GEOLOGICAL EXPLORATIONS FOR CHARACTERISATION OF DAMS SITE

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ABSTRACT-The review paper discussed the geological exploration process for dam site characterisation. It discussed the broad aspects of exploration such as, approach to the investigations, stages of exploration, identification of critical data needs, extends and methods of exploration, data evaluation and data representation. The understanding of exploration process is elaborated through failure case study elaborating extend of exploration required and need for proper data analysis. This typical failure case study has also emphasizes the need to honour the geological exploration.

***KEY WORDS*-Discontinuity Surveying, Geological Exploration, Geophysical Methods, Rock Mass classification**.

INTRODUCTION

Due to the varying complexity, uniqueness of projects and variable subsurface conditions, it not possible to establish a rigid format, which could be followed as standard procedure for geological investigations. However, considering the engineering design requirement there is fundamental data, which needs to be obtained,through basic procedure and steps, followed for any engineering project investigation. The collected field data and its evaluation are the basis for all the subsequent engineering decisions, successful completion and implementation of a project.By defining and describing these requirements and steps, it will be possible to standardize procedures, to considerably reduce time, and expense (NDOT 2005.).

Each dam site have its own unique geologic and geotechnical set up. In addition, the design requirements are variable for dams of different types, size, purpose and hazard potential classification.Objectives of the dam site investigation must be decided in consultation with the design engineers,to include the investigations for required design parameters and design assumptions. In addition, the investigation planning should include a scopeto reinvestigate and perform additional exploration and tests, if necessary, for supporting the design and subsequent design modifications incorporated to accommodate actual geological information disclosed. Site investigations for a dam need to be undertaken with a good understanding of the local and regional geological environment.The investigations should be aimed at answering all questions relevance to dam construction and operation in that environment.

The investigations relating to the rim and floor of the storage reservoir , changes in relief and slope, landform and drainage characteristics, identification of potential landslide terrain, and possible problem areas within the project periphery needs to be thoroughly investigated. Remote sensing data can be effectively used for large-scale regional interpretations of geologic structure, regional lineaments, drainage patterns, general soil and rock characteristics, and identification of associated geologic hazards (NDOT 2005.).

The first step in performing a geotechnical investigation is a thorough review of the project requirements. The project requirements will be the deciding factor for the degree and extends of investigation to be carried out. There should be thorough understanding of the project details such as Project type, location and size, Project criteria (alignment, approximate structure locations, structure loads, etc.), Project constraints, and Project design.

Geological factors play a major role in designing and constructing a dam as they control the nature of geological formations and the availability ofconstruction materials.The primary purpose of all field and laboratory investigations is to obtain the data needed for analysis and design. This must be accomplished in a planned systematic manner to collect all critical design data efficiently and economically. The preliminary data compiled can be evaluated to develop several design and construction alternatives. Since the preliminary data is being used to select a type of dam and other appurtenant structures from a number of possible alternatives, the further data that might be needed for the final design may varied. The data for each alternative needs to be developed by considering the input parameters required for the specific types of design analyses.The field investigations needs to be customise to collect baseline data to be used for development of these designalternatives. Once the design alternatives are evaluated anda preferred alternative is selected, thefinal field investigations are then concentrated on collectingdata for a specific conceptual design. The more detailed geotechnical testing can be scheduled at specific critical locations based on the selected design alternative. The project investigation approach should be data-driven. The potential design alternatives determine the specific input data parameters and the analyses needed, which in turn determine the field investigation methods and tools for the required data(Rogers G. D., et al., 2012).

The geology must be integrated into answering the engineering considerations. Collecting geologic data without consideration of the engineering questions is not productive or useful. Geologic data must be collected with specific questions and potential failure hazards. The Geologic Data must be synthesized and understood in terms of the dam’s vulnerabilities (potential Failure Modes). The potential issues must be understood (“new” vulnerability?). Understanding a structure’svulnerabilities is key for focusing data collection and exploration priorities. (Shaffner Peter, 2011.).

Dam foundation requirements are based on the type of proposed dam and is largely dependent on the strength, deformation, and permeability characteristics of site materials. The Assessment of embankment and spillway foundation conditions, stripping depths, foundation treatment measures including lithology, rock mass conditions, is the objectives of site investigation. It should also assist in confirmation of construction materials sources, its quantities and theirengineering properties. The geological environment of the reservoir, including water- tightness, impact on groundwater, stability of slopes, erodibility of soils and siltation potential should also be assessed.

