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Laboratory Analysis of Deformation Behavior in Layered Weak Rocks under Large-Scale Lateral Loading

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***Abstract*:** This study investigates the deformation behavior of layered sedimentary rocks with diverse geotechnical properties under large-scale lateral loading conditions. These loads, primarily induced by tectonic activities, significantly alter the stress-strain distribution in geotechnical structures such as tunnels and roads built on slopes. Understanding these deformations is crucial for assessing the stability and performance of such structures. To analyze these effects, a series of controlled laboratory experiments were conducted using a specialized testing device designed to simulate lateral loading scenarios. The device measures layer deformations in meganeutons per square meter, providing precise insights into the mechanical response of bedded rock formations. The experimental setup involved systematically applying varying lateral loads while monitoring deformation patterns in different sedimentary rock samples. The recorded results highlight how weak sedimentary rocks respond to stress redistribution and lateral forces. The findings reveal critical deformation trends, structural weaknesses, and failure mechanisms that influence the long-term stability of geotechnical structures. This research contributes to a better understanding of the lateral load effects on layered rock formations and provides valuable data for designing more resilient infrastructure in geologically active regions.

Keywords: Laboratory deformation model, Layered sedimentary rocks, Axial loading, Slope stability, Large-scale testing.

I. INTRODUCTION

Sedimentary rocks are one of the three main types of rocks found on Earth, formed by the accumulation and compaction of mineral and organic particles over time (Tucker, 2011). They often develop in layers, each representing a different period of deposition (Rafiei et al., 2016). These rocks are typically classified based on their composition and the processes through which they are formed. The primary types of sedimentary rocks include clastic, chemical, and organic sedimentary rocks (Hoek et al., 2005). Clastic sedimentary rocks, such as sandstone and shale, are formed from fragments of other rocks that have been transported and deposited by water, wind, or ice (Rafiei et al., 2016). Chemical sedimentary rocks, such as limestone and gypsum, form when minerals precipitate from a solution (Tucker, 2011). Organic sedimentary rocks, such as coal, are composed of organic materials like plant debris or shells that have been compacted over time (Diamantis et al., 2021). The nature of sedimentary rocks is strongly influenced by the environment in which they form (Tucker, 2011). Factors like water temperature, chemical composition, and the rate of sediment deposition can impact the final characteristics of the rock. Sedimentary rocks tend to have a relatively low strength compared to igneous or metamorphic rocks, but their structure and composition can vary greatly (Tsiambaos & Sabatakakis, 2004). For example, limestone is often soft and easily eroded, while sandstone can be much harder and more durable (Millon et al., 2016). This variation in strength and composition plays a key role in determining the behavior of sedimentary rocks under stress, particularly when subjected to external forces like lateral loading or tectonic activity (Tucker, 2011).

There are many different types of sedimentary rocks, each with their own unique characteristics and importance (Chang et al., 2006). For instance, sandstone is often used in construction due to its durability, while shale is known for its ability to hold hydrocarbons, making it an important source rock for oil and gas (Altindag, 2012). Limestone is widely used in cement production and as a building material (Kara, 2021; Sharma et al., 2021). Understanding the different types of sedimentary rocks, their formation processes, and their physical properties is crucial for many fields, including geology, engineering, and resource extraction (Tucker, 2011). The study of sedimentary rocks is particularly important in understanding the stress field and the potential for failure when these materials are subjected to external forces (Waqas & Ahmed, 2022). Under natural or artificial loading conditions, such as earthquakes or the construction of large-scale infrastructure, the stress on sedimentary rock layers can lead to deformation and, in some cases, catastrophic failure (Tucker, 2011). The way these rocks deform depends on their composition, strength, and the specific nature of the forces applied to them (Mughieda et al., 2022). For instance, layers of sedimentary rock with varying geotechnical properties may experience different types of deformation, such as sliding, shearing, or buckling (Latib et al., 2023). This makes it essential to understand how these rocks will behave under stress in order to predict the potential for failure and take appropriate measures to mitigate risks (Meng et al., 2021).

The impact of fracturing and failure in sedimentary rocks is another important area of study, particularly in the context of large-scale lateral loading (Du et al., 2022). When a sedimentary rock layer fails, it can lead to significant shifts in the surrounding geology, such as the formation of faults or the movement of underground fluids (Krabbendam et al., 2021). For example, in areas where sedimentary rocks are involved in oil or gas extraction, failure of rock layers can lead to the collapse of well bores or cause a release of fluids into the surrounding environment (Gage et al., 2022). In construction and engineering projects, failure can result in the collapse of foundations or the destabilization of infrastructure (Goodarzi et al., 2021). The study of fracture mechanics in sedimentary rocks helps engineers and geologists design more resilient structures and predict where and how failure might occur (Zaid & Sadique, 2021). Additionally, understanding the stress field in sedimentary rock formations is key for predicting the behavior of these materials over time (Barbieri et al., 2021). When sedimentary rocks are subjected to long-term loading, they may undergo slow deformation processes such as compaction, which can affect their strength and stability (Tucker, 2011). The buildup of stress over time can lead to brittle fracture or ductile flow, depending on the type of rock and the conditions it is subjected to (Wang et al., 2022). In areas of active tectonic activity or where large-scale industrial operations are taking place, monitoring the stress field and potential fracture zones is vital for ensuring the safety and stability of structures built on or within sedimentary rock formations (Shahani et al., 2021). Finally, research into the deformation behavior of sedimentary rocks under stress is important for advancing both theoretical knowledge and practical applications (Khajevand, 2023). As our understanding of the mechanisms behind stress and fracture in sedimentary rocks improves, it becomes possible to develop better predictive models and design strategies for engineering projects (Barbieri et al., 2021). Whether for construction, resource extraction, or environmental protection, this knowledge can help mitigate risks and optimize the use of sedimentary rock formations, ensuring the safety and sustainability of human activities in areas where these rocks are prevalent (Goodarzi et al., 2021).

