



SEISMIC RESPONSE AND STABILITY ASSESSMENT OF CHANG DAM UNDER VARYING GROUND MOTION INTENSITIES

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Abstract: Dams located in seismically active regions are highly susceptible to structural damage due to strong ground motions. Several small to medium-sized dams, ranging in height from 10 to 25 meters, have experienced various forms of distress, including longitudinal cracks along the crest and failures of upstream and downstream slopes. Chang Dam, situated in the Kachchh region of Gujarat, India, was among the most severely affected structures, highlighting the need for a detailed seismic stability assessment. This study employs PLAXIS, a widely used finite element software for geotechnical analysis, to model and evaluate the seismic response of Chang Dam under different ground motion intensities. The numerical analysis considers factors such as soil-structure interaction, dynamic loading, and deformation patterns to assess the dam's stability and failure mechanisms. By simulating real earthquake conditions, the study provides insights into the dam's vulnerability and helps identify critical failure zones. The findings from this analysis contribute to a better understanding of the seismic performance of embankment dams and offer valuable input for developing improved design and retrofitting strategies. This study underscores the importance of advanced seismic assessment techniques to enhance the resilience of critical infrastructure in earthquake-prone regions.

Index Terms –Seismic Response, Ground Motion, Structural Stability, Finite Element Analysis, Dynamic Loading, Seismic Performance, Earthquake-Prone Regions

I. INTRODUCTION

Seismic events can have catastrophic impacts on civil infrastructure, and earthen dams are particularly vulnerable to ground motion-induced instabilities. Large-magnitude earthquakes often cause substantial structural damage to these dams due to factors such as liquefaction, longitudinal cracking, subsidence, and lateral spreading. The structural integrity of earthen dams is a critical concern, as many were not originally designed with seismic resistance considerations. This lack of seismic resilience necessitates a thorough stability analysis to assess their safety under dynamic conditions and to formulate appropriate remedial and rehabilitation strategies. Statistics indicate that thousands of people have lost their lives due to dam failures triggered by earthquakes, highlighting the pressing need for improved seismic safety measures [1].

The seismic behavior of earthen dams under varying ground motion intensities requires advanced analytical methods to accurately predict the response of these structures. Finite element analysis has emerged as a robust technique for evaluating the stability and response of earthen dams subjected to seismic loading. Using numerical simulations, it is possible to assess variations in stresses, strains, accelerations, and displacements, thereby identifying potential failure mechanisms and devising mitigation measures. Studies have shown that nearly 20% of dam failures worldwide are attributed to seismic activities, emphasizing the need for rigorous assessment and safety enhancements.

In this work, stability analysis of an earthen dam was conducted using a finite element software, which facilitates a two-dimensional representation of complex three-dimensional geotechnical problems. The computational approach employed effective stress and displacement principles to investigate the dam's behavior under seismic excitation. Advanced soil models were utilized to obtain accurate predictions for both static and dynamic conditions, ensuring a comprehensive understanding of the dam's response. The findings emphasize the importance of incorporating seismic design considerations into dam construction and retrofitting practices to enhance resilience against earthquake-induced forces. By identifying critical vulnerabilities, the research provides valuable insights into the necessary engineering interventions for ensuring the safety and stability of earthen dams in seismically active regions [2].

Earthen dams are vital components of infrastructure, serving multiple purposes, including irrigation, flood control, and hydroelectric power generation. However, their safety is often compromised in seismically active regions due to inadequate engineering and outdated construction techniques. Historical records indicate that seismic events have led to numerous dam failures, causing significant loss of life, environmental destruction, and economic setbacks. The evaluation of seismic response, therefore, plays a crucial role in mitigating the adverse impacts of future earthquakes. Conducting stability assessments ensures that essential infrastructures can withstand seismic forces and continue functioning without catastrophic failures [3].

One of the primary concerns regarding the seismic performance of earthen dams is liquefaction, which occurs when loose, water-saturated soil loses its strength and behaves like a liquid under earthquake-induced shaking. This phenomenon has been observed in various case studies where dam failures were linked to severe liquefaction, leading to settlement, lateral spreading, and instability of the dam structure. Longitudinal cracks and subsidence of the crest further aggravate the issue, making the structure vulnerable to complete collapse. Consequently, it is imperative to analyze the potential for liquefaction and implement measures such as soil compaction, reinforcement, or drainage systems to mitigate its effects.