The principal factors that constrain the geomechanical properties of rocks are geological structure, mineralogical composition, discontinuities, and degree of weathering. Accordingly, the geological and geotechnical properties of rocks that comprise the basement to major engineering structures (such as dams) should be determined in the field and in the laboratory prior to construction. Engineering geological properties of rock masses, such as discontinuities, degree of weathering, strength and hydraulic conductivities along the dam axis, strength, and stability of abutments and the feasibility of diversion tunnels, power tunnels and spillways, needs to be investigated in order to determine probable problems and necessary precautions to be taken prior to construction. (Kocbay A., et al., 2006.A).

INVESTIGATION LOCATIONS

Investigations has to be performed in the areas of the proposed dam, within the dam footprint, valley floor, possible borrow sites, access roads. Investigation is also needed along the natural slopes of abutment and reservoir rim and other and suspected landslides prone areas within reservoir area. The detailed mapping of the stratigraphy of the dam area for deciding the location and form of the transition between the reinforced cement concrete (RCC), embankment sections of the dam with natural abutments. (Mike Marley, et. al., 2007.)

It is usually impossible to investigate, understand and communicate foundation conditions without detailed geologic sections and maps. Geologic mapping of the foundation and downstream abutments to define the geologic discontinuities and potential sliding blocks is essential. The design must never be considered complete until the foundation is exposed, inspected, understood and approved. In steep terrain, can be specifically checked for potential sliding in the reservoir (Vaiont Dam Failure) and evaluate the hazard using maps and aerial photographs. There should be robust geological investigations beyond the dam footprint. (Shaffner Peter, 2011.)

STAGES OF GEOLOGICAL STUDY IN DAM PROJECTS.

Construction of dam project can be divided into four stages: 1. Pre-feasibility, 2. Feasibility, 3. Preconstruction or Design Support and 4. Construction. Surveying, geological and geophysical exploration are carried out mainly in the first three stages, while in the construction phase, geological and geotechnical control is mainly exercised to solve the local problems encountered, during the actual underground excavation.

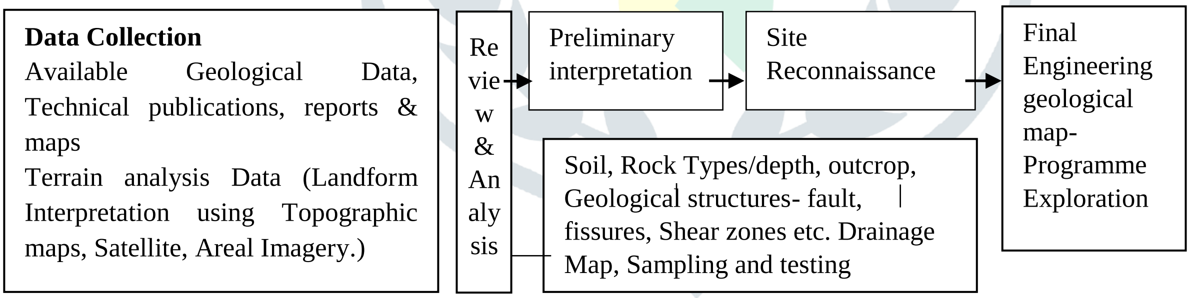

Fig.1 Geological Investigation

LEVEL OF EXPLORATION

One of the more difficult aspects of dam safety studies is the process of determining the appropriate level of exploration and analysis necessary at each step. The ultimate purpose of the geological exploration is to ensure the timely and affordable construction of proposed project, with standard safety conditions (stability, strength to expected earthquakes, etc.) and a service life.The quantity and quality of geological exploration are important variables that define the accurate of the construction program, its budget and safety deviations. The following three guides taken from the International Commission on Large Dams (ICOLD, 1989.)for saving in dam constructions

i. Geological investigations should be as complete as possible to obtain full knowledge of the site more accurately.
ii. In complex geological structures, in order to obtain an appropriate design parameter prior to construction, it is advisable to dig the affected parts with the purpose to clarify possible doubts about the appropriate types of foundations.
iii. Designs must be based on real information, not theoretical data from limited research.

Following the initial evaluation of potential failure modes, it is always necessary to perform additional work focused on the specific data important to the most significant potential failure modes identified. If significant failure modes are identified requiring additional analysis and data collection, the drawings developed during the risk process serve as an excellent tool to plan exploration for the next phase, to plot data in real time as it is collected, and to evaluate the potential for additional data to reduce uncertainty.