The deformation behavior of layered sedimentary rocks with diverse geotechnical properties under large-scale lateral loading conditions is a key aspect of geotechnical engineering, with significant implications for construction, natural disaster response, and environmental stability (Birien & Gauthier, 2023). Sedimentary rocks, formed through the accumulation of materials over time, typically consist of layers that exhibit varying physical and mechanical properties (Tian et al., 2021). These properties, such as strength, elasticity, porosity, and permeability, are influenced by factors such as the composition of minerals, the degree of cementation, and the depositional environment (Cui et al., 2023). As a result, understanding how these layered rocks respond to lateral loading is essential for designing safe and stable structures in areas where such rocks are prevalent (Zhai et al., 2021).

Lateral loading, which refers to the application of forces parallel to the surface of the earth, can occur due to natural phenomena like earthquakes, landslides, or human activities such as construction or excavation (Liu et al., 2023). When layered sedimentary rocks are subjected to such forces, the behavior of the material can be highly complex, with deformation occurring differently across the various layers (Cong et al., 2023). The stratification of these rocks often leads to a heterogeneous response to stress, making the study of their deformation under lateral loading conditions both challenging and critical for accurate prediction of their behavior in real-world scenarios (Maheshwari, 2021). One of the key challenges in understanding the deformation of layered sedimentary rocks is the significant variation in their geotechnical properties (Schuster et al., 2021). Different layers may have widely varying strengths, shear resistances, and elastic moduli (Li et al., 2021). For example, clay-rich layers may exhibit low shear strength and high compressibility, while sandstone layers may be stronger and more resistant to deformation. This variability leads to a complex interaction between the different layers when subjected to lateral stresses, resulting in non-uniform deformations such as sliding, buckling, or shear failure (Zhao et al., 2022). Such behaviors must be carefully examined to understand the overall response of the rock mass to lateral loading (Zaid & Sadique, 2021).

Another important aspect of the deformation behavior of layered sedimentary rocks is the impact of scale (Tian et al., 2021). In laboratory experiments, the conditions under which rocks are tested are typically smaller in scale compared to real-world applications (Cui et al., 2023). However, when these materials are subjected to large-scale lateral loading, such as during an earthquake or large construction project, the response can differ significantly (Barbieri et al., 2021). The larger the loading is, the more pronounced the heterogeneity between the layers may become, and the more difficult it is to predict the overall deformation behavior (Zaid & Sadique, 2021). Understanding the relationship between scale and deformation is, therefore, crucial for accurately modeling these materials in geotechnical design (Du et al., 2022). The interaction between different layers within sedimentary rock formations under lateral loading is another important factor to consider (Tian et al., 2021). Layers with contrasting properties can lead to differential movement between them, resulting in sliding, sharing, or even fracturing. The extent to which these layers interact depends not only on their mechanical properties but also on the contact conditions between them. For example, if the layers are weakly bonded or have high porosity, the risk of sliding and shear failure increases (Cui et al., 2023). Conversely, strong bonding and low porosity may inhibit such movements, but still lead to other forms of deformation, such as buckling or plastic deformation (Zhai et al., 2021). Therefore, accurately modeling these interactions is key to understanding the overall response of the rock mass (Meng et al., 2021).

Moreover, the effect of environmental factors, such as moisture content, temperature, and pressure, plays a significant role in the deformation behavior of layered sedimentary rocks (Tucker, 2011). Moisture can reduce the shear strength of clay-rich layers, making them more susceptible to failure under lateral loading (Zhao et al., 2022). Similarly, temperature changes can influence the elasticity and strength of different rock layers, altering the way they deform under stress (Zhai et al., 2021). Pressure, particularly from overlying rock layers, can also change the deformation characteristics of the underlying strata (Gage et al., 2022). These environmental factors must be accounted for in any model designed to predict the behavior of layered sedimentary rocks under large-scale lateral loading (Du et al., 2022).

The practical implications of understanding the deformation behavior of layered sedimentary rocks under lateral loading are vast (Krabbendam et al., 2021). In areas prone to earthquakes or landslides, accurate predictions of rock behavior can help inform the design of structures such as buildings, roads, and bridges to ensure their stability (Cui et al., 2023). Similarly, in the context of natural resource extraction, such as mining or oil drilling, understanding how sedimentary rocks respond to lateral forces can help prevent catastrophic failures and optimize extraction methods (Barbieri et al., 2021). Furthermore, this knowledge is essential for environmental conservation, as the deformation of these rocks can have significant impacts on groundwater flow, soil stability, and the overall health of ecosystems (Li et al., 2021). Finally, ongoing research and advancements in geotechnical engineering techniques continue to improve our understanding of the deformation behavior of layered sedimentary rocks (Latib et al., 2023). Through laboratory testing, numerical modeling, and field observations, researchers are developing more accurate models that account for the complex interactions between different rock layers under large-scale lateral loading (Zaid & Sadique, 2021). These models help engineers and scientists predict the behavior of sedimentary rocks in a variety of scenarios, improving the safety and sustainability of engineering projects and contributing to the broader field of geotechnical science (Cui et al., 2023). As such, further study in this area remains essential for advancing both theoretical knowledge and practical applications in the geotechnical and environmental fields (Tucker, 2011).

