ISSN 2616-5767 Vol.6, Issue 12: 31-38, DOI: 10.25236/AJETS.2023.061205

Discrete Element Simulation of the Influence of Basin Slope Zone Morphology on the Development of Secondary Faults during Extensional Movements

Zheng Jinbin[1,2]

[1]*School of Earth Sciences and Engineering, Xi'an Shiyou University, Xi'an, China*
[2]*Shaanxi Key Laboratory of Petroleum Accumulation Geology, Xi'an Shiyou University, Xi'an, China*
wdcbjz666@163.com

Abstract: *The slope belts are widely distributed, and basin slope belts play a crucial role in studying the geological movements, tectonic evolution, and fracture combinations within basins. The investigation of the morphology of basin slope belts contributes to a better understanding of the structural characteristics and geological features within basins. This paper employs the Discrete Element Method (DEM) numerical simulation to study the influence of different morphologies of basin slope belts on the development of secondary faults during extensional movements. Simulation results indicate: During the extension process, secondary faults tend to develop in the hanging wall strata controlled by the basin slope belt and above the location where the slope of the basin slope belt changes. Under the influence of shovel-shaped slope belts, the developed secondary faults exhibit different orientations. In contrast, under the influence of ramp-flat slope belts, the developed secondary faults mostly share the same orientation. Ultimately, the comparison of the discrete element simulation results with the east-west profiles of the Xinzhen structure in the Dongying Depression adds practical significance to the simulation.*

Keywords: *Discrete Element Simulation; Fault; Extensional Movement; Basin Slope Zone*

1. Introduction

Slope structures are considered crucial tectonic units in oil and gas basins, situated between uplifts and depressions. They typically form the primary zones of sediment accumulation along the basin margins and within the basin interior. Slope belts are categorized into two types based on the predominant fracture shapes: shovel-shaped slope belts and ramp-flat slope belts. Shovel-shaped slope belts feature primarily shovel-shaped faults, which are faults with curved surfaces. Ramp-flat slope belts have ramp-flat faults as the main fractures, exhibiting steep slopes and flat platforms, generally forming a structure of steep slope-terraced land-steep slope. Due to variations in the steepness of the slopes and the length and inclination of the terraced lands, various sub-forms of ramp-flat slope belts exist in nature.

The Discrete Element Method (DEM) was first proposed by Cundall and Strack in the 1970s. Initially developed to simulate the motion and interactions of particles in rocks and soil, DEM has primarily been utilized in the fields of geology, civil engineering, and mining engineering research. The Discrete Element Method (DEM) has been widely applied in the study of structural geology, including research on phenomena such as jointing and fracturing of rock blocks, faults and fault-related folding, as well as the evolutionary processes of compressional and thrust structures.[1,2,3,4,5]

This paper employs the PFC2D granular flow numerical simulation software from Itasca, based on the principles of the Discrete Element Method (DEM), to construct a two-dimensional discrete element model. The focus of the simulation is on investigating various forms of basin slope belts. The study is concentrated on the development and evolutionary characteristics of fracture systems during extensional deformation in a single period and direction. This aims to reveal the influence of different forms of basin slope belts on the development of secondary faults. The findings provide valuable insights for a deeper understanding of the effects of diverse basin slope belt forms and their impact on the accumulation and storage of oil and gas.

ISSN 2616-5767 Vol.6, Issue 12: 31-38, DOI: 10.25236/AJETS.2023.061205

2. The principles of DEM

The theoretical foundation and methodology of Discrete Element Method draw inspiration from molecular dynamics and serve as a numerical simulation approach for addressing problems in discontinuous media. DEM is based on the following fundamental principles and concepts:

2.1. Particle model

DEM treats particles or assemblies of particles as discrete entities. Each particle possesses its own mass, position, velocity, shape, and interaction rules. These particles simulate the behavior of materials by moving and interacting in space.

2.2. Time step

DEM utilizes time steps to simulate the movement of particle systems. In each time step, DEM updates the positions and velocities of particles to reflect their motion and interactions. Typically, this process involves applying Newton's second law to calculate the particles' movement.

