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Progressive failure analysis of soil slopes considering the influences of humidity and loading

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To analyze the progressive failure of structural loess slopes due to changes in humidity and loading, this study analyzes the degrees of influence of these changes on slope failure and their relationships with various structural parameters. According to the analysis, the shear failure of the soil gradually develops with the change of the water content. When the water content reaches a 17%, with the development of shear deformation, the shear zone is formed and finally penetrates the soil body. With the increase of the water content, the total displacement of the slope body gradually develops. When the water content reaches 17%, the total displacement of the slope body changes suddenly. This mutation is consistent with the formation of the shear zone. The sudden change of displacement indicates the penetration of the shear zone and the damage and slippage of the slope. With the increase of the soil moisture of the slope, the strain localization phenomenon occurs, the development of strain localization and shear bands increases, the structural damage increases, and the quantitative structural parameters decrease. The quantitative parameters can therefore be used to evaluate the feasibility and rationality of the progressive failure process of homogeneous structural loess slopes.

KEYWORDS

progressive failure, influence of humidity and load, structural loess, slope, structural parameters

1 Introduction

During infrastructure construction in loess regions, numerous loess foundation and slope engineering problems will inevitably be encountered. The concept of slope progressive failure was first proposed by Terzaghi (1936), who believed that slope failure was caused by the strain softening of the soil mass. Skempton (1964) used the slope progressive failure theory to analyze the stability of a slope, and found that the shear strength of the soil at different positions of the over consolidated cohesive soil slope was asynchronous. According to the concept of progressive failure, the strength of the soil mass does not affect the entire sliding surface simultaneously; only when the shear stress

increases at a certain point and exceeds the soil strength does shear failure occur. With the development of soil deformation, shear failure gradually transfers to adjacent elements, and the asymptotic failure surface gradually expands. Finally, when the sliding thrust of the entire soil mass exceeds the shear strength of the soil screen, the entire slope slides (Lo and Lee, 1973; Troncone, 2005; Conte, 2010). Via research on the shear strength of clay materials, Lu (1986) found that for a slope body composed of strain-softening materials, the shear strength of the local soil on the sliding surface decreases from the peak strength to the residual strength during soil failure. Liu and Wang (1994) proposed an asymptotic failure analysis model of an infinite-plane slope via slope stability analysis. While the analytical model can simulate the asymptotic failure process of the slope very well, the simulation can only be applied to bedding landslides with a planar slope fracture surface. Tan et al. (2000) simulated the process of slope failure from the toe and top of the slope to the middle via a physical similarity model that considered the proportions of fine sand, gypsum, mica powder, and engine oil. Cheng et al. (2000) established a corresponding slope finite element model by introducing the viscoelastic-plastic constitutive relationship, and analyzed the progressive failure of a rock mass with a high slope. Wang (2000) used a new contact element model to simulate the contact friction state on the sliding surface, and carried out the progressive failure process and stability analysis of the slope. Through examples, it was demonstrated that the stability coefficient of the slope while considering progressive failure was 5–10% less than that without the consideration of progressive failure. Zhang and Zhang (2007), Lu et al. (2021), Lu et al. (2022), Xue et al. (2016), and Shen et al. (2016) also analyzed progressive failure according to the characteristics of the soil strain-softening stage.

Loess is a typical structural soil. Due to the existence of the structure, when the initial structural strength is high, the stress-strain relationship curve of the soil usually presents a softened or weakly softened curve. Before the peak value of the softened stress-strain relationship curve, the shear strength gradually develops with the increase of shear strain. After the peak value occurs, the soil structure is gradually destroyed and the shear strain develops. Finally, the regional stability value of the soil strength is the residual strength. Therefore, the sliding failure of loess slopes is a typical asymptotic failure mode.