An understanding of potential failure modes, enhanced by a multi-disciplinary evaluation, is very important to provide focus for foundation data collection and analysis. Additionally, when risk analyses are performed, the varying degrees of uncertainty commonly associated with most subsurface data must be clearly documented and understood to avoid potential misuse.

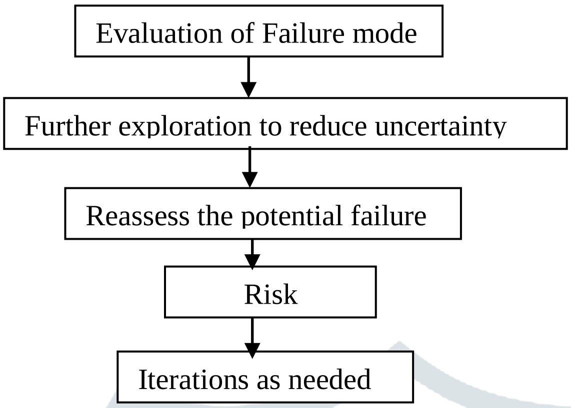

Fig.-2 Investigation and Analysis

Geologists must take responsibility for understanding and portraying uncertainty. The significance of the information must be clearly communicated (Dam Safety Case). The designers should understand and incorporate actual geologic information into the design. Thegeologist must involve in design decisions and account for geologic uncertainty in the design. Only the existence of geologic reports, logs, maps, cross sections and other data did not result in a robust design or prevent failure.

Past incidences and failures MUST be shared, published, studied, understood and applied to current designs. St. Francis Dam (Failure by Paleo landslides), Malpasset Dam (Failure by hydraulic uplift beneath the dam's left abutment). (Shaffner Peter, 2011.)

ITERATIVE APPROACH TO THE INVESTIGATIONS

Activity flow in the site investigation (ISRM, Stapledon D. H.1975.)

- **Activity 1.** - Define the objectives of the work, or, engineering and geological questions to be answered.
- **Activity 2.** - collect and assess existing relevant geological data and evolve tentative site geotechnical model, to find tentative answers to the questions in Activity 1. New geological questions are usually added at this stage, arising from the understanding obtained from the existing data.
- **Activities 3.**- Plan work to fill in gaps
- **Activities 4.** - Prepare cost estimate and set out in a report to management, seeking approval to proceed.To answer the remaining questions and to confirm the tentative answers, the various sub-objectives and geological and engineering activities of Activity 5 to activity 7 are defined.
- **Activity 5.** - Determine semi- quantitative engineering - geological model

This relates to achieving all of the essentially geological sub-objectives defined in Activity 3. The 'engineering geological model' at this stage implies a sufficient understanding of the regional geology, geological history, and detailed site geology.

- **Activity 6.** - Quantify – field and laboratory tests to quantify values for engineering properties.

The test results are assessed in the light of the geological model and values or ranges of valuesmay be adopted as realistic, and included in the geotechnical model.

- **Activity 7.** - Analyse – answer the questions.

Engineering analyses are then carried out involving the proposed structure and the site geotechnical model. It is desirable that the analyses provide answers in terms of probability of failure, as well as factor of safety.If at the end of Activity 7, all questions are answered with sufficient confidence, the investigation is complete. If not, further cycles of investigation are carried out until the required level of confidence is reached.

METHODS OF EXPLORATION

The investigation involves geological mapping, geotechnical drilling including water pressure testing, excavation and geological mapping of large excavations, the specific investigative techniques such as seismic refraction profiling, downhole geophysical logging, and hydrogeological investigation involving investigative drilling and pumping tests.(Mike Marley, et. al., 2007.).Field studies also include intensive discontinuity surveying, data collection for kinematic analysis of excavation slopes, and sampling for laboratory testing for determination of rock mass strength parameters.

The logging of soil and rock samples and drilling information in the field to create draft logs could be used to develop geologic cross sections and profiles to assist in evaluating field data and evaluation of project deliverables. The use of carefully identified data needs and rapid turnaround of field data is a powerful combination. It provides the design engineers with critical data early in the project thus allowing them to maintain the project schedule and identify any additional data needs. (Rogers G. D., et al., 2012)

Downhole Testing

Downhole testing included packer permeability testing, televiewer surveys, and seismic velocity testing. Downhole optical or acoustical televiewer surveys can be performed in the borings. The downhole geophysical logging (Natural gamma, calliper, sonic, magnetic susceptibility and acoustic scanner tools)can be performed in borehole. These surveys provide information relative to in-situ orientation of rock fracture, joints, foliations, and other rock mass features.(Schug David L., et.al. 2011., Mike Marley, et. al., 2007.)