II. TECTONICAL LATERAL LOADING

Tectonic loading refers to the stresses and forces exerted on the Earth's crust due to large-scale geological processes such as plate movements, fault activity, and subsurface pressure changes (Zheng, 2023). Figure 1 provides an illustration of large-scale geological processes leads fault activity. These forces cause deformation in rock formations (Ghanbarian et al., 2021), leading to the development of fractures, faults, and folds over time (Egorov et al., 2021). Tectonic loading is a key factor influencing the stability of geological formations and has significant implications for both natural hazards and engineering projects (Kovács et al., 2021). The way different rock layers respond to these stresses depends on their mechanical properties, such as strength, elasticity, and porosity, making the study of tectonic loading essential for understanding and predicting geological behavior (Agrawal et al., 2022). One of the primary consequences of tectonic loading is the generation of in-situ stress fields, also known as the in-situ stress state or pre-existing stress field (Zheng, 2023). This refers to the natural stress presented within the Earth's crust before any human intervention (Xiong et al., 2022).

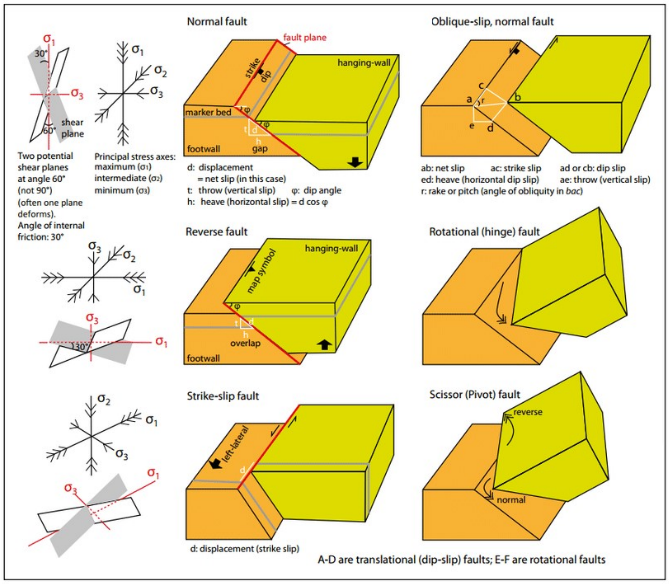

Fig. 1 Example of a large-scale geological in-situ stress field (Underschultz et al., 2018)

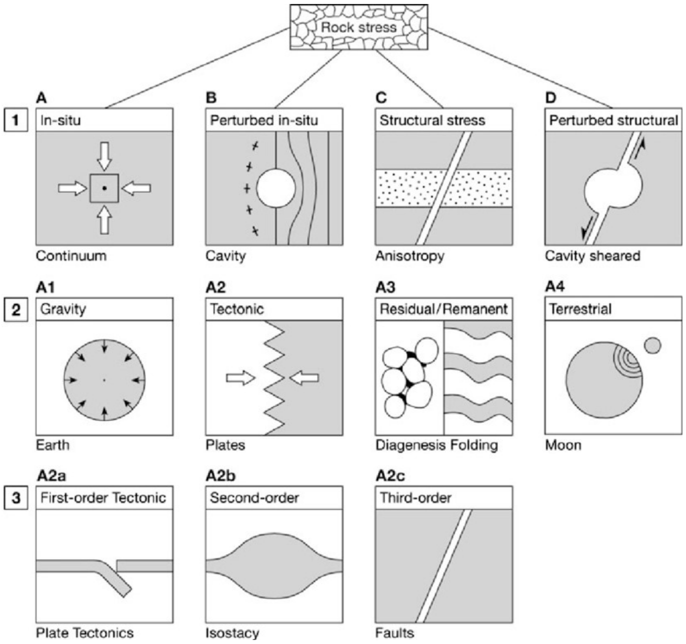

Fig. 2 In-situ rock stress field with hierarchical levels terminology (Stephansson and Zang, 2012)

In geotechnical engineering, understanding the in-situ stress field is crucial for designing stable and safe infrastructure. When constructing tunnels, dams, mines, or deep foundations, engineers must account for the stresses already present in the ground (Stephansson & Zang, 2012). If the state of the natural stress is not properly considered, the excavation or construction process can lead to unexpected deformations, excessive settlements, or even structural failure (Zheng, 2023). For example, in tunneling projects, ignoring high in-situ stresses can result in excessive rock bursting or collapse, posing significant safety risks to workers and infrastructure (Stephansson & Zang, 2012). One of the key effeareectonic loading and in-situ stress fields is their influence on rock stability and failure mechanisms.

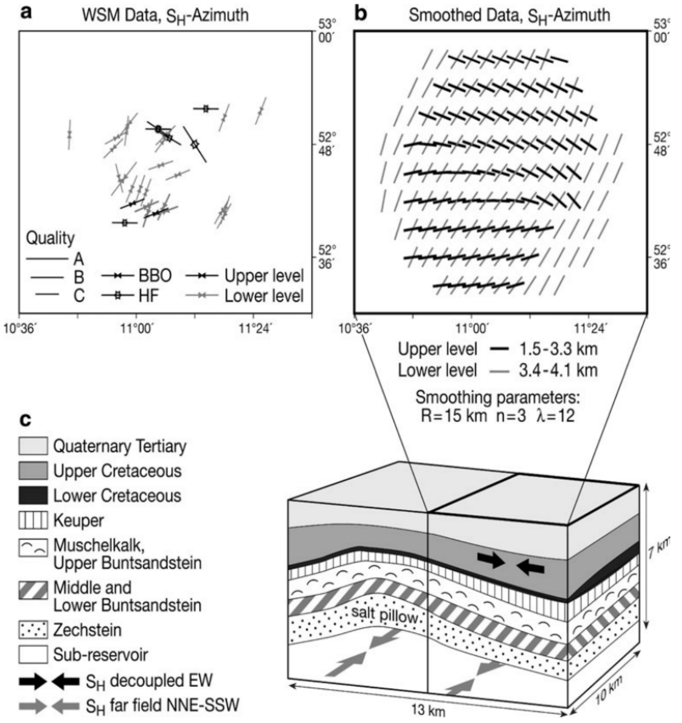

Fig. 3 Large-scale geological-based in-situ stress field example (Stephansson & Zang, 2012)