There have been many theoretical studies on slope progressive failure. However, for loess, a special soil with a strong structure, the gradual failure analysis theory considering the coupling effect of humidification and overload has not been studied. Under the coupling effect of slope overload and possible wetting, the strength and deformation of yellow soil change with the attenuation of the structure. In the present work, reference is made to the structural constitutive models of humidity and loading (Luo et al., 2015a; Luo et al., 2015b; Luo et al., 2016; Luo and Fang, 2018) established based on the understanding of the mechanism of the structural strength and deformation change of loess. By considering the structural evolution and change law of loess slopes under the conditions of overloading and humidification, the distribution laws of the structural parameters and the slip band in the distribution of structural loss are revealed. The stability analysis of loess slopes provides a theoretical basis for

reasonable reinforcement measures. Guiding the construction of infrastructure in loess areas and the exploration of a more practical method for the study of the soil structure are of great significance.

2 Moisture distribution and permeability of loess

2.1 Moisture distribution of loess

The existing structural state of natural loess was formed in semi-arid climates and aeolian sediment environments after a long period of geological deposition. The structural connection of loess reflects comprehensive external and internal influences throughout the entire historical formation process. Furthermore, the existing structural state determines the possible change tendency of the loess structure under a new external environment. The structure of loess is composed of structural units, cements, and pores. Due to the unique geological environmental conditions, loess particles are mainly coarse powder accompanied by some large sand particles. Coarse silt is the main skeleton of loess, and fine silt, clay, and detritus are attached to the surface of sandy soil grains. Together with the solution formed by soluble salt and deposited at the contact point of the grains, they form a cementation connection, which strengthens the structural characteristics of loess. Skeleton particles are an important pillar of the loess structural system, and their morphology represents the force transfer performance and deformation properties of loess under external loads. Their connection forms directly affect the structural strength of the loess itself, and their arrangement directly determines the stability of the entire structural system under external loads.

The structural strength of the structural soil largely depends on the composition and corresponding properties of the intergranular cement. For loess, a special structural soil, the main components of intergranular cement are clay minerals and intergranular calcium carbonate. Due to the special activity of finely dispersed clay minerals and their large specific surface area, they more easily aggregate or adsorb on the surface of larger skeleton particles. This is more conducive to the formation of aggregate particles and clay films in loess, which form a special structural system with different structural strengths as the water content changes. These aggregates mainly include non-water-stable aggregates, water-stable aggregates, water-resistant aggregates, and highly-water-resistant aggregates. The main reason for the structural damage change of loess is the existence of a large number of non-water-stable aggregates, which are formed by the cementation of soluble salt and reversible dry adhesive film, and are destroyed when they encounter water; this is also one of the main reasons for the strong water sensitivity of structural loess.

Therefore, the soil humidity is an important indicator of the engineering properties of loess, and its change has serious impacts. Changes in humidity are mainly due to the rise and fall of the groundwater level and absorption and evaporation caused by rainfall. Generally, loess has a very low natural water content. The natural water content of loess on the tableland and beam where the groundwater is deeply buried usually varies from 6% to 10%, and that of loess on a plain terrace varies from 11% to 21% due to groundwater with a

shallow buried depth and high level. In addition, due to the influence of the climate, the moisture content of surface loess varies greatly with the season. In the stratum and buried depth of loess, the change of the moisture content as a humidity indicator will inevitably affect the changes of the compressibility, collapsibility, and shear strength indicators of loess, and will further affect the stability of the loess project site and region. The research of Wang (2008) revealed that under the same slope conditions, the moisture content of a shady slope is higher than that of a sunny slope, but the difference is relatively small after a certain depth range. Moreover, with the increase of the slope of the loess plateau, the water content of the corresponding layers in the soil slope decreases. Furthermore, the seepage generated during rainfall increases with the decrease of the slope.