The importance of numerical modeling and simulation in geotechnical earthquake engineering has been widely acknowledged. Finite element software enables engineers to analyze the complex interactions between soil and structures under seismic loads, facilitating a deeper understanding of dam behavior. Computational models incorporate varying ground motion intensities, allowing researchers to assess different seismic scenarios and predict failure mechanisms effectively. Studies have demonstrated that by using advanced soil constitutive models, more accurate predictions of stress distribution and deformation can be achieved, ensuring reliable assessments for dam safety [4].

Dams in seismically active regions must be designed to withstand both horizontal and vertical ground motions. The accelerations and forces exerted on the dam body during an earthquake can lead to excessive deformation and structural compromise. Previous research has indicated that dynamic loading significantly affects the stability of embankments and earth dams, leading to an urgent need for robust design considerations. In addition, the varying soil properties within the dam body and its foundation play a critical role in determining the overall seismic response. A comprehensive study of soil characteristics, including cohesion, friction angle, and permeability, is necessary to develop an effective seismic resistance strategy.

Another critical aspect of dam safety is the development of emergency preparedness plans and early warning systems. Given the unpredictable nature of earthquakes, it is crucial to have monitoring systems in place that can detect early signs of structural distress. Instrumentation such as accelerometers, piezometers, and inclinometers provide valuable data on the performance of a dam during seismic events. This real-time information helps engineers and authorities take necessary precautions and implement timely interventions to prevent catastrophic failures [5].

The economic implications of dam failures due to seismic activities are significant. Beyond the immediate impact of infrastructure loss, the destruction of downstream areas, displacement of communities, and disruption of water supply systems result in long-term socio-economic consequences. Reconstruction efforts require substantial financial resources, and the environmental impact of failed dams further exacerbates recovery challenges. As a result, ensuring the seismic resilience of earthen dams is not just an engineering challenge but also a crucial socio-economic concern that must be addressed proactively.

In light of the findings presented in this study, it is evident that integrating advanced analytical techniques with engineering best practices is essential for improving the seismic stability of earthen dams. Future research should focus on refining numerical models, incorporating real-time monitoring data, and developing innovative reinforcement strategies to enhance the performance of dams under seismic loading. By adopting a proactive approach, engineers, policymakers, and stakeholders can work towards ensuring the safety and reliability of earthen dams, thereby minimizing the risks associated with seismic events [6].

Overall, the analysis underscores the significance of finite element methods in assessing the dynamic behavior of earthen dams and proposes strategic recommendations for future seismic safety improvements.

The results contribute to the broader field of geotechnical earthquake engineering, offering guidance for engineers and policymakers in designing safer infrastructure to withstand seismic hazards. Given the increasing frequency and intensity of seismic events, prioritizing the stability and resilience of critical infrastructure, such as earthen dams, remains a key imperative in disaster risk management and infrastructure sustainability.

II. LITERATURE REVIEW

When any analysis or project is initiated, it is essential to have a general understanding of the subject, including previous research conducted in the field. A detailed review is necessary to obtain general information on material properties and failure patterns of the Chang Dam.

The author addressed the issue of crest displacements and stability conditions of earth dams in seismic regions. They highlighted that due to deformations, overtopping of earth dams could occur, leading to severe loss of life and property. Finite element analysis was used to evaluate the response of homogeneous earth dams under earthquake conditions [7]. The author in their study compared the finite element method with the limit equilibrium method. They concluded that PLAXIS is more reliable for parametric studies and determining stability and factor of safety, making it a superior approach to traditional methods [8].

The author explored how to determine the liquefaction potential of soil using cyclic stress ratio. They demonstrated how cyclic stress and critical stress ratio could serve as measures of earthquake loading and seismic vulnerability in earthen dams [9]. The author analyzed the impact of seismic forces on the dam's stability. With advancements in understanding soil behavior under dynamic load conditions, they established that the finite element approach provides better predictions of seismic response than the traditional limit equilibrium method [10].

The author conducted numerical simulations to evaluate dam deformations under strong ground motions. Their study emphasized the importance of incorporating soil-structure interaction and nonlinear material behavior for accurate results. The author investigated the impact of different intensity levels of ground motion on dam behavior. Their findings reinforced those variations in acceleration and displacement influence dam stability significantly. The author demonstrated how computational models incorporating advanced soil constitutive properties can provide more reliable assessments of stress distribution and deformation patterns in embankment dams. The author analyzed case studies of past dam failures due to seismic activity. Their research highlighted key failure modes such as liquefaction, crest settlement, and slope instability, providing insights into necessary mitigation strategies.

