPT) blow counts, corrected values, and other test results like Cone Penetration and Vane Shear, are categorized by geologic units and elevation.
7. **Detailed Cross Sections:** Detailed cross-sections showcase the continuity and engineering properties of foundation materials, along with soil properties that hold significance for analysis.
8. **Geophysical Testing Results:** Results from geophysical tests, including borehole surveys and ground surveys, are presented. These results contribute to the analysis process.
9. **Instrumentation Response:** Information on instrumentation response, which monitors changes in the foundation, is included to understand the dynamic behaviour of the site.
10. **Grouting and Water Testing:** Grout takes data and associated water testing results are depicted, along with grouting lines or holes. These data are organized by lithology, elevation, or weathering, providing insights into the grouting process.

11. CONCLUSION:

Geological exploration is a critical phase in dam projects that demands careful planning, scientific rigor, and collaboration among multidisciplinary teams. Properly characterizing the site's geological conditions ensures the safety, stability, and success of the dam, serving as the basis for informed engineering decisions.

1. **Well-Planned Exploration:** Geological explorations are a foundational step in dam projects. Thorough planning and execution are crucial to ensure accurate data collection and assessment of geological conditions.
2. **Detailed Site Exploration:** In-depth site exploration is essential to understand the geological context of the project area. This includes mapping rock formations, studying soil properties, and identifying potential hazards. Placing the dam project within the regional and local geological context is vital. It helps to anticipate potential geological challenges and adapt designs accordingly.
3. **Scientific Analysis:** Geological investigations are grounded in scientific analysis. Data collected through various techniques are analyzed to assess the stability and safety of the dam site.
4. **Team Efforts:** Geological investigations involve collaboration between various experts such as geologists, engineers, and surveyors. Their collective efforts contribute to comprehensive and accurate results.
5. **Knowledge-Based Site Characterization:** A strong knowledge base is essential to accurately characterize the site. This characterization informs engineering decisions, ensuring the project's successful implementation. Geological exploration provides the foundation for any engineering project, including dams. The understanding of subsurface conditions guides design, construction, and risk assessment.

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