2.2 Permeability of loess

The factors affecting the permeability of loess include the properties of the soil particles, the shape and grading of the soil particles, the void ratio, the structure, cracks and bedding, according to the research of Xu (2021), Hong et al. (2019), and Liu et al. (2022, 2023). The extant research is far from meeting the needs of engineering practice. Due to spatial constraints, this study does not consider the permeability law of loess, but only describes the general law of loess permeability, which provides the corresponding humidity field for the application of the compression-shear constitutive model under the condition of soil moisture. Previous studies have shown that there are vertical tubular macropores in Q3 loess, which endows the permeability of loess with obvious anisotropy. The vertical permeability is far greater than the horizontal permeability. When loess is soaked and collapses, due to the loss of the structure, the permeability in both directions gradually becomes similar. There is no obvious relationship between the permeability coefficient and the void ratio of loess in the natural state. For loess after disturbance and compaction, the permeability coefficient decreases with the decrease of the void ratio due to the elimination of uneven large pores in the loess. The permeability of Q3 loess is related to its particle composition and structural characteristics, and the permeability of loess in the contact state of coarse particles and overhead is large. During the collapse development of loess, due to the change of the structural state, the permeability coefficient also changes and gradually decreases. In the natural state, the water content of loess is low, and the soil mass is in a three-phase state. When water begins to permeate loess, the permeability coefficient becomes high, gradually decreases with time, and finally approaches stable seepage.

3 Progressive failure of a homogeneous loess slope under humidification

3.1 Numerical model and calculation parameters

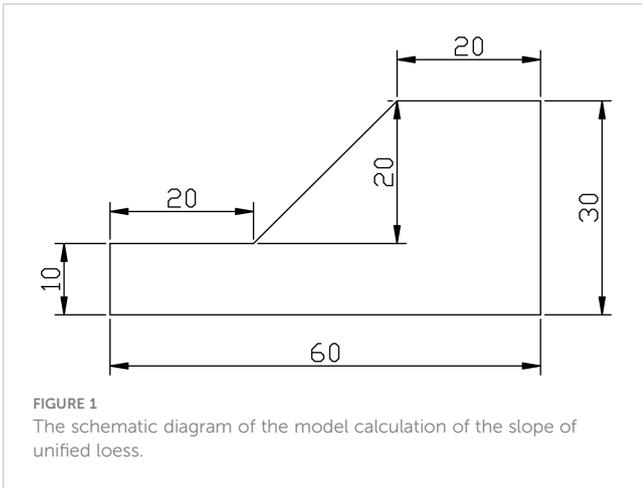
In slope stability analysis, the factors that influence the slope stability mainly focus on two aspects, namely (1) the change of the

stress or structure state of the slope itself, and (2) the change of the external environment of the slope area, such as excavation, rainfall, overload, etc. In fact, the asymptotic failure of the slope is mainly caused by the following two factors and their coupling effects. First, the internal cause of the progressive instability failure of the slope is the destruction of the internal structure of the slope body and the generation of a plastic failure area under stress conditions, such as humidity and load conditions. The residual energy is fully released, which causes the readjustment of the local stress state of the slope. The elastic region around the plastic region then further develops into a plastic region due to the superposition of residual stress. The soil skeleton structure is further destroyed, and the secondary stable structure is further generated. Second, changes of the hydrogeology and boundary environment of the slope result in the reduction of the mechanical properties of the rock and soil mass within a certain range of the slope, and the local area changes from elastic to plastic. Simultaneously, the stress field adjusts and releases energy, which further expands the plastic failure area. This is also the main reason for the gradual failure of the excavated slope.

Considering the analysis purpose of this study, the change of the stress field of loess slopes caused by excavation and the exertion of the structural strength of slope soil are not considered. Only the asymptotic failure and development mechanism of the slope caused by humidity and load stress after excavation, as well as the exertion characteristics of the strength of the slope soil, are analyzed. Figure 1 presents the model of the slope. The three directions at the bottom are fixed displacement boundary conditions. The displacement in the x-direction is respectively fixed in the two boundary directions, and the displacement in the y-direction is fixed at 1 m.