In DEM simulations, time is divided into discrete time steps, meaning that the simulation system undergoes updates and calculations at each time step. The foundation of DEM simulations is Newton's second law, which states that the motion of particles can be predicted by calculating the forces acting on them and considering their mass. Within each time step, DEM employs Newton's second law to compute changes in the positions and velocities of particles. The calculation of these forces within each time step is typically based on the positions, velocities, and interaction models of the particles.

Based on the calculated forces and Newton's second law, the DEM simulation updates the velocity and position of each particle. The position update is achieved by multiplying the velocity by the time step.

2.3. Collision detection and response

DEM employs collision detection algorithms to determine whether collisions occur between particles. Once a collision is detected, DEM also needs to calculate the response to the collision, including changes in velocity, transmission of forces, and potential particle splitting or merging.

2.4. Forces and Interactions

Discrete Element Method considers various forces and interactions, such as gravity, elastic forces, friction, etc. These forces have an impact on the motion and interactions of particles.

3. Model Establishment

This experiment primarily investigates the impact of different forms of basin slope belts on the development of secondary faults under the influence of extensional forces in a single direction. To achieve this, two sets of basin slope belts with shovel-shaped and ramp-flat forms were established. Discrete element particle simulation was employed for modeling the stratigraphy, with rigid walls serving as boundaries for the basin slope belts, bottom, and sides. The active wall at the bottom simulated a pre-existing basement detachment structure.

3.1. Model One

Model One (Figure. 1) has a vertical height of 100m, a length of 500m, and an active base of 300m. The model (Figure. 2) is set with a gravitational acceleration of 9.8N/kg. The bottom active base and the right basin slope belt are both rigid walls. The basin slope belt in Model One has a high degree of inclination, making it steep. Rigid circular particles with a density of 2600kg/m^3 and a radius ranging from 0.8m to 1.2m fill the experimental model to simulate the main stratum. The experimental model is divided into 8 layers, each with a thickness of 12.5m, distinguished by different colors to facilitate the observation of fault development during the experiment. The rigid active base at the bottom, with a length of 300m, extends unilaterally from left to right while the left vertical wall simultaneously extends to the left. The extension speed is 0.2m/s, and the extension distance is 100m.

ISSN 2616-5767 Vol.6, Issue 12: 31-38, DOI: 10.25236/AJETS.2023.061205

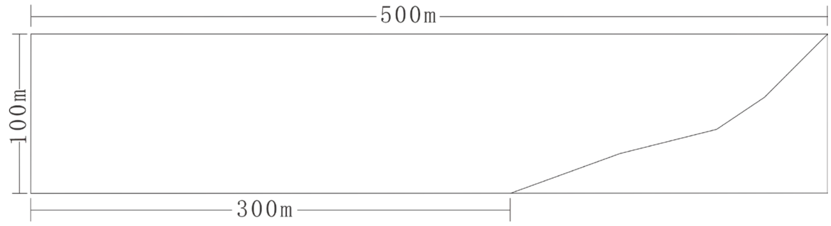

Figure 1: Diagram of model one.

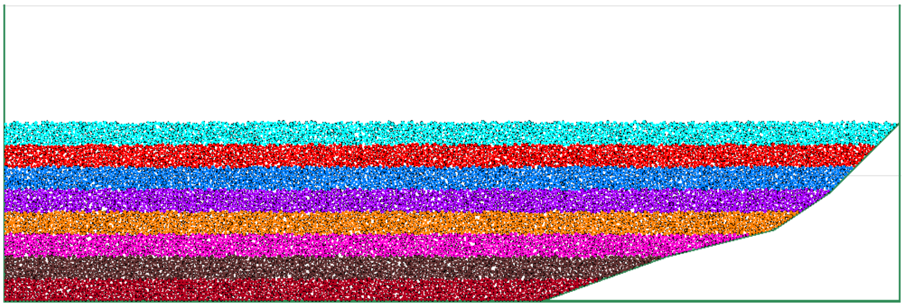

Figure 2: Model one.