Figure 2 provides a hierarchical levels terminology to explain the stress conditions in the field. As seen in Figure 3, rocks that are subjected to high tectonic stress may already be close to their failure threshold (Stephansson & Zang, 2012). When additional loads from engineering activities are applied, stress conditions may exceed the rock's strength, leading to sudden failure (Zhang & Zhang, 2017). This is particularly important in earthquake-prone areas, where tectonic loading contributes to stress accumulation along fault lines. When this accumulated stress is suddenly released, it can trigger seismic events that have devastating effects on buildings, roads, and other structures (Casey et al., 2016).

In the context of underground construction, such as tunnels and caverns, the impact of in-situ stress fields is even more pronounced. High horizontal or vertical stress can lead to uneven deformation, requiring engineers to implement reinforcement techniques such as rock bolting or shotcrete to maintain stability (Martin et al., 2003). In deep mining operations, stress-induced failures such as rockbursts can occur, where sudden violent failures of rock cause hazardous working conditions (Chang et al., 2010). By understanding and measuring the in-situ stress field, engineers can predict and mitigate these risks, ensuring safer excavation and construction processes (Xiang-Hui et al., 2014). Another critical application of studying tectonic loading and in-situ stress is in oil and gas extraction. Hydrocarbon reservoirs are often located within sedimentary rock formations that have been subjected to tectonic stresses over millions of years (Liu et al., 2022). The in-situ stress conditions influence the permeability and fracture networks within these reservoirs, affecting the efficiency of oil and gas extraction. If the stress state is not properly analyzed, drilling operations can result in wellbore instability, leading to costly failures or loss of valuable resources. Hydraulic fracturing, a technique used to enhance oil and gas recovery, relies on precise knowledge of the stress field to create fractures that optimize fluid flow (Zhao & Qin, 2023).

The study of tectonic loading is also vital for assessing the long-term stability of geotechnical structures such as dams and retaining walls. These structures often interact with rock masses that have pre-existing tectonic stresses. If these stresses are not adequately accounted for during design, they can contribute to structural deformation, foundation movement, or even catastrophic failures (Xiang-Hui et al., 2014). A thorough understanding of these stresses helps engineers design structures that can withstand long-term loading conditions without compromising safety (Taherynia et al., 2016). By analyzing tectonic loading patterns and stress accumulation along fault lines, geologists and engineers can estimate the likelihood and intensity of future earthquakes. This information is essential for designing earthquake-resistant structures, implementing zoning regulations, and developing early warning systems (Xiang-Hui et al., 2014). Failure to consider tectonic stress in seismic design can lead to severe damage and loss of life during major seismic events (Bousquet et al., 1988).

Beyond engineering applications, tectonic loading also has implications for natural hazard management. Landslides, for example, are often triggered by changes in the in-situ stress field due to tectonic forces, weathering, or human activities such as excavation. When tectonic stress weakens rock masses along slopes, the risk of sudden slope failure increases. Understanding these stress conditions allows for better hazard prediction and mitigation, reducing the risks to communities and infrastructure located in landslide-prone regions. The necessity of studying tectonic loading and in-situ stress fields extends to large-scale geological projects such as carbon sequestration and nuclear waste storage. These projects require stable underground formations to safely contain carbon dioxide or hazardous materials over long periods. The presence of tectonic stresses can impact the integrity of storage sites, increasing the risk of leakage or failure. Detailed stress analysis ensures that such projects are carried out in stable geological conditions, minimizing environmental and safety risks. Given the wide-ranging impacts of tectonic loading on engineering and environmental stability, the study of these phenomena is not only necessary but essential for sustainable development. Advances in geophysical measurement techniques, such as borehole stress testing and numerical modeling, have allowed engineers to better understand and predict in-situ stress behavior. These tools enable more accurate risk assessments and the design of geotechnical solutions that are resilient to tectonic forces.

The primary objective of this study is to enhance the understanding of how layered sedimentary rocks with diverse geotechnical properties respond to large-scale lateral loading conditions. Given that tectonic activities are a major source of such loads, investigating their impact on stress-strain distribution is essential for predicting and mitigating deformation in critical geotechnical structures such as tunnels, roads, and slopes. By conducting controlled laboratory experiments with a specialized testing device, this research aims to quantify the mechanical response of sedimentary rock formations under varying lateral loads. The data obtained will help identify deformation trends, structural weaknesses, and potential failure mechanisms, providing a scientific basis for improving engineering design strategies in geologically active regions. The necessity of studying these deformation behaviors lies in their direct influence on the safety and longevity of infrastructure projects. Many urban and transportation networks are constructed on or within sedimentary rock formations, making them highly susceptible to stress redistribution and lateral forces. Without a comprehensive understanding of how these rocks behave under such conditions, structures may suffer from unexpected failures, leading to costly damages and safety hazards. This research provides crucial insights that can aid in developing more resilient construction techniques, optimizing material selection, and implementing better risk assessment models. Ultimately, by addressing the challenges posed by lateral loading, this study contributes to the advancement of geotechnical engineering practices, ensuring greater structural stability and safety in tectonically active environments.