3.2 Analysis of the calculation results

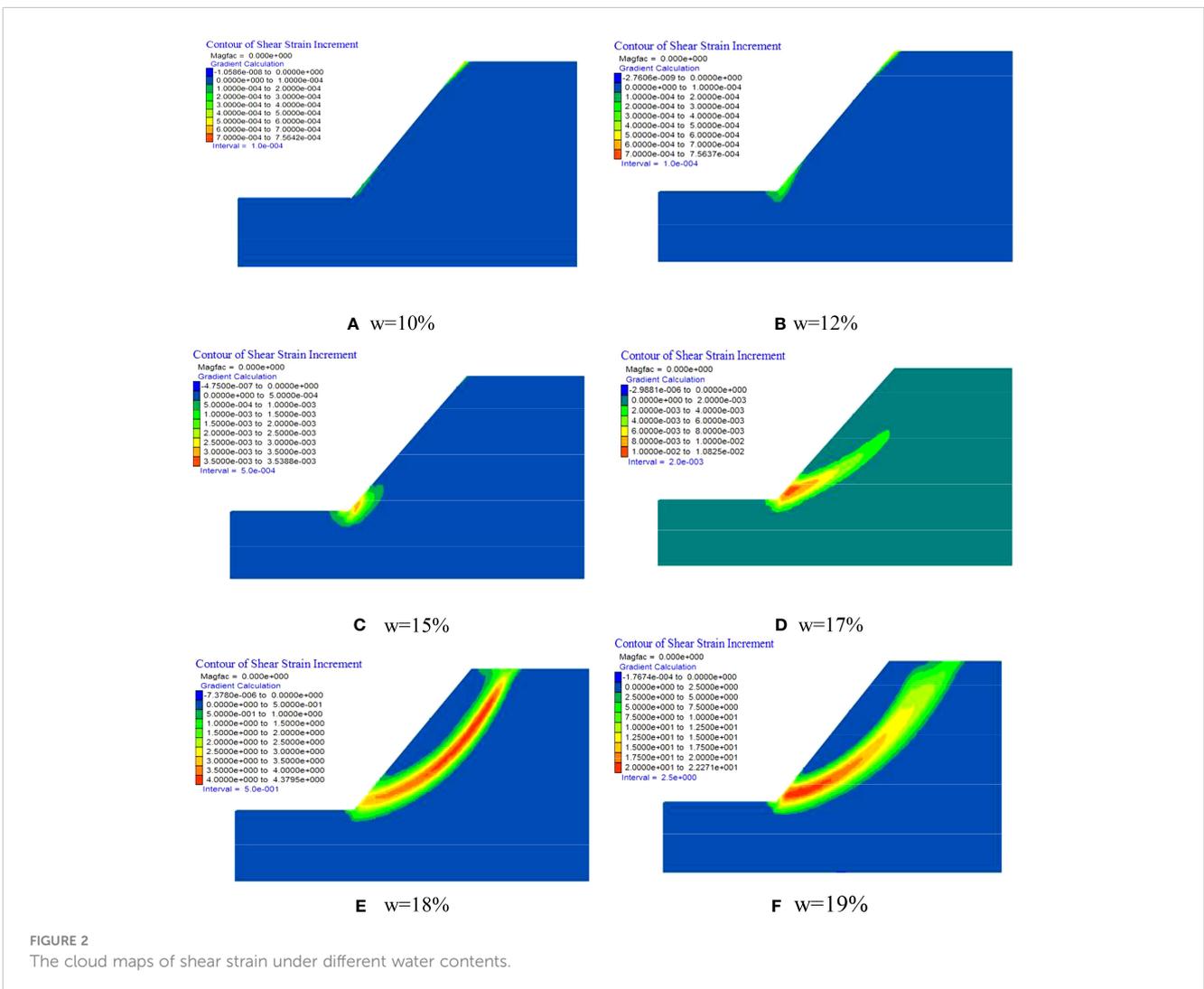
To analyze the gradual destruction of the homogeneous loess slope caused by the humidification process, the stability of the loess slope caused by the change of the humidity field under the self-weight condition was analyzed. The moisture content was changed from 10% to shear band formation. Figures 2 and 3 present the nephograms of the shear strain increment and total displacement during the progressive failure of a homogeneous self-weight loess slope under the humidification condition. With the change of the moisture content, the shear failure of the soil mass gradually develops. When the moisture content reaches 17%, with the development of shear deformation, the shear band is formed and finally connected. In Figure 4, with the increase of the soil moisture content, the total displacement of the slope gradually develops. When the moisture content reaches a certain value, the total displacement of the slope suddenly changes, which is consistent with the formation of the shear band. With the change of the displacement, the shear band is cut through and the slope produces destructive sliding. When the stress of the slope is concentrated to a certain extent due to the change of the humidity field of the slope, the plastic region first appears at the foot of the mean loess slope and becomes the initial failure point. The analysis shows that due to the strain localization phenomenon at the slope toe, there is strong