III. MATERIALS & METHODS

Chang Dam, an earthen structure, was built with a height of 15.5 meters and a crest length of 370 meters. The subsurface soil beneath the dam consists of loose to medium dense sand mixed with silt, while the bedrock is composed of sandstone. At the time of the seismic event, the reservoir was nearly empty, but the foundation soil was likely saturated. The earthquake led to the near-total collapse of the dam, with sand boils appearing near its upstream toe. The deformation pattern suggests that liquefaction occurred within the foundation soils, contributing to the structural failure.

The altered structure of Chang Dam is illustrated in Fig. 1, while Fig. 2 presents its pre-failure configuration as modeled in PLAXIS for comparison.

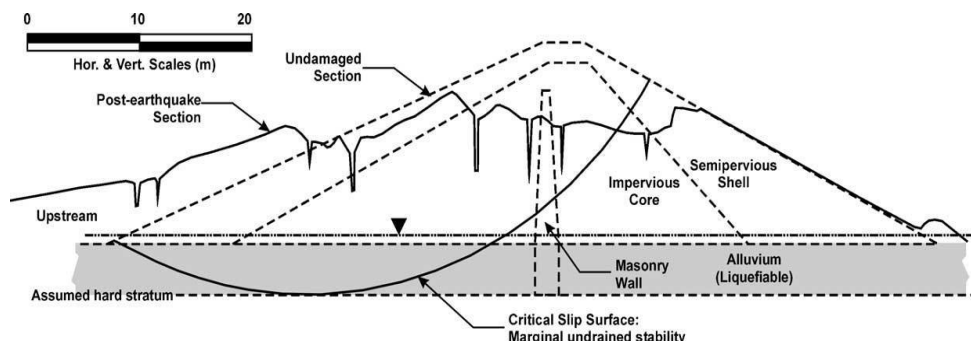


Fig1. Cross-section of Chang Dam

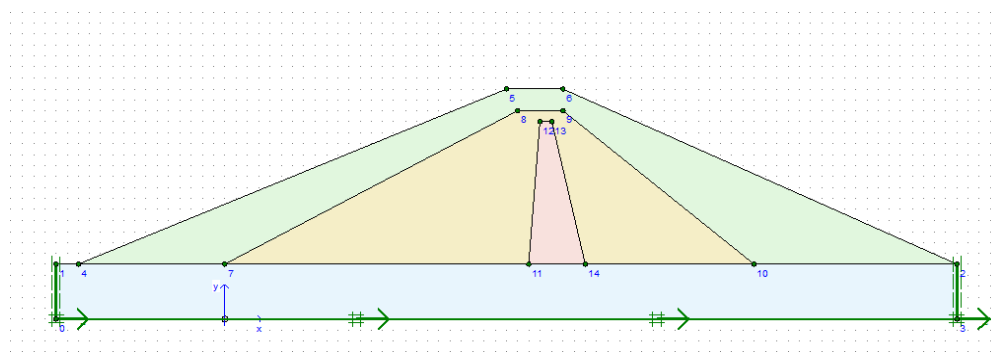


Fig 2. Pre-failure Cross section of Chang dam by PLAXIS 2D

Table 2. Yield acceleration, estimated and observed displacement (R. Singh et al. (2005)

Dam	Yield Acceleration	Estimated Displacement(m)	Observed Horizontal Displacement
Chang	Marginal undrained stability	0.70 m	0.60

Table 3. Soil properties of the Chang Dam. (R. Singh et al. (2005)

Layer no	Soil Unit	Unitweight(γ) (kN/m ³)	Cohesion (kPa)	ϕ (degree)	S_u/σ_v'
1	Semi-pervious shell	18	22	30.5	
2	Impervious core	20	50	0	
3	Liquefied soil	18	0.0		0.209
4	Non-liquefied foundation soil	18	0.0		0.411
5	Deep alluvium	20	0.0	41.5	

The simulation process begins by identifying four distinct clusters within Chang Dam and determining the properties associated with each. Fig. 3 presents the generated mesh section of the dam. A convergence test revealed that using a medium-sized mesh had minimal impact on the results. Further refinement to fine or very fine mesh did not produce significant variations compared to the medium mesh. Consequently, the medium mesh size was selected for the analysis.