III. MATERIALS AND METHODS

This study employs a controlled laboratory modeling approach to investigate the deformation behavior of layered sedimentary rocks under large-scale lateral loading conditions. A specially designed experimental device, measuring 14 × 22 × 40 cm, was used to simulate tectonic forces acting on sedimentary rock formations as presented in Figure 4. The lateral force was applied through a movable jaw positioned on one side of the device, generating uniaxial horizontal compression. To enable direct observation of deformation patterns occurring at different depths within the sedimentary layers, one side of the apparatus was constructed using a transparent acrylic sheet. The distance between the movable jaw and the opposite fixed wall was set at 26 cm, ensuring adequate space for lateral displacement and fault development. Given that thrust faults typically form within layered sequences of varying mechanical properties, the experimental model incorporated alternating layers of clay and sand, mimicking natural sedimentary formations subjected to tectonic stresses. Figure 5 illustrates the theoretical model principle, depicting the movement of weaker sedimentary layers over more resistant underlying formations under lateral loading conditions. This representation highlights the differential deformation behavior, where the less compacted upper layers experience greater displacement and strain, while the more competent lower layers provide structural support but also develop internal stress concentrations. The figure effectively demonstrates how thrust faulting and shear deformation propagate through the layered system, emphasizing the role of material strength contrast in governing the overall deformation pattern. This theoretical framework serves as a basis for understanding real-world geological processes, particularly in regions subjected to tectonic compression.

The preparation of the model involved systematically depositing alternating layers of clay and sand within the testing apparatus. Each layer was carefully compacted to ensure consistent density and mechanical behavior. The applied lateral load was introduced incrementally using both manual and mechanical handles, allowing precise control over the stress distribution. The testing sequence consisted of ten loading stages, with each stage imposing a 5% reduction in the initial model length, simulating progressive compressional deformation. To replicate natural rock properties, highly compacted soil layers (compacted to 95% density) were used to represent sandstone, siltstone, and weak claystone layers. These layers were distinctly colored to enhance the visibility of deformation structures, such as fault initiation, shear band development, and strain localization. Throughout the experiment, detailed observations and measurements were recorded, focusing on the evolution of deformation patterns, fault propagation, and displacement trends. The transparent section of the device allowed for direct visual analysis, while additional digital image processing techniques were utilized to track strain accumulation and layer distortion over time. This methodology provides valuable insights into how sedimentary rock layers respond to tectonic loading, offering a controlled framework for analyzing stress redistribution, failure mechanisms, and structural instabilities in geotechnical projects exposed to lateral forces (Figure 6).

The loading process in this experiment was conducted in a controlled manner to simulate the effects of lateral tectonic forces on layered sedimentary formations. The model was subjected to incremental compressive loading, where a horizontal force was applied gradually using a manual and mechanical handle system. This force was exerted from the left side of the testing apparatus, pushing the movable jaw toward the fixed wall. To ensure a systematic approach, the loading was divided into ten stages, with each stage reducing the model's initial length by 5%. This step-by-step process allowed for the gradual accumulation of strain, enabling the observation of progressive deformation patterns within the layered rock formations. At each 5% shortening stage, the deformation behavior of the layers was carefully monitored. As the lateral force increased, the weaker layers (such as clay) exhibited early signs of strain localization, while the stronger layers (such as compacted sand) initially resisted deformation.