Geophysical Methods

Geophysical methods of exploration provides a rapid and economical means of supplementing subsurface borings and test pits. Geophysical investigations like seismic refraction and electrical resistivity & self-potential can be conducted to have continuous information of both spatial and depth wise data. Geo-electric method provides good approximation of position of bedrock, and ground water conditions. Seismic refraction method also provides bedrock morphology and qualitatively gives ideas about the rock density.The geophysical studies will be helpful to reveal the presence of fault and shear zones in the critical areas. The results of the geophysical surveys can be used to optimise the geotechnical drilling programme for areas of anomalies. The laboratory velocities and the field seismic refraction studies can be helpful in estimating the soundness of the rock formations, delineating the structurally weak zones and suggesting remedial measures.Seismic refraction profiling can be undertaken to supplement borehole information, and allow bedrock levels to be interpolated between boreholes. The final refraction tomography models (RTM) can be converted into layer velocity plots as a simple means todisplay the seismic data on a long section along with borehole data.This data can be used primarily for theinterpretation of the boundary between distinctly weathered and slightly weathered material(Mike Marley, et. al., 2007.)Relatively closely spaced seismic refraction profiles can be performed within the dam foundation excavation area along and perpendicular to the dam axis for evaluating the weathering and rippability of the subsurface materials. Seismic tomography and in situ jacking tests can be used to establish reasonable foundation deformation properties for use in structural analyses and loading calculations.

Discontinuity Surveying

Surface discontinuity surveys can be performed to compile additional rock fracture data. The mapping objectives are to evaluate the character of the rock mass, and to gather rock discontinuity data to evaluate potentially unstable blocks and/or wedges that could cause instabilities of the dam.

Geologic mapping performed should include observations of rock weathering and identifying discontinuities (e.g. joints, shears, contacts, sheared surfaces/seams, and crushed seams/zones and faults). Geologic mapping must be performed to characterize rock discontinuities such as fractures, joints and shears. The geologic mapping provided summaries of rock fracture and joint trends in the dam site area. Discontinuity data can be processed for the determination of dominant sets and for the rock mass characterization in terms of rock classification systems.

Joints are the dominant planes of weakness in rock masses. The predominant strike and dip directions of joints, orientations of the fissures, their degree of openness, frequency, filling and its characteristics, directly influence the characteristics of the rock mass. Quantitative description of discontinuity i.e. orientation, spacing, persistence, roughness, aperture filing materials and spacing, characteristics of the joints may be determined in situ by exposure logging according to the International Society for Rock Mechanics' (ISRM) standards (1981)

Stereonets can be plotted by individual boreholes to analyse the spatial distribution of the sheared zones. (Mike Marley, et. al., 2007.). All of the rock fracture data obtained during planning and final design can be compiled and grouped to create the Stereonet plots. The Stereonet analyses are primarily for evaluation of the rock joints, which can be used to evaluate the stability of proposed excavations (Schug David L., et.al. 2011.).

The Packer Test

The packer test data provides estimates of in-situ hydraulic conductivity. The packer tests typically involved increasing the test zone pressure in a series of increments, or steps, and then decreasing the test pressure in a similar series of steps. This procedure allowed monitoring the rate of water loss for rapid variations, which might be indications of hydraulic jacking. The packer test pressures are selected to increase up to the estimated baseline pressure, depending on the borehole depth. The maximum test zone pressures can be ranged to simulate the raised reservoir head.Packer tests can beperformed at intervals of the geologic contact between the bedrock units, to check the contribution of contact towards the hydraulic conductivity of the rock mass. (Schug David L., et.al. 2011.)

The water pressure test can indicate the necessity of providing a grout curtain below the dam foundation. The heterogeneous permeability of the rock foundations may indicate the needs for designing the seepage control and uplift pressure reducing measures.A correct estimation of bedrock permeability and thickness of its weathered and loose layer to calculate the hydraulic conductivity from borders should be performed in order to determine the condition and penetration depth of dam's curtain or wall to the bedrock.