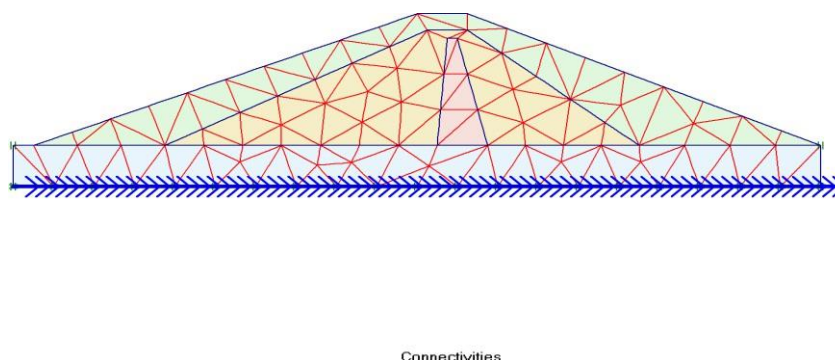


Fig 3. Section of generated Mesh of Chang Dam by PLAXIS

The influence of input motion on the seismic response of Chang Dam is evaluated and presented below. The dam was subjected to an accelerogram obtained from the Strong-Motion Virtual Data Centre (VDC). The closest recording station was the IITR station in Ahmedabad, India. The excitation was applied for a duration of 60 seconds. The base acceleration data recorded at Ahmedabad during the seismic event is shown in Fig. 4 and was used for the analysis.

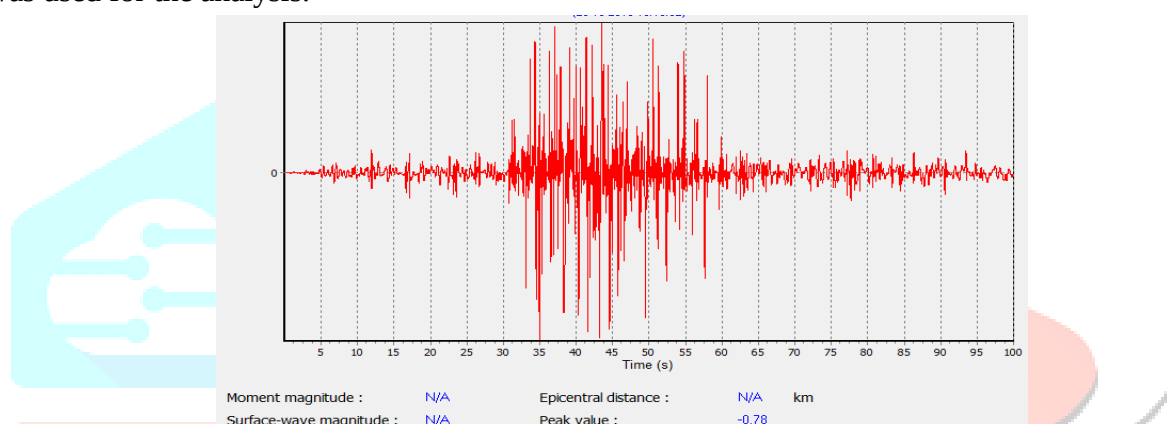


Fig 4. Acceleration- T time history plot of Bhuj earthquake

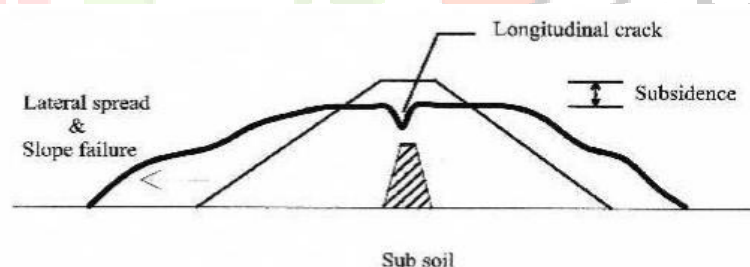


Fig 5. Typical failures observed in earth dams

The mathematical modeling using PLAXIS software is carried out in three stages. Initially, a plastic analysis is conducted once the dam construction is complete. The next phase involves a plastic analysis considering the dam's self-weight. Finally, a dynamic analysis is performed under seismic loading, incorporating the accelerogram input. The resulting deformed shape of the dam is illustrated in Fig. 6, while Fig. 7 presents the range of horizontal displacement.

