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INTEGRATED STABILITY AND STRUCTURAL PERFORMANCE EVALUATION OF AN RCC GRAVITY DAM UNDER MULTI-LOAD CONDITIONS

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ABSTRACT

Gravity dams are among the most reliable hydraulic structures due to their ability to resist external forces primarily through self-weight. This project presents a comprehensive structural and stability analysis of a Reinforced Cement Concrete (RCC) gravity dam considering critical loading conditions such as water pressure, uplift pressure, silt pressure, and seismic forces. Detailed site investigation data, hydrological parameters, and foundation characteristics were incorporated to ensure realistic design assumptions. Stability checks against sliding, overturning, and foundation overstress were performed using analytical methods in accordance with standard dam design guidelines. Additionally, structural modeling and verification were carried out using STAAD.Pro to validate manual calculations. The results demonstrate that the designed gravity dam satisfies all safety requirements with adequate factors of safety, confirming its structural integrity and suitability for long-term operation. The study highlights the importance of uplift pressure consideration and combined load effects in ensuring the overall safety and performance of gravity dams

KEYWORDS: Gravity Dam, RCC Gravity Dam, Hydraulic Structures, Stability Analysis, Sliding Stability, Overturning Stability, Uplift Pressure, Seismic Forces, Hydrostatic Pressure, Silt Pressure, Finite Element Analysis (FEA), STAAD.Pro, Foundation Stress Analysis, Dam Safety, Structural Integrity, Hydrological Investigation.

I. INTRODUCTION

A gravity dam is a massive hydraulic structure constructed primarily from concrete or masonry and designed to resist the forces exerted by stored water through its own self-weight. The fundamental principle behind the design of a gravity dam is stability through gravity. The horizontal hydrostatic pressure exerted by the reservoir water tends to push the dam downstream and cause overturning or sliding. However, the enormous weight of the dam counteracts these forces and ensures equilibrium. For a gravity dam to remain stable, the resultant of all acting forces must pass within the middle third of the base to avoid tensile stresses and maintain compression throughout the structure.

Gravity dams are widely used in water resource development projects due to their durability, structural reliability, and low maintenance requirements. They serve multiple purposes such as irrigation, hydroelectric power generation, flood control, water supply, navigation, and recreation. Among different types of dams—such as arch dams, buttress dams, and embankment dams—the gravity dam is considered one of the safest when constructed on a strong and impervious rock foundation. Because of their rigid structure and massive construction, gravity dams are particularly suitable for sites with narrow valleys and sound bedrock conditions.

The design of a gravity dam requires careful evaluation of various forces acting on the structure. These forces include hydrostatic water pressure, uplift pressure, silt pressure, wave pressure, wind pressure, ice pressure (in cold regions), and seismic forces. Stability analysis must be performed to ensure safety against sliding, overturning, and foundation overstress. Modern design practice combines analytical calculations with numerical modeling techniques such as Finite Element Analysis (FEA). Software tools like STAAD.Pro help engineers verify stress distribution and deformation behavior under different loading combinations. Proper site investigation, hydrological studies, geological assessment, and foundation evaluation are essential before finalizing the design to ensure long-term safety and performance of the dam structure.

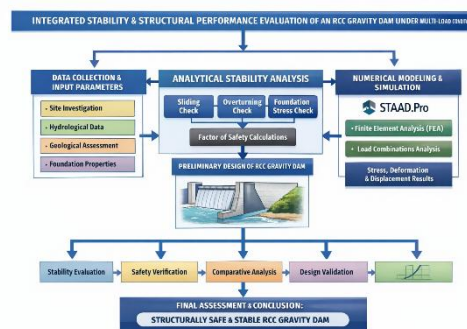


Fig1: System Architecture

II. LITERATURE REVIEW

The design and stability analysis of gravity dams have been extensively studied by researchers and engineering organizations over the past decades. The U.S. Army Corps of Engineers (1995) provided comprehensive guidelines on gravity dam design, emphasizing stability against sliding, overturning, and excessive foundation stresses. Their work highlighted the importance of considering uplift pressure and drainage systems in improving safety margins. Similarly, the Bureau of Reclamation (1976, 1994) published detailed manuals on the design of gravity dams and small dams, outlining load combinations, stress analysis procedures, and safety criteria. These manuals established the conventional middle-third rule and factor of safety requirements that are still widely adopted in dam engineering practice.