Experimental Grouting

The potential of water seepage can be evaluated by the study of joint systems of the rock units, and by conducting in-situ tests to estimate the permeability's values. The corrective measures such as grouting can be suggested for uncontrollable seepage.

Grouting of dam foundation can be considered for consolidation and impermeability. The grouting system (grout curtain /consolidation grouting) can be design for improving the geomechanical quality of bedrock at foundation and abutments areas, based on the data obtained from probe drillings, permeability tests and test grouting. Permeability and hydro-fracture tests results can used in the foundation for the design of the grouting programme.

Decision regarding location, extend and the degree of foundation treatment such as grouting, required for unfavourable geological strata can also be decided based on results of geological investigations. Experimental grouting can be carried out to determine rock mass groutability and to determine parameters such as effective radius of grout influence, maximum pressure and optimum mixture for a grout, suitable method and pattern of grouting to reduce water leakage. Based on the test-grouting results, to find out the average grout take and the grouting efficiency.

Laboratory Testing:

Various laboratory and in-situ tests can be performed on the intact undisturbed rock specimens to assess the characteristics of rock masses.Laboratory testing on rock core samples can be used to evaluate foundation and excavation characteristics. Laboratory tests has to be conducted to characterize rock mass properties by quantifying the physical and geomechanical properties of intact rocks at the dam site. The tests and test methods, typically in accordance with ASTM International standards, included direct shear, unconfined compression (with modulus), triaxial tests, tensile strength, and point load tests. (Schug David L., et.al. 2011. , Kaveh M. T.et al., 2011.)The investigation can include, bearing capacity tests (cone penetrometer and standard penetration), classification and grain size distribution as well as tests for compaction, consolidation and compressive strength.Pressure meter testing can be performed on the borings to obtain in-situ values of undrained shear strength and elastic properties of selected site soils.The cohesion, internal friction angle and deformation parameters (in situ jacking tests).dry unit weights, saturated unit weights, porosity weighted water absorptions, volumetric water absorptions, permeability, specific gravities, point-loadstrength indices, uniaxial pressure strengths, velocitiesof P and S waves, dynamic and static elasticity modules,and Poisson ratios for the rockcan be determined on thebasis of ASTM (1980, 1996) and ISRM (1978, 1981,1985).

Potential sites for burrow areas in the dam axis and reservoir areas can be suggested based on the evaluation of material properties. During the design investigation, material recovered from a test pit can be crushed and tested for trial RCC mixes. Aggregate quality testing on crushed materials obtained from an on-site test quarry can also performed to check its suitability for RCC aggregate. Similarly, the required engineering properties of soil can be checked for use for earthen embankment dams.

Engineering Classification of Rock Mass

Rock mass classifications can serve as a powerful design tool in Dams construction. The numerically expressed rock mass classification methods are commonlyused at the preliminary design stages of a construction project. Itforms the bases for design and estimation of therequired amount and type of rock support andgroundwater control measures.Engineering geological investigations and rock mechanics studies for rock mass characterization include discontinuity surveying, core drilling, in situ and laboratory testing.

Total core recovery (TCR) and Rock quality designation (RQD) values can be determined for different important structural areas of the dam site such as along the dam axis, spillway and diversion tunnel alignment and other appurtenant structures. Rock mass classifications, strength characteristics, and constants of rock masses can beexpressed by using Hoek-Brown empirical failure criteria, Rock Mass Rating (RMR), Geological Strength Index (GSI), and Rock mass quality (Q) values. Engineering classification of the rock mass. The rocks can be classified according to the RMR(Bieniawski, 1989) and Q (Barton et al., 1974; Barton N., 2002) systems for empirical rock mass quality determination, site characterization and support design for the diversion and power tunnels.

Bieniawski (1974) has initially developed RMR system. In order to apply this system for the classification of rock mass, the uniaxial compressive strength of intact rock, RQD, joint spacing, joint condition, joint orientation and ground water conditions have to be known. The system also include the ratings given to ground water, joint condition and joint spacing.

Barton et al. (1974) have developed Q rock mass quality system. Q system is also known as NGI rock mass classification (Norwegian Technical Institute). This system is defined by the function of joint sets (Jn), discontinuity roughness (Jr), joint alteration, (Ja), water pressure, (Jw), stress reduction factor (SRF), and RQD. Recently, Barton (2002) has compiled the system again and has made some changes on the support recommendations. He has also included the strength factor of the rock material in the system. (Dadkhah R., et al., 2010.).