stress concentration at this point, at which the local stress concentration exceeds the soil strength of the loess. When the structural strength of the material is high, damage begins and develops, and the plastic deformation also develops simultaneously; thus, a plastic failure zone appears inside the slope. The appearance of the local plastic failure area causes the

obvious decrease of the bearing capacity of this area. The stress field of the slope is redistributed, which leads to the destruction of the new primary structure and the generation of a plastic failure area. In this way, during the mutual adjustment and coupling change between the destruction of the primary structure and the generation of the secondary structure, the plastic zone continues to expand until the failure surface and plastic zone are formed. Therefore, it is suggested that the method of “displacement mutation + shear band connection” be used to qualitatively evaluate the stability of loess slopes when determining the slope stability and the position of the slip surface.

Figure 5 presents the evolution process of the structural damage of a homogeneous structural loess slope from near to complete instability. Under certain water content conditions, when the slope is close to the local shear zone, the quantitative structural parameters at the shear band of the slope attenuate relative to other areas of the slope due to the development of shear deformation. Moreover, the attenuation trend of the structural parameters of the stress ratio in the slope is consistent with the development of the shear band caused by the strain localization of the slope. In the past, the strength reduction method was generally used to calculate the safety factor of slope stability in the analysis of progressive slope failure. This method was established based