Wiegel (1970) contributed significantly to understanding earthquake effects on hydraulic structures. His research demonstrated that seismic forces can considerably increase tensile stresses and overturning moments in gravity dams, especially in seismic-prone regions. Wastedaard (1993) further investigated dynamic water pressure during earthquakes and emphasized the need to include hydrodynamic effects in seismic analysis. Modern approaches now incorporate response spectrum and time-history analysis methods to capture realistic dam behavior under earthquake loading.

Richards and Reddy conducted critical studies on seepage and piping phenomena in embankment dams, highlighting the importance of seepage control and drainage systems. Although their work primarily focused on earth dams, the findings regarding uplift pressure and internal erosion are also relevant to gravity dam foundations. Fredlund et al. analyzed combined seepage and slope stability during rapid drawdown conditions, showing that transient pore water pressures significantly influence stability. These studies emphasize the importance of detailed hydrogeological investigations and proper drainage design in gravity dams.

Recent advancements in computational modeling have improved the analysis of gravity dams. Finite Element Analysis (FEA) tools such as STAAD.Pro are increasingly used to simulate stress distribution, deformation, and load combinations more accurately than traditional analytical methods. Researchers have demonstrated that numerical modeling helps identify stress concentrations near the heel and toe of the dam and provides better understanding of structural behavior under combined loading conditions. Overall, literature indicates that while traditional analytical methods remain fundamental, integration of modern software tools and detailed site investigations significantly enhances safety, economy, and reliability in gravity dam design.

III. WORKING METHODOLOGY

The methodology adopted for the structural and stability analysis of the RCC gravity dam consists of systematic analytical evaluation combined with numerical modeling. Initially, detailed project data including topography, hydrology, geological conditions, and foundation properties were collected from available site investigation reports. Important parameters such as water depth, silt level, uplift pressure conditions, seismic zone factor, and material properties of concrete and foundation soil were established. Based on these inputs, the preliminary dimensions of the gravity dam cross-section were fixed following standard design principles and guidelines. The geometry was proportioned to ensure that the resultant force remains within the middle third of the base under normal loading conditions to avoid tensile stresses.

After defining the geometry, all forces acting on the dam were identified and calculated. These included self-weight of the dam, hydrostatic water pressure, uplift pressure, silt pressure, wind pressure, and seismic forces wherever applicable. The forces were resolved into vertical and horizontal components, and moments about the toe were calculated. Stability analysis was then carried out manually by checking safety against sliding, overturning, and foundation overstress. The factor of safety against sliding was computed using frictional resistance and cohesion at the foundation level, while the factor of safety against overturning was determined by comparing stabilizing and destabilizing moments. Base pressure distribution was evaluated to ensure that maximum compressive stress remained within allowable bearing capacity limits and that no tensile stress developed at the base.

To validate the analytical results, the dam section was modeled using STAAD.Pro in space frame mode. The geometry was created using beam and plate elements, and appropriate material properties were assigned. Fixed supports were provided at the base to simulate foundation conditions. Dead load (self-weight) and hydrostatic loads were applied as per calculated values. Load combinations representing critical conditions were analyzed. Post-processing results such as stress contours, bending moments, shear forces, and displacement patterns were examined to verify structural

performance. The comparison between manual calculations and software outputs ensured accuracy and reliability of the design, confirming that the RCC gravity dam satisfies all stability and safety requirements under critical loading scenarios.

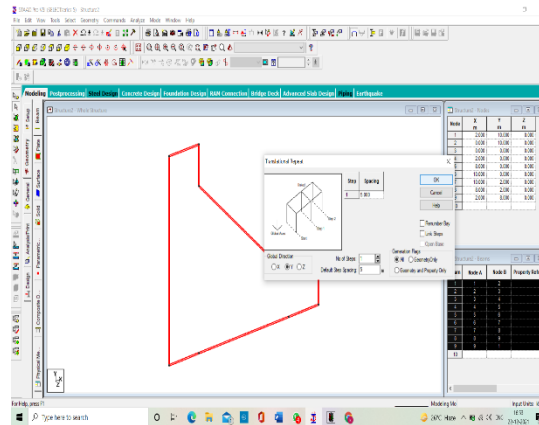


Fig2 RCC gravity dam cross-section in STAAD

Fig.2 shows the two-dimensional modeling of the RCC gravity dam cross-section in STAAD.Pro. In this stage, the dam profile is created using beam elements by defining nodal coordinates according to the designed geometry. The trapezoidal shape represents the upstream vertical face and the downstream sloping face of the dam. The “Translational Repeat” dialog box indicates that the 2D section is being prepared for extension along the longitudinal direction to form a three-dimensional structure. The node and beam details visible on the right confirm proper connectivity and geometric accuracy. This stage represents the initial geometric modeling phase of the dam section before converting it into a full 3D structural model.