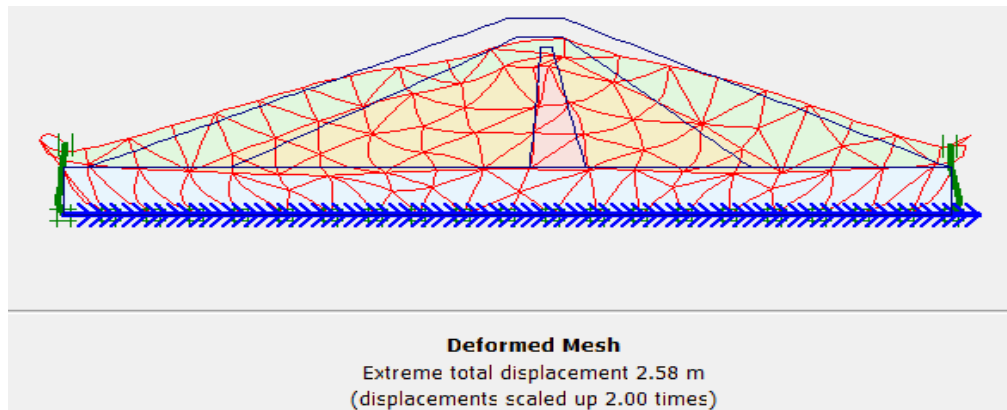
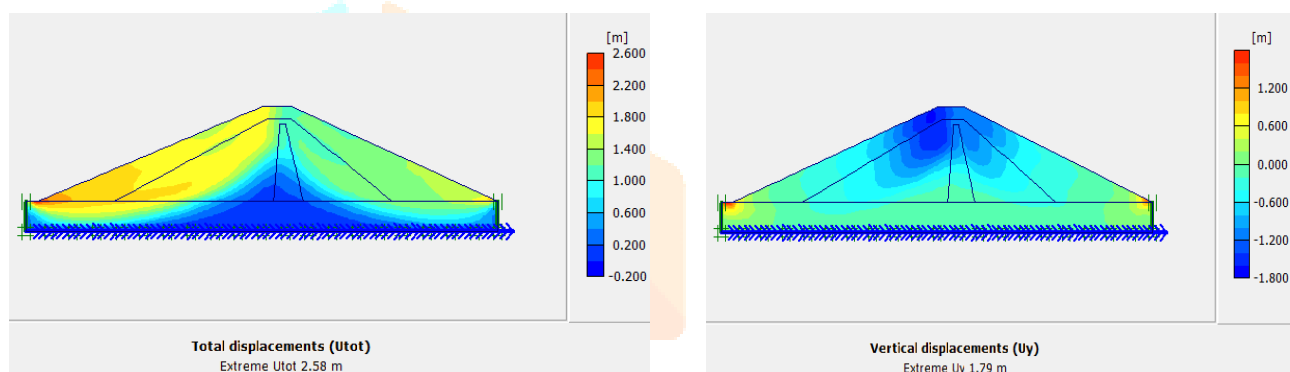


Fig. 6. Deformed mesh of Chang Dam

The deformed shape represents the finite element mesh in its altered state after analysis. The total displacement is the combined effect of horizontal and vertical displacement components at all nodes, visually represented on the geometric model. Similarly, the individual horizontal (x) and vertical (y) displacement components are determined upon completing the calculations. The total deformation of the dam was measured at 2.58 meters.

Fig.7. Total Displacements (U_{tot}), Extreme U_{tot} 2.58m and Extreme vertical displacement $U_y=1.79$ m

IV. RESULT & DISCUSION

Before initiating the calculation, specific points are selected at different levels along the dam's cross-section to determine stress values. Three points (A, B, and C) are chosen at the base level, while additional points are placed on the upstream side (Point E), the middle section (Point G), the downstream side (Point F), and the top of the dam (Point D). In total, seven stress points are identified, as illustrated in Fig. 8. Load-time curves can be generated using the software's draw curve option. The corresponding horizontal displacement-time curves for these points are presented in Fig. 9.