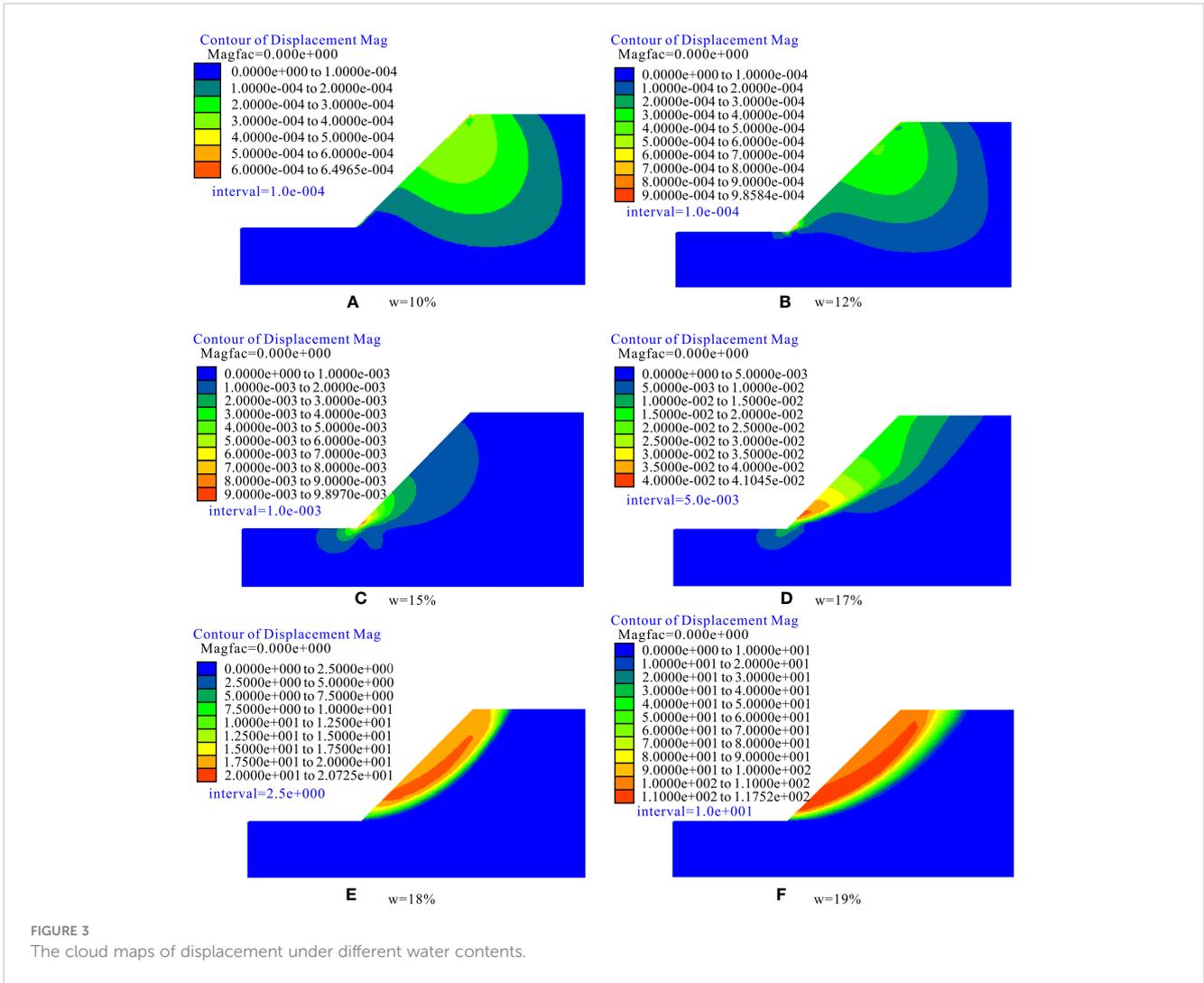


FIGURE 3 The cloud maps of displacement under different water contents.

on the previously mentioned criteria for slope instability. When slope instability occurs, the corresponding reduction factor is specified as the safety factor of the slope. The safety factor defined by this analysis method has no physical significance, nor can its correlation with different soil properties be established. It can be seen that in the stability analysis of homogeneous structural loess slopes, the progressive failure process of the slope is actually the evolution and

development process of structural damage; in other words, the development and change of the quantitative structural parameters of the slope can actually be used as some of the instability criteria for the progressive failure analysis. If it is assumed that the quantitative structural parameters of the slope attenuate to a certain extent during the processes of humidification and loading, the slope can be defined as having suffered from instability and failure. At this time, the quantitative structural parameters corresponding to the local shear zone of the slope are consistent with the safety reserve of the slope, i.e., the stability of the homogeneous structural loess slope can be quantitatively evaluated by the quantitative structural parameters of the slope.

4 Progressive failure of a homogeneous loess slope under loading

A homogeneous structural loess slope with an initial moisture content of 0.15 was selected to investigate the progressive failure process of the slope under loading. The load was increased by 20 kPa per section. After the shear band of the slope appeared, the

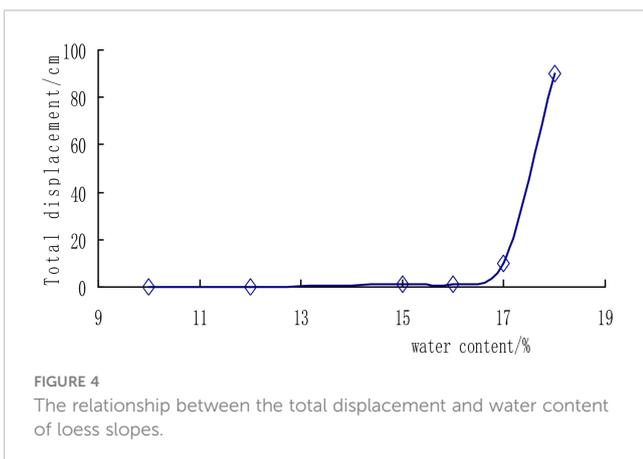


FIGURE 4 The relationship between the total displacement and water content of loess slopes.