3.2. Model Two

All numerical values for Model Two (Figure. 3) are the same as those for Model One, with the only difference being the different form of the basin slope belt. In Model Two, the basin slope belt takes the form of a ramp-flat slope belt. The model (Figure. 4) undergoes unilateral extension to the left, simultaneously with the bottom active base and the left wall, with extension speed and distance consistent with Model One.

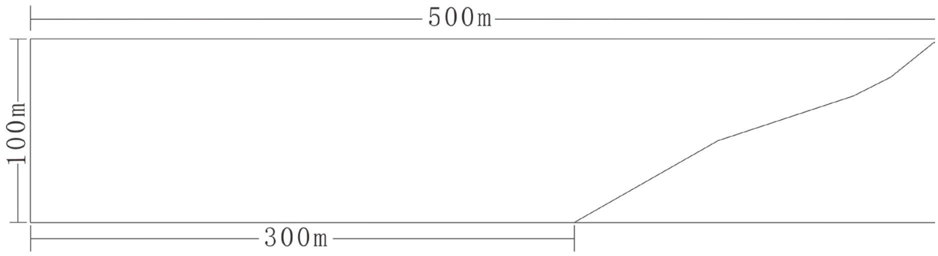

Figure 3: Diagram of model two.

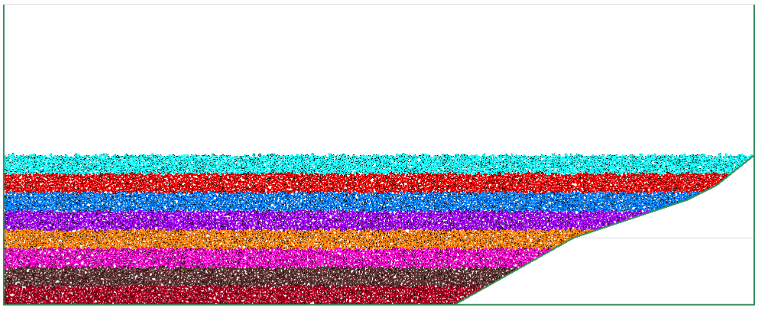

Figure 4: Model two.

3.3. Model Parameters

Based on previous research results and relevant literature, it is evident that there are differences between the model parameters of the DEM and the discrete element simulation software PFC and the macroscopic mechanical parameters of actual rock mechanics. DEM models are typically based on idealized disk shapes, whereas actual rock particles may have more complex structures and shapes. The DEM model is defined at the microscopic scale, while actual rock mechanics parameters are determined at the macroscopic scale. Microscopic mechanical parameters of the model and macroscopic rock mechanics parameters are convertible. By simulating a triaxial compression experiment with the microscopic mechanical parameters of the DEM model to obtain rock mechanics parameters, comparing them with the actual macroscopic rock mechanics parameters, and adjusting through repeated experiments, when the simulation results match the actual macroscopic rock mechanics parameters, the obtained microscopic mechanical parameters of the DEM can be used in the model. In this study, the microscopic mechanical parameters are set as follows: the elastic modulus of the stratum particles is set to 1×10^8 Pa, the ratio of normal to tangential stiffness of the particles is 1.5, the normal bonding strength is 3×10^6 N, the tangential bonding strength is 3×10^5 N, and the friction coefficient between model particles is 1 (equivalent to an overall friction coefficient of 0.57 for the model, i.e., an internal friction angle of 30°).