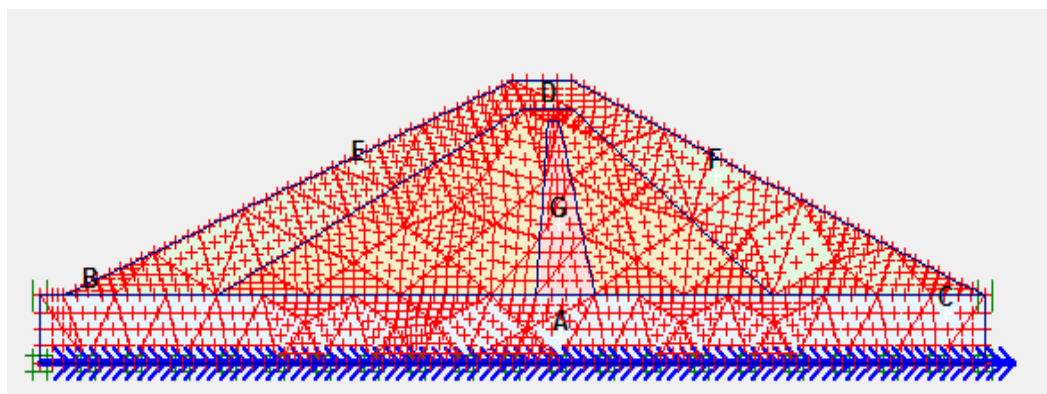


Fig.8 Location of nodes for time-displacement curves

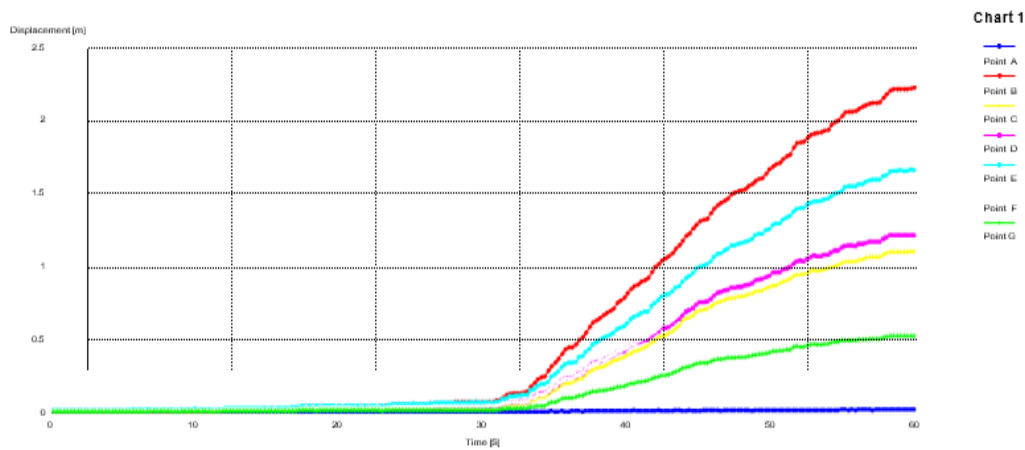


Fig 9. Time displacement curves for different points

From Fig. 9, it is observed that minimal displacement occurs during the first 30 seconds of shaking. The maximum displacement is recorded at points on the upstream side, particularly at Points B, D, and E. In contrast, the stress points located at the center experience the least displacement, likely due to the presence of the masonry wall in the central section of the dam.