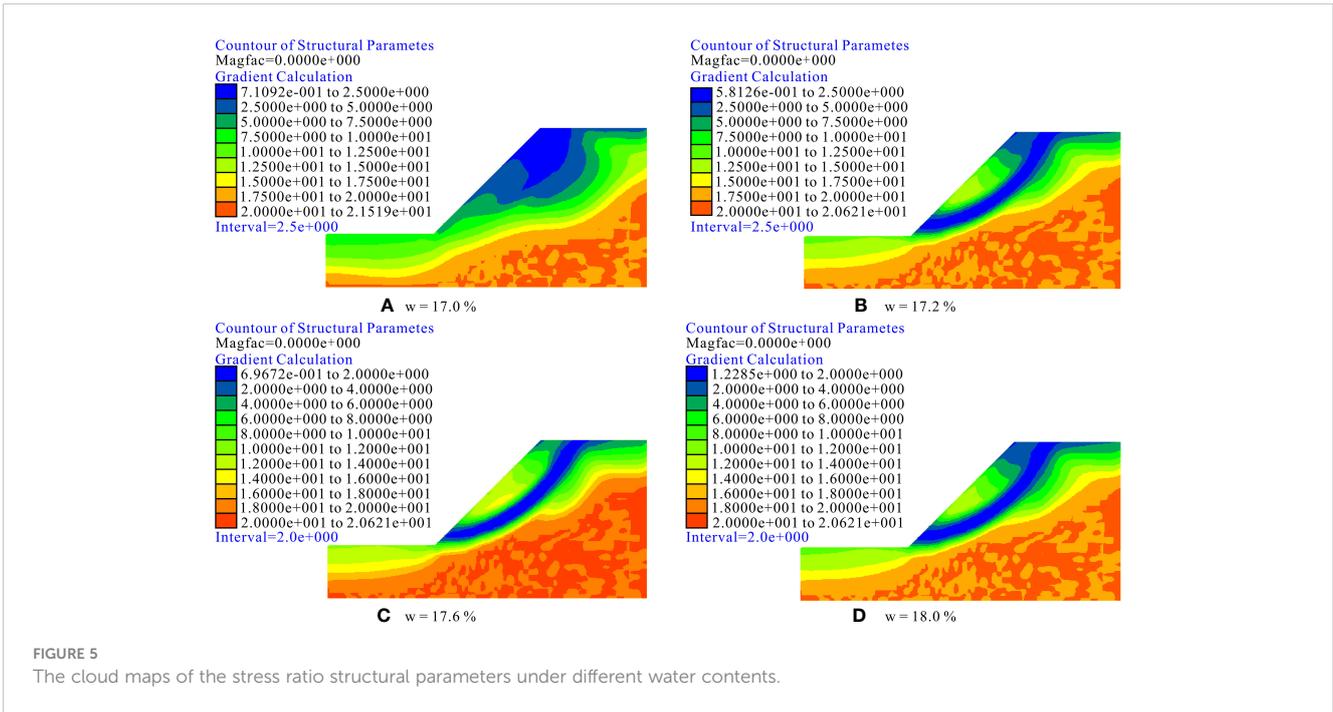


FIGURE 5 The cloud maps of the stress ratio structural parameters under different water contents.

acceleration rate of load application was reduced to investigate the progressive failure evolution process of the slope. The load was uniformly distributed, and the operating distance was 5 m from the slope top.

Figure 6 displays the development and change of the shear strain increment under different top loads under the condition of a 15% water content. The strain increment was found to increase with the increase of the top load of the slope. With the increase of the top

load of the slope to 240 kPa, the shear band begins to appear and develop. With its increase to 244 kPa, a shear band forms and runs through the slope. Different from the gradual failure of slopes caused by humidification, the gradual failure of slopes caused by loading begins from the top of the slope, and when the shear band develops to the bottom of the slope, the slope will lose its stability.