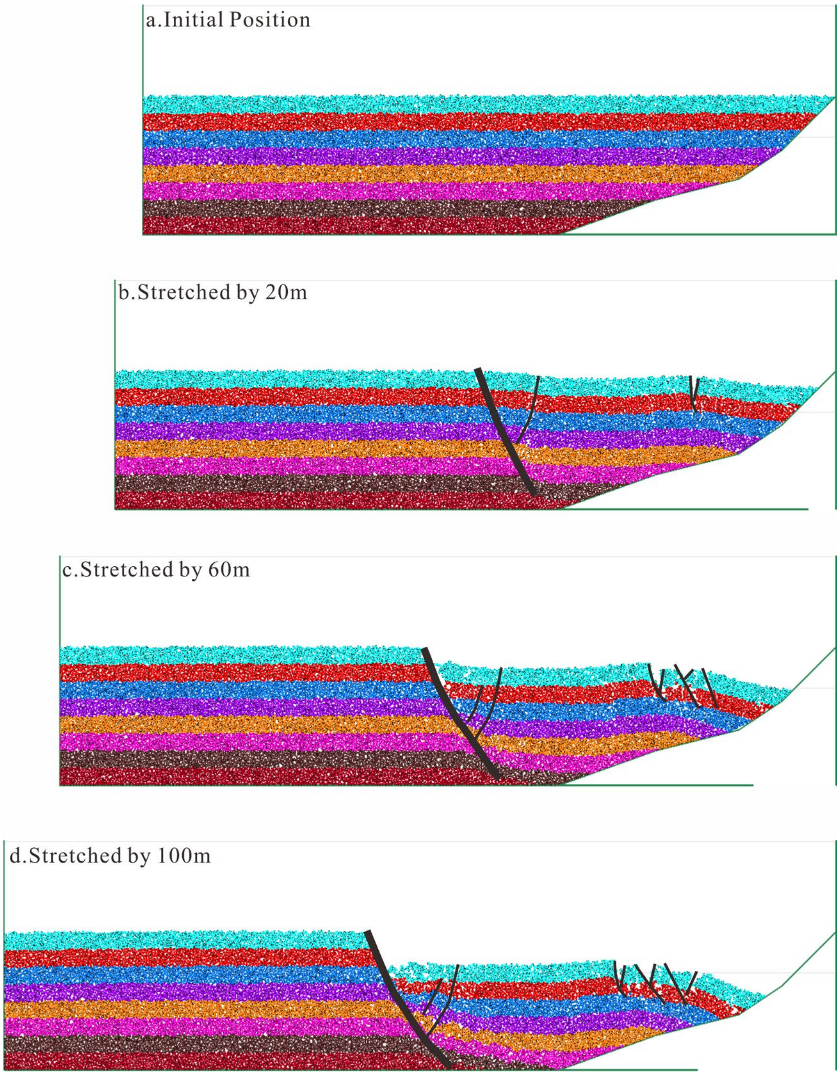

Figure 5: Experimental results for model one.

4. Simulation Results

The focus of this simulation is to study the impact of basin slope belts on the formation and evolutionary development of secondary faults during extensional deformation.

4.1. Experimental results for model one.

The model starts extension from its initial position (Figure. 5a), with the active base and the left boundary wall extending uniformly from right to left at a speed of 0.2 m/s. This drives the layers above the base to undergo unidirectional extension, resulting in corresponding deformation. In the early stage of extension, when the extension reaches 20 meters (Figure. 5b), two fracture faults develop in the layers above the basin slope belt, forming an anti-"Y"-shaped fault system. On the left side of the basin slope belt, a smaller secondary fault develops with a similar orientation to the basin slope belt, and on its left side, a larger fault develops with an opposite orientation to the pre-set basin slope belt, forming an anti-"Y"-shaped fault system. When the model extends to 60 meters (Figure. 5c), the number of fractures in the layers above the basin slope belt increases, and their orientations are mostly different. The pre-set larger fault on the left side of the basin slope belt combines with the basin slope belt to form a graben. As the model extends to 100 meters (Figure. 5d), the layers above the basin slope belt continue to develop secondary faults with different orientations, forming an anti-"Y"-shaped fault system in pairs. The collapse of the graben formed by the large fault on the left side and the pre-set basin slope belt deepens. In the experiment of Model One, the developed faults mostly have different orientations.

4.2. Experimental results for model two.

The model starts extending from its initial position (Figure. 6a), with the active base and the left boundary wall extending uniformly from right to left at a speed of 0.2 m/s. This drives the layers above the base to undergo unidirectional extension. When the model extends to 20 meters (Figure. 6b), a secondary fault develops in the layers above the basin slope belt with an orientation similar to that of the basin slope belt. On the left side, a larger normal fault develops with an orientation opposite to the pre-set basin slope belt. When the model extends to 60 meters (Figure. 6c), the graben is formed by the collapsing left normal fault and the pre-set basin slope belt. The layers above the basin slope belt develop new faults with mostly the same orientation. As the model extends to 100 meters (Figure. 6d), the collapse of the graben formed by the left normal fault and the pre-set basin slope belt deepens. New faults with the same orientation develop in the layers above the graben.