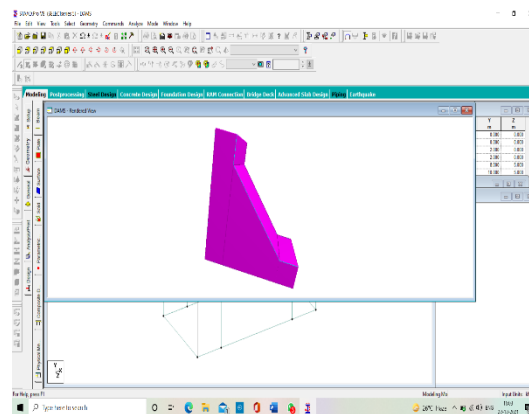


Fig3: the RCC gravity dam section after assigning surface

Fig.3 presents the rendered solid view of the RCC gravity dam section after assigning surface or plate elements. The magenta-colored surface represents the concrete body of the dam, showing the actual mass and shape more realistically compared to the wireframe model. This view helps verify that the geometry has been correctly formed and that the surfaces are properly connected. The rendered visualization ensures that the dam section accurately reflects the intended structural dimensions before proceeding with further modeling steps. This stage confirms the proper formation of the solid dam body.

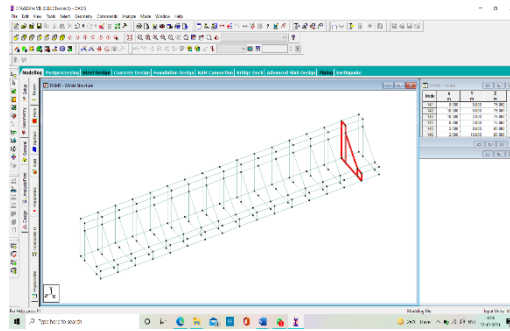


Fig4: three-dimensional structural model

Fig.4 illustrates the complete three-dimensional structural model generated using the translational repeat command in STAAD.Pro. The original 2D cross-section is replicated along the longitudinal axis to simulate the full length of the dam. The model now consists of multiple connected frames and elements forming the entire structural system. The highlighted section indicates a selected segment during modeling. This figure represents the finalized 3D structural configuration of the RCC gravity dam prior to load application and analysis.

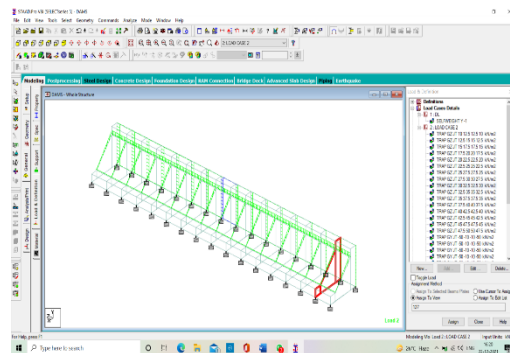


Fig5: the load application stage in STAAD.Pro

Fig.5 shows the load application stage in STAAD.Pro, where different load cases are defined and assigned to the model. The load case includes self-weight and trapezoidal loads that simulate hydrostatic water pressure variation with depth. The supports at the base represent foundation conditions. The green-highlighted structure indicates the model under load visualization mode. This stage is crucial as it prepares the structure for stability and stress analysis under various loading conditions such as water pressure, uplift pressure, silt pressure, and seismic forces.

IV.CONCLUSION

The present study successfully carried out the structural and stability analysis of an RCC gravity dam under various critical loading conditions including water pressure, uplift pressure, silt pressure, and seismic effects. The design procedure incorporated site investigation data, hydrological parameters, and foundation characteristics to ensure realistic assumptions. Stability checks against sliding, overturning, and foundation overstress were performed using analytical methods in accordance with standard dam design guidelines. The calculated factors of safety against sliding and overturning were found to be greater than the permissible limits, confirming adequate stability of the dam section. Base pressure calculations indicated that compressive stresses were well within allowable bearing capacity and no tensile stresses developed at the foundation level.

The structural modeling carried out using STAAD.Pro validated the manual computations. The stress distribution, bending moments, and displacement results obtained from the finite element analysis were consistent with theoretical expectations. The study highlights that proper consideration of uplift pressure and combined loading conditions is essential for ensuring long-term structural safety. It is

concluded that the designed RCC gravity dam is structurally safe, stable, and suitable for long-term hydraulic operation provided proper construction quality control and maintenance practices are followed. Future studies may include dynamic time-history analysis and detailed foundation interaction modeling for enhanced design optimization.

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