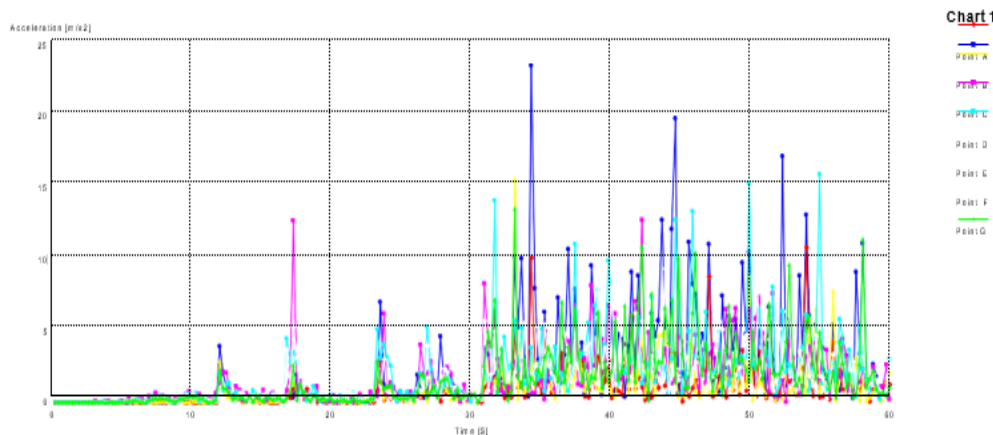


Fig 10. Time Acceleration curves for different points

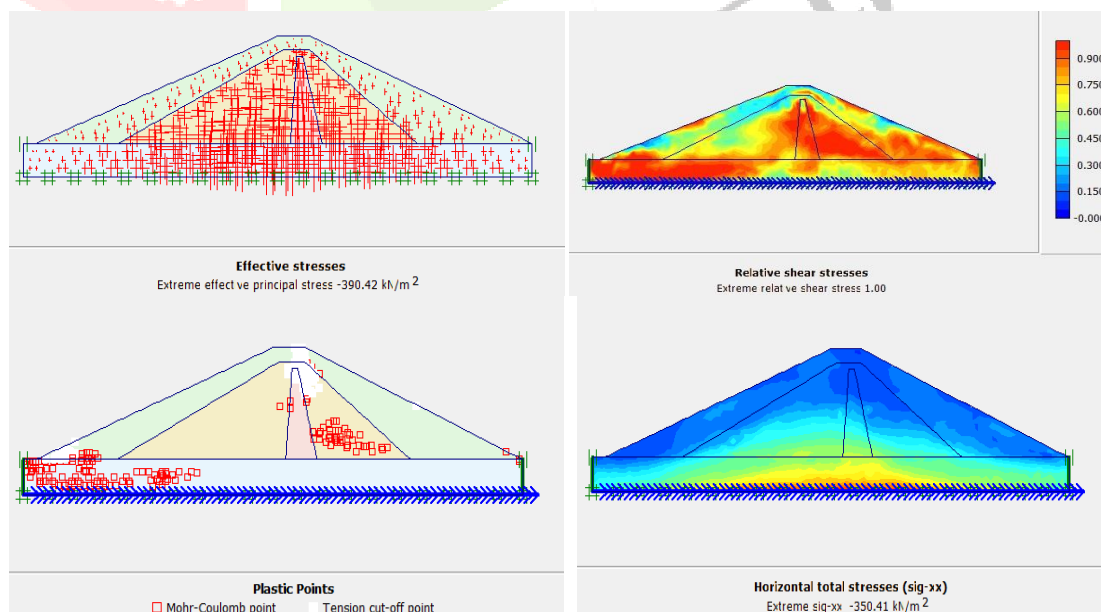


Fig 11. Effective stress, Total stress, Tension cut-off points and plastic points

From Fig. 10, it is observed that acceleration rises steeply after 30 seconds, with the highest acceleration recorded at Point A, located at the center of the base (indicated in blue). Pore water pressure is generated due to water seepage through the dam. Active pressures include total water pressure, which combines steady-state

pore pressure and excess pore pressure. In this analysis, the active pore water pressure was found to be -50 kN/m^2 . During seismic events, excess pore pressure can lead to liquefaction and structural failure. However, in this study, active pore pressures remained constant, indicating no excess pressure buildup and, consequently, no liquefaction.

PLAXIS enables the determination of effective stress, total stress, plastic points, active pore water pressure, and excess pore water pressure. In this analysis, the extreme effective principal stress was found to be -390.42 kN/m^2 . Fig. 11 illustrates the plastic points generated within the dam section. The results indicate that Mohr-Coulomb failure points are concentrated on the upstream side, while tension cut-off points are observed on the downstream side, aligning with the bulging of soil depicted in the failure diagram

V. CONCLUSION

The analysis of Chang Dam revealed significant seismic displacements, with the maximum displacements occurring at the crest, where a vertical depression of 1.79 meters was observed. The total extreme displacement was calculated to be 2.58 meters, and the extreme effective principal stress was determined to be -390.42 kN/m^2 . Through dynamic finite element analyses and literature review, it was concluded that seismic shaking caused large lateral displacements of the dam's downstream face, leading to a substantial drop in the crest elevation. This drop rendered the dam vulnerable to overtopping, initiating water release over the crest, followed by erosion, breach, and eventual collapse of the dam.

The findings emphasize the critical risk posed by seismic activity to those living near dam sites, particularly on the downstream side. The numerical analysis highlights the need for urgent seismic safety assessments of existing dams, as future earthquakes could lead to greater disasters if these risks are not addressed. It is crucial not only to design dams capable of withstanding future seismic events but also to conduct thorough investigations and maintenance of existing structures. This study underscores the importance of both design and ongoing safety evaluations to ensure the stability and safety of dams in earthquake-prone regions.

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