In summary, in the experiments of Model One and Model Two, both experiments developed a larger normal fault on the left side of the pre-set basin slope belt, and this normal fault combined with the pre-set basin slope belt to form a graben. In both experiments, during the early stage of extension, when extended by 20 meters, sporadic secondary faults developed in the layers above the pre-set basin slope belt where the slope changed. In the experiment of Model One, influenced by the pre-set basin slope belt as a shovel-shaped slope belt, the developed faults had mostly different orientations. Conversely, in the experiment of Model Two, where the pre-set basin slope belt was a ramp-flat slope belt, most of the faults developed during the extension had the same orientation.

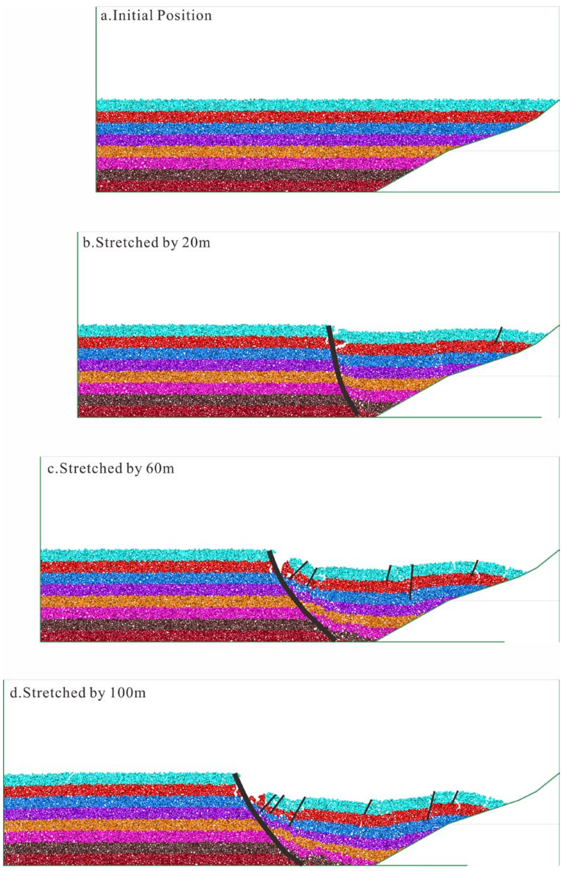

Figure 6: Experimental results for model two.

ISSN 2616-5767 Vol.6, Issue 12: 31-38, DOI: 10.25236/AJETS.2023.061205

5. Discussion

The Dongying Depression is a Mesozoic and Cenozoic fault depression within the Jiyang Depression of the Bohai Bay Basin. The Xinzhen Structural Zone is located in the eastern part of the central uplift of the Dongying Depression. It is an asymmetric and elongated anticline oriented approximately east-west, covering an area of about 50 square kilometers. Its northern boundary adjoins the Minfeng Depression, and its southern part is close to the Niuzhuang Depression.

The Chennan Fault (Figure. 7, F1) is the main controlling fault of the Xinzhen structure, taking the form of a basin slope belt. Influenced by the morphology and activity of the Chennan Fault, the Xinzhen structural area has developed multiple secondary faults with varying combinations. The Chennan Fault exhibits different forms in the east-west segments of the Xinzhen structural zone. In the eastern part of the Xinzhen structure, the Chennan Fault is a ramp-flat fault, while in the western part, it takes the form of a listric fault. This makes it an ideal location for studying the influence of different forms of basin slope belts on the development of secondary faults.