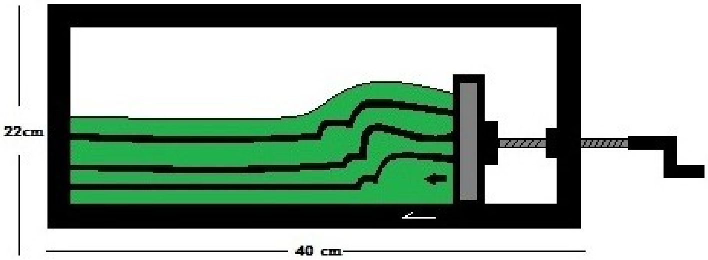

Fig. 4 A simple explanation of laboratory model used in this study

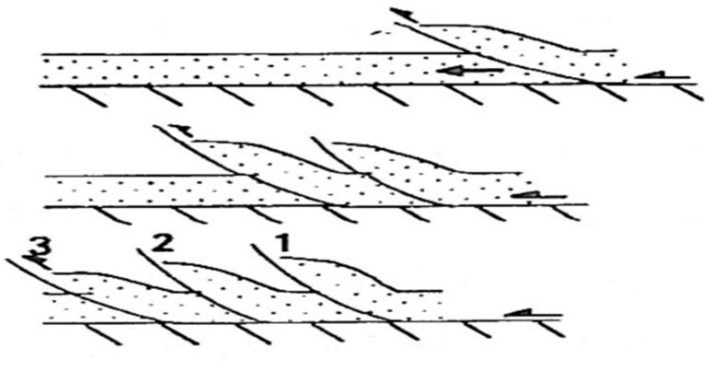

Fig. 5 The theoretical principle of the analysis

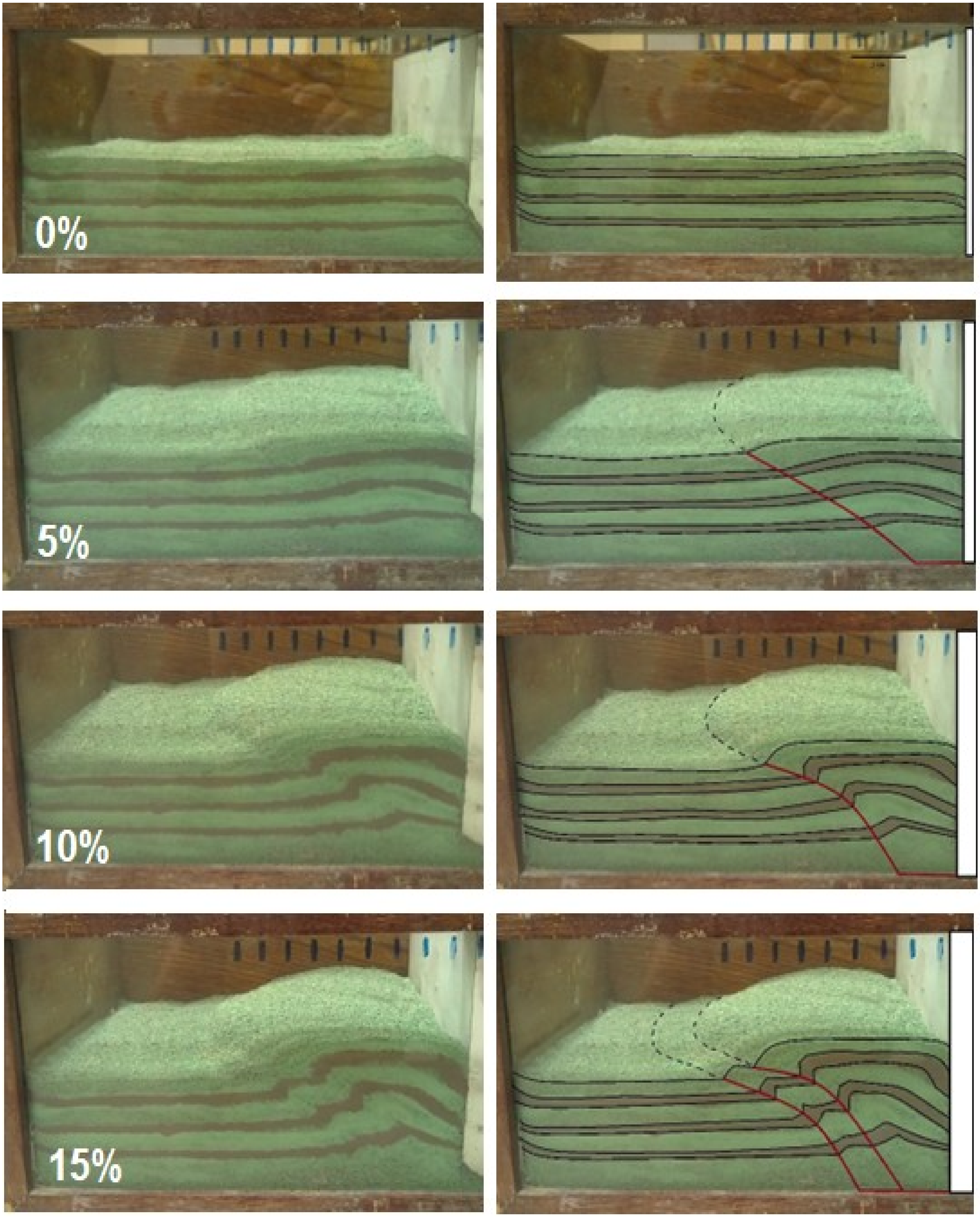

Fig. 6 The lateral loading process demonstrated using the laboratory device in this article and layered rocks behaviors