Figure 7 shows the development and change process of the total displacement of the slope under the action of the load on the top of

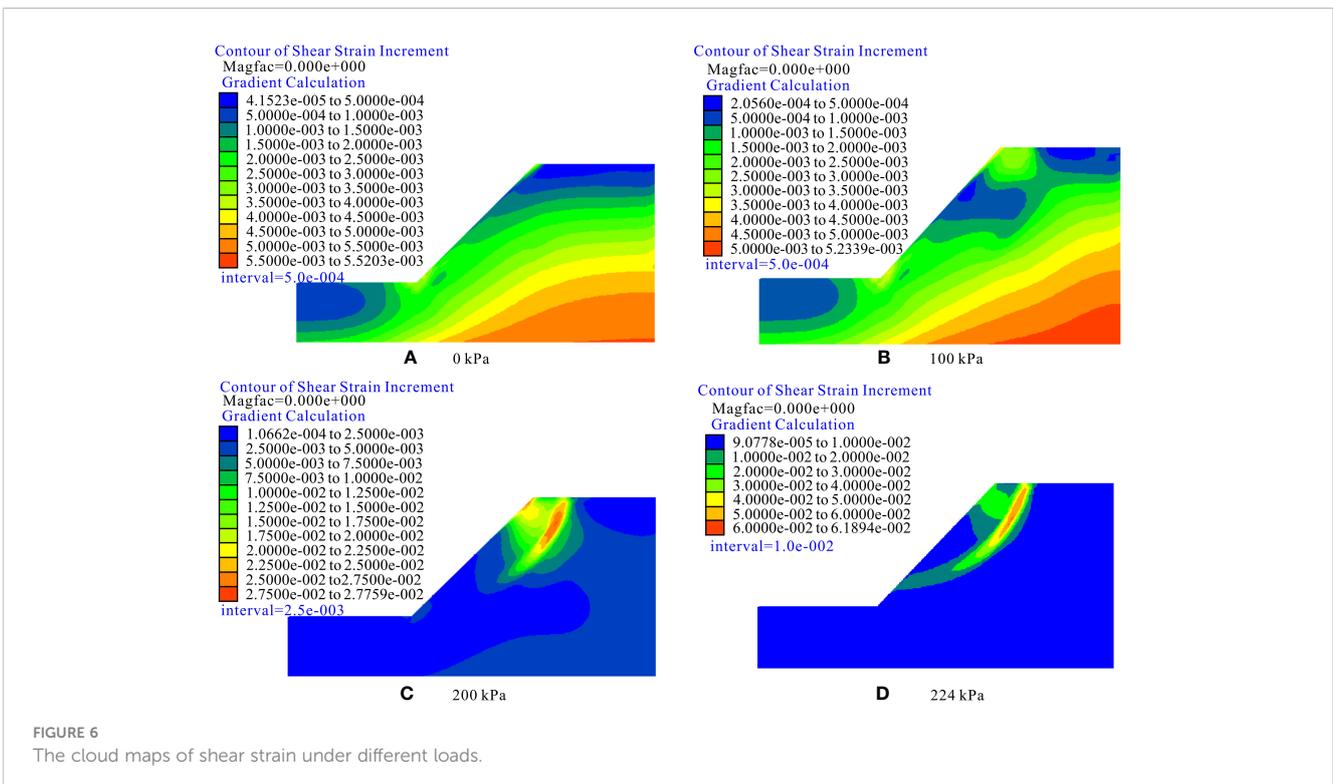


FIGURE 6 The cloud maps of shear strain under different loads.

the slope. The maximum total displacement of the slope was found to first decrease and then increase, and the areas that appear are different before and after the failure. When the load on the top of the slope is low, the total displacement appears at the top of the slope far away from the free surface. When the slope is close to sliding failure, the maximum displacement preferentially moves on the side of the free surface. At this time, the position at which the maximum displacement occurs is consistent with the position on the slope at which sliding instability failure occurs.