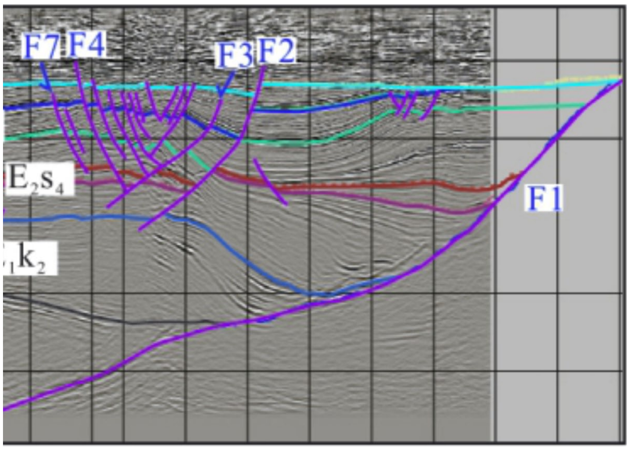

Figure 7: Cross-section A-A' of the Xinzhen structural zone in the western segment.[6]

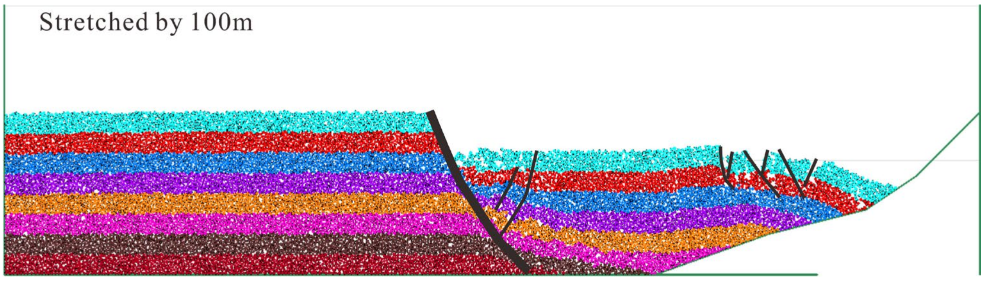

Figure 8: Extension of model one to 100 meters.

The experimental model of Model One (Figure. 8) has a pre-set basin slope belt, and its morphology is similar to the main controlling fault, the Chennan Fault, in the western segment of the Xinzhen structural zone.

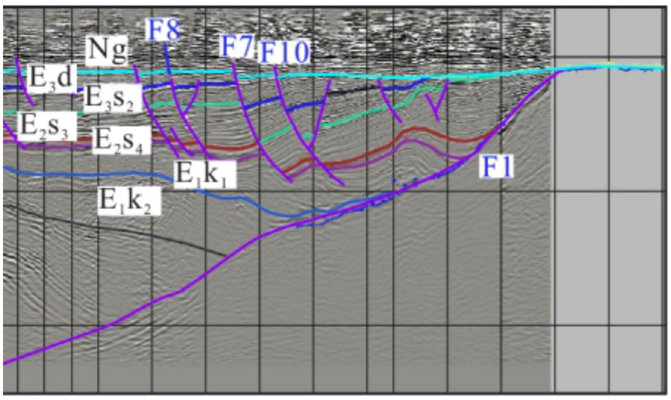

Figure 9: Cross-section C-C' of the Xinzhen structural zone in the eastern segment. [6]

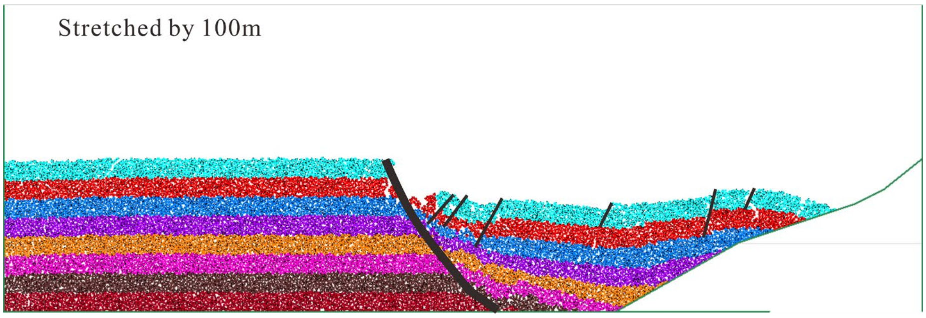

Figure 10: Extension of model two to 100 meters.