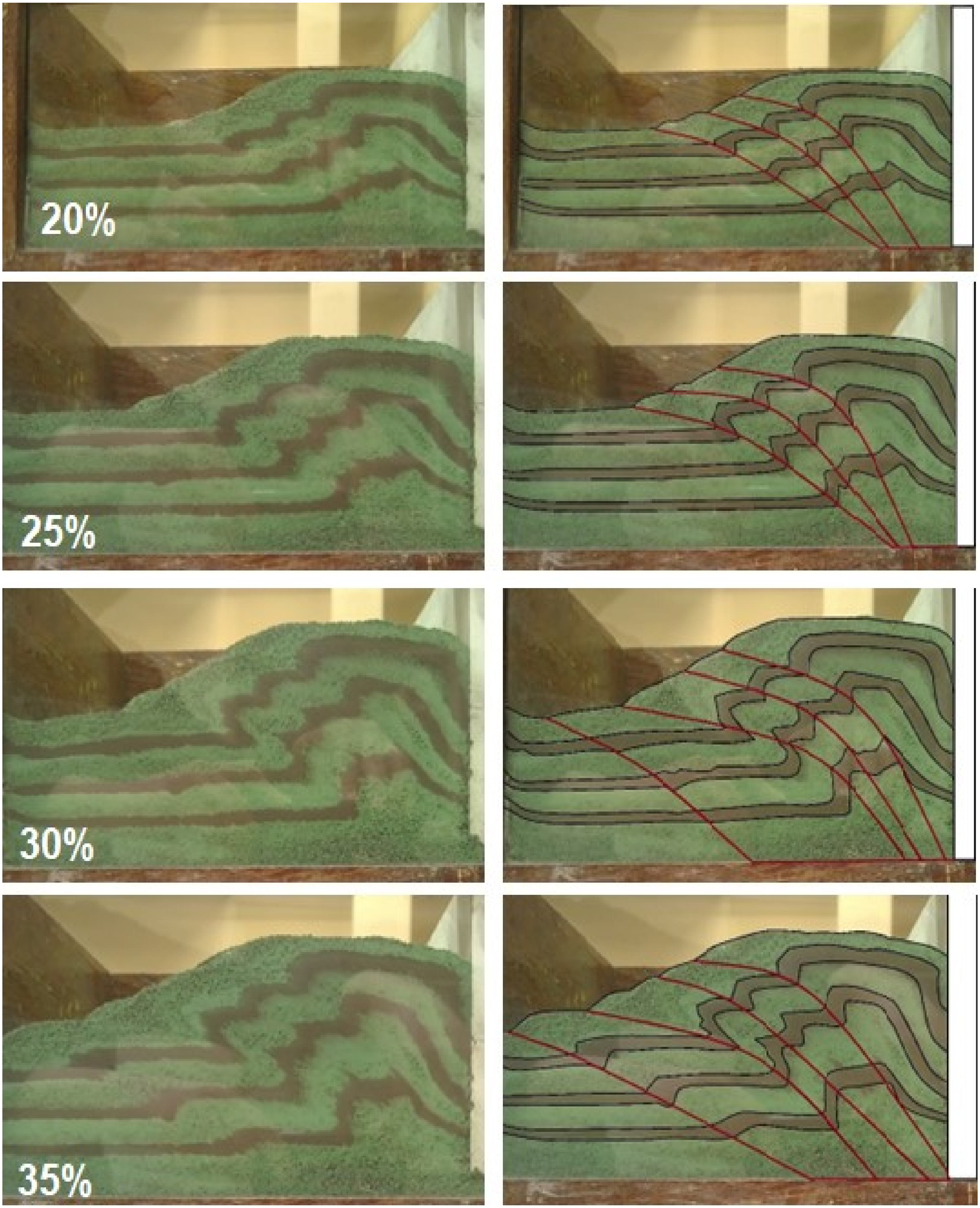

Fig. 6 Continued

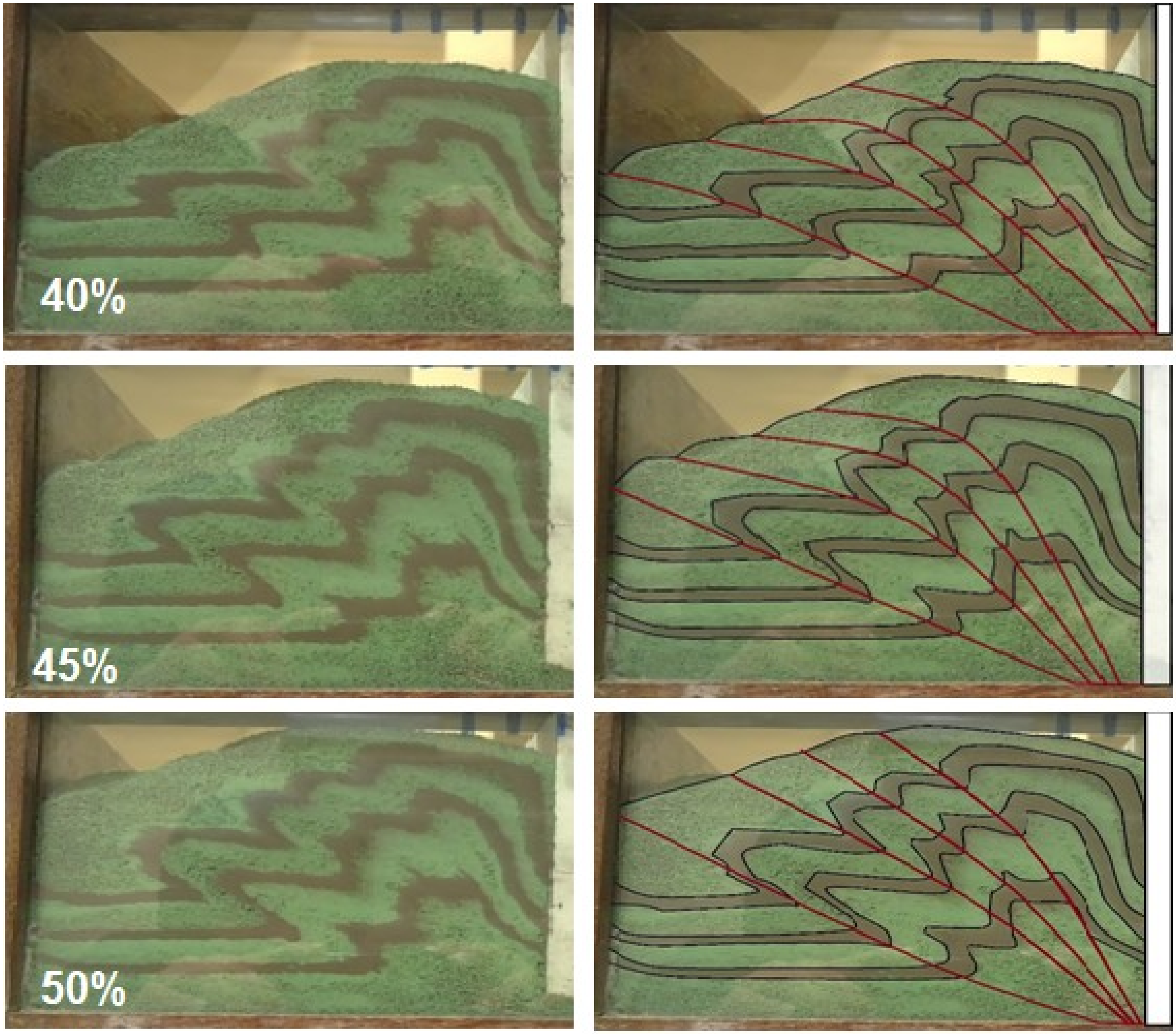

Fig. 6 Continued

However, as loading progressed, differential movement between layers led to the development of thrust faults, shear bands, and layer folding. These structural changes were more pronounced in the upper sections of the model, where less compacted materials experienced greater displacement, whereas the more resistant lower layers acted as a foundation, transferring stress and generating internal fractures. By the midway point of loading (around 50% total shortening), significant structural changes had occurred, with multiple fault zones forming within the weaker layers. The displacement of sedimentary layers followed a progressive faulting sequence, where pre-existing weaknesses governed the failure mechanisms. Slip planes began to develop, allowing portions of the upper layers to shift over the lower, more stable formations. The transparent side of the device provided a clear view of how lateral forces redistributed stress, leading to a cascading effect of deformation throughout the model. As the experiment reached the final loading stages (up to 95% compaction), the accumulated stress caused major structural failures, with highly deformed zones forming at key stress concentration points. Some layers experienced complete detachment and movement, while others displayed buckling and intense shear deformation. These observations confirmed that the progressive application of 5% incremental loading effectively replicated natural tectonic processes, highlighting the critical role of material strength contrast in governing deformation patterns. The results provided essential insights into the mechanical response of layered sedimentary formations, which can be applied to real-world geotechnical challenges, such as slope stability, tunnel construction, and fault zone behavior in tectonically active regions.