The most widely known of thesemethods are RQD (Deere D.U. 1968.),RMR (Bieniawski1973), and GSI (Hoek & Brown 1997), whichemployed for rock mass characterization studies. The Geological Strength Index (GSI) provides a system for estimating the reduction in rock mass strength for different geological conditions as identified by field observations.The modified versionof RMR (Bieniawski 1989) and the modified versions of GSI (Hoek et al. 1998; Sonmez & Ulusay,1999, 2002) can alsobe considered.

Dam mass rating DMR (Romana, 2004) has been proposed as an adaptation of RMR, giving tentative guidelines for several practical aspects of dam engineering and for dam foundation appraisal in preliminary studies taking account of the effects of rock mass anisotropy and water saturation. (Kaveh M. T.et al., 2011.)

Kinematic Analysis

Kinematic refers to the motion of bodies without referring to the forces causing them to move. Kinematic analysis for abutments of Dam site can be carried out after identifying the dominant discontinuity sets on the banks of the reservoir area. Kinematic analysis with respect to slope orientations is very useful for investigating possible rock mass failure modes and determiningmaximum safe slope angle (MSSA). Many studies have determined slope failure modes and evaluated slope stability using a stereographic projection technique. Kinematic analysis used for the study area gives estimate of the MSSA regarding the three basic failure modes: plane-sliding, wedge sliding and toppling. The analysis revealed possible wedge, planar and toppling failures in the area and preliminary assessments of support options undertaken.(Mike Marley, et. al., 2007.) (Ozsan A., et al., 2002.) (Kaveh M. T.et al., 2011.)

INVESTIGATIONS TO INCLUDE POTENTIAL FAILURE MODES

The ultimate goal of any investigation should be to evaluate the safety of the dam with respect to all identifiable and foreseeable failure mechanisms, and to monitor changes that may indicate development of a hazardous condition.

Overtopping leads to 1/3 of all dam failures globally. The poor geological conditions at site may lead to overtopping by settlement of the dam crest (foundation defects) or a landslide in the reservoir that creates overtopping. Another major reason for dam failure is Foundation defects, which contributes to nearly 1/3 of all dam failures. Defects can occur in the foundation supporting the dam. If the weight of a dam structure is not properly taken into account in the engineering of the dam, the ground underneath can settle unequally and compromise the foundation. Similarly, dams built on slopes must be properly engineered to avoid issues with instability or landslides. Any event causing the movement of a foundation, such as an earthquake, can also compromise a dam's foundation. The main cause of concrete dam failure is a problem with the foundation. High uplift pressures and uncontrolled foundation seepage and piping can also compromise the dam's foundation. (Example of catastrophic dam failure due to foundation defects: St. Francis Dam) (FEMA).

The overtopping and quality problems led to nearly 80% of all failure in earthen dam. It is clearly seen that 58% of quality problems are associated with piping in the dam body or foundation. For piping in the dam body or foundation, the single adverse factor is crack, which may be caused by differential settlement, material shrinkage, foundation defects, and imperfect interface, the most important potential location at risk is at the spillway. Whether piping occurs or not primarily depends on the dam system itself, including the configuration of the dam, the construction quality of the dam, and the geologic conditions. (Zhang L. M. et al., 2009.)

Most dams on rock foundations perform very well. Stability issues stem from uncertainties about the significance of local high transmissibility, erodibility, deformability, or inelasticity; interaction with landslides and rock falls; weathering; and the hazard potential of contiguous bedrock faults. Among the many issues some of the common issues are Sheet joints in the rock, Rapid erosion of jointed rock, Potential instability of removable rock blocks, Unsustainable leakage through open-jointed rocks.(Goodman Richard E., et al., 2013.)