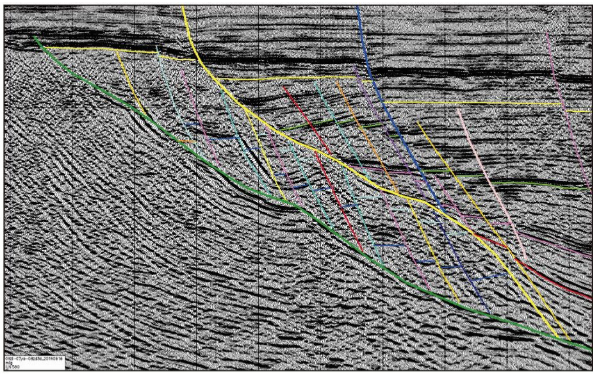

Figure 11: The Zhenwu fault zone in the Gaoyou depression.[7]

The main controlling fault, Chen Nan Fault (Figure. 9), in the eastern segment of the Xinzhen tectonic zone shares a similar morphology with the assumed slope belt in Model 2 experimental setup (Figure. 10). The simulated results reveal consistent trends in the development of secondary faults. This similarity is also observed in the Zhenwu Fault Zone of the Gaoyou Depression (Figure. 11), where a slope belt with ramp-flat slope morphology exists, leading to the development of secondary faults with similar orientations.

This study utilized the DEM numerical simulation to simulate the influence of different morphologies of basin slope belts on the development of secondary faults during extension. The numerical simulation results demonstrate that the various forms of basin slope belts have a significant impact on the development and orientation of secondary faults during large-scale extensional movements.

6. Conclusions

Influenced by the pre-set basin slope belt, during the experimental extension process, secondary faults mostly developed in the hanging wall strata controlled by the basin slope belt and above the location where the slope of the basin slope belt changed. Under the influence of the shovel-shaped basin slope belt, the secondary faults developed during the extension process exhibit different orientations. Conversely, under the influence of the ramp-flat basin slope belt, the developed secondary faults mostly share the same orientation.

References

[1] Zhao, C., HOBBS, B., E., ROBERT, P., A, & HORNBY, et al. (2007). Phenomenological modelling of crack generation in brittle crustal rocks using the particle simulation method – science direct. Journal of Structural Geology, 29(6), 1034-1048.
[2] Strayer, L. M., & Suppe, J. (2002). Out-of-plane motion of a thrust sheet during along-strike propagation of a thrust ramp: a distinct-element approach. , 24(4), 637-650.
[3] Strayer, L. M., Erickson, S. G., & Suppe, J. (2004). Influence of Growth Strata on the Evolution of Fault-related Folds— Distinct-element Models.
[4] Hughes, A. N., Benesh, N. P., & Shaw, J. H. (2014). Factors that control the development of fault-bend versus fault-propagation folds: insights from mechanical models based on the discrete element method (dem). Journal of Structural Geology, 68, 121-141.

ISSN 2616-5767 Vol.6, Issue 12: 31-38, DOI: 10.25236/AJETS.2023.061205

[5] Zhang, J., Morgan, J. K., Gray, G. G., Harkins, N. W., Sanz, P. F., & Chikichev, I. (2013). Comparative FEM and DEM modeling of basement-involved thrust structures, with application to Sheep Mountain, Greybull area, Wyoming. Tectonophysics, 608, 408-417.

[6] Wang, Z. Y., Chen, S. P., Wu, G., Cao, M. L., Xue, B., & Zhao, H. B. (2021). Main controlling factors of the faults development in Xinzhen Structure and its adjacent area of Dongying Sag and their reservior controlling effects. Petroleum Geology & Oilfield Development in Daqing, (02), 42-49.

[7] Qiu, X. M., Chen, W., Li, H. Y., & Duan, H. L. (2023). Strike-slip structures and hydrocarbon accumulation in complex fault blocks in Subei Basin. Petroleum Geology & Experiment, (03), 393-401.