IV. RESULTS AND DISCUSSION

The experimental results provide a detailed understanding of the deformation behavior of layered sedimentary rocks under large-scale lateral loading conditions. As lateral compression increased, the stress redistribution within the model followed a hierarchical pattern, leading to progressive strain accumulation, fault development, and displacement variations. The results clearly demonstrate that the interaction between weak and strong sedimentary layers governs the formation and evolution of deformation structures. The recorded data indicate that weaker clay-rich layers experienced greater lateral displacement, while more compacted sand layers exhibited higher internal stress concentrations before failure. At this stage, minor deformations were observed in the weaker layers, while the stronger layers remained largely stable. The stress distribution was relatively uniform, with no significant fault initiation. However, small stress concentrations began forming at layer boundaries, indicating early signs of mechanical instability. This stage highlights the elastic behavior of sedimentary layers before reaching the yield threshold.

As lateral loading progressed to the medium stage, stress redistribution became more pronounced, leading to the formation of localized shear bands and early thrust faults. The hierarchical stress field showed increased differentiation between the weak and strong layers, with deformation zones concentrating in clay-rich layers. The sand layers acted as stress barriers, but internal fracturing was observed in some sections due to accumulated strain. This stage marks the transition from elastic deformation to plastic and brittle failure, with the first signs of fault propagation becoming visible. At the advanced stage of loading, significant structural changes occurred within the model. Multiple thrust faults and shear zones had fully developed, causing layer displacements and large-scale deformations. The weaker layers experienced intense shear failure, while the more compacted layers showed fracture propagation and stress redistribution. The hierarchical in-situ stress field at this stage highlights the complex interaction between stress concentration zones, fault mechanics, and strain localization. This phase closely resembles real-world geological settings, where prolonged tectonic compression leads to major fault systems and large-scale rock mass movements.

One of the key observations from the study is the role of compaction in controlling deformation behavior. The 95% compacted layers showed significantly higher resistance to lateral deformation compared to loosely compacted layers. This finding reinforces the importance of material density and mechanical properties in predicting the response of rock formations to tectonic stresses. The study also confirmed that the distribution of faults and deformation structures depends on the initial stress state, meaning that pre-existing stress fields must be carefully analyzed when assessing geotechnical stability. Another important aspect is the engineering implications of these findings. The results highlight the necessity of incorporating accurate stress field analyses when designing tunnels, slopes, and infrastructure in tectonically active areas. The development of thrust faults and shear bands under lateral compression suggests that engineering designs should consider reinforcement strategies, such as rock bolting, flexible retaining structures, or controlled excavation sequences, to mitigate failure risks. The experiment further emphasizes the importance of stress monitoring techniques, such as borehole stress testing and numerical modeling, to predict real-world deformation trends more effectively.

Generally, the study provides valuable insights into stress redistribution, fault mechanics, and geotechnical stability under lateral loading conditions. The findings not only enhance our understanding of how sedimentary rock formations behave under tectonic forces but also contribute to the development of better risk assessment models and structural design approaches. Future research could expand on these results by incorporating real-time stress measurements, 3D numerical simulations, and additional lithological variations to further refine our understanding of deformation behavior in complex geological settings.

V. CONCLUSION

This study provides a comprehensive analysis of the deformation behavior of layered sedimentary rocks under large-scale lateral loading conditions, simulating the effects of tectonic forces on geotechnical structures. Through controlled laboratory experiments, we examined how varying geotechnical properties influence stress redistribution, failure mechanisms, and structural instabilities. The results demonstrate that weaker sedimentary layers exhibit greater displacement and deformation, while stronger, more compacted layers resist movement but experience internal stress accumulation. This contrast in material strength plays a significant role in the formation of thrust faults, shear bands, and progressive failure patterns, which are critical factors in geotechnical stability. The experimental methodology, involving incremental 5% loading stages, effectively replicated natural tectonic deformation processes. The results indicate that as compressive stress increases, thrust faulting and shear failure propagate, particularly within weak clay-rich layers. The transparent observation window allowed for direct visualization of deformation, confirming that stress redistribution and fault propagation follow predictable trends based on material composition and compaction levels. These findings align with real-world geological behaviors, particularly in tectonically active regions, where sedimentary formations undergo continuous stress accumulation and displacement. From a geotechnical perspective, this research highlights the importance of understanding in-situ stress fields and deformation trends in the design and maintenance of infrastructure such as tunnels, slopes, and road networks. Without proper consideration of these factors, engineering projects may be vulnerable to unexpected deformations, slope failures, or structural instability. The study also reinforces the need for advanced numerical modeling and real-world stress monitoring to complement laboratory findings. Ultimately, this research provides valuable insights for geotechnical engineering, hazard assessment, and infrastructure resilience, emphasizing the necessity of incorporating tectonic loading effects into design strategies. By improving our understanding of lateral stress-induced deformations, we can develop more effective, durable, and safe construction practices in geologically dynamic environments.

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AUTHORS' CONTRIBUTIONS

Zahra Ghaderpour conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Mohammadreza Narouei performed experiments, conceptual guidance, and critical revision of the manuscript, overall project administration and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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