DATA REPRESENTATION

The results of the geological, geotechnical investigations should be presented in standard formats specified. One of the most important tools available for summarizing, focusing, and understanding dam foundation performance and potential failure modes is a robust set of foundation drawings with assimilation of geologic and geotechnical data with monitoring instrumentation response information.Understanding the range of the data and details of the location and magnitude of material property estimates may be very important in distinguishing whether an adverse condition does or does not exist.These drawings must provide an unbiased presentation of factual data, separate from interpretations. They must make judicious use of details instead of generalizations. The type of information displayed on geologic drawings is of course a site-specific decision tied directly to the failure modes of concern and the information of significance. The drawings and products required depend on the failure modes being analysed, and commonly include following products, which should serve as the basis for the discussion of subsurface conditions. (Shaffner P.T., 2011.). The geological and geotechnical information of site exploration is represented in following various forms,

- A variety of plan maps showing the location of all exploration, location of all geologic sections, location of weak zones or delineation of problem materials or potential failure planes, continuity of various units of importance.
- Water loss,water pressure contour maps and sample loss in drill holes and other drilling notes.
- Top of rock, thickness of liquefiable zones, top of soil units of concern, dip of fault or shear zones, dip of key rock units forming failure planes. Orientation of bedrock discontinuities with key properties. Structural contour or isopach maps.
- Standard Penetration Test (SPT) blow counts, preferably corrected values, other test data (Cone Penetration, Vane Shear, etc.), sorted by geologic units and elevation.
- Detailed cross sections showing: continuity and engineering properties of foundation materials Soil properties of significance to analysis.
- Geophysical testing results of use in the analysis, including borehole surveys and ground surveys.
- Instrumentation response.
- Grout takes of significance and associated water testing,grouting lines and/or holes, Grout takes sorted by lithology or elevation or weathering, etc.

CASE STUDY

Case study of Bhama Askhed Dam is discussed to highlight the importance of geological exploration process. The Bhama-Askhed irrigation project, consisting of earthen embankment dam ($18^0$15'N ,$73^0$43'E) has been constructed on the Bhama river, a right bank tributary of the River Bhima, near village Waki, Tal. Khed, District Pune, Maharashtra, India. It has a 57 m wide side spillway at the left bank and a proposed 105 km long canal on the right bank. Since the suitable foundation strata are not available, in the main river gorge, the side spillway is located on the left abutment. The side spillway consist of an approach channel, a flow control structure, a discharge channel, an energy dissipater assembly (EDA) and a tail channel. The EDA, is designed as a flip bucket, to dissipate the high kinetic energy of discharge flow over the spillway. A dyke of 2-2.5 m width across the spillway section was uncovered during the tail channel excavation that continue from tail channel to approach channel. The upstream portion of a dyke in an approach channel was treated whereas the rest of the portion below spillway and in tail channel section was untreated.During the 2005 monsoon, 13 RCC panels of EDA portion in the discharge channel were uplifted and displaced, revealing the underneath weathered jointed hydrothermally altered volcanic breccia and basalt. Continuous high seepage (10-15 liters/s.) was observed at failure area (near RD 83 m.). Although, the RCC panels were firmly secured in the bedrock, with anchor bars, at some places they were either bent or broken and had been partly removed with the uplifted panels.

The geological investigation of tailrace channel by Dr. S.R. Kulkarni, was consist of 23 drill holes at various chainages along tailrace centerline alignment. Geologically, the tailrace channel consist of chlorophacitic porphyritic basalt flows underlain by soft erodible hydrothermally altered volcanic breccia with a red tachylitic basaltic matrix. The fractured closely jointed compact basalt with block splitting tendency or the weak and soft volcanic breccia with a red tachylitic basalt matrix in spillway and tail channel were not treated.The borehole logging at spillway section had indicated potential weak and permeable red breccia zone, probably responsible for the seepage at RD 83 m. It was concluded that the pervious substratum rocks, had created an uplift pressure resulting in panel'sfailure. It was also inferred that there was need for treatment to the underline closely jointed fractured, compact basalt and weathered volcanic breccia with a red tachylitic basalt matrix.

The further post failure investigation by nuclear logging test reveals low-density weak zone at 34m depth, corresponding to a weak red breccia zone. The dye tracer studies showed interconnectivity of seepage at failure location of EDA portion and low-density permeable red breccia below the foundation. Caliper logging for the borehole drilled 6 m below the foundation level reveals jointed and fractured basalt formations below foundation. The seepage with associated uplift pressure has led to EDA failure.

All these post failure investigations have reinforced the earlier interpretations of geological explorations by core logging. It has also provided basis for suggested grouting treatment measures and designed uplift reducing drainage system. This typical failure case study has emphasizes the need to honour the geological exploration.

CONCLUSION

Geological explorations need to be very well planned and executed as team efforts.The detailed site exploration and scientific analysis is required to place the project site in regional and local geological context.Theknowledge based site characterization is required for successful implementation of any engineering project including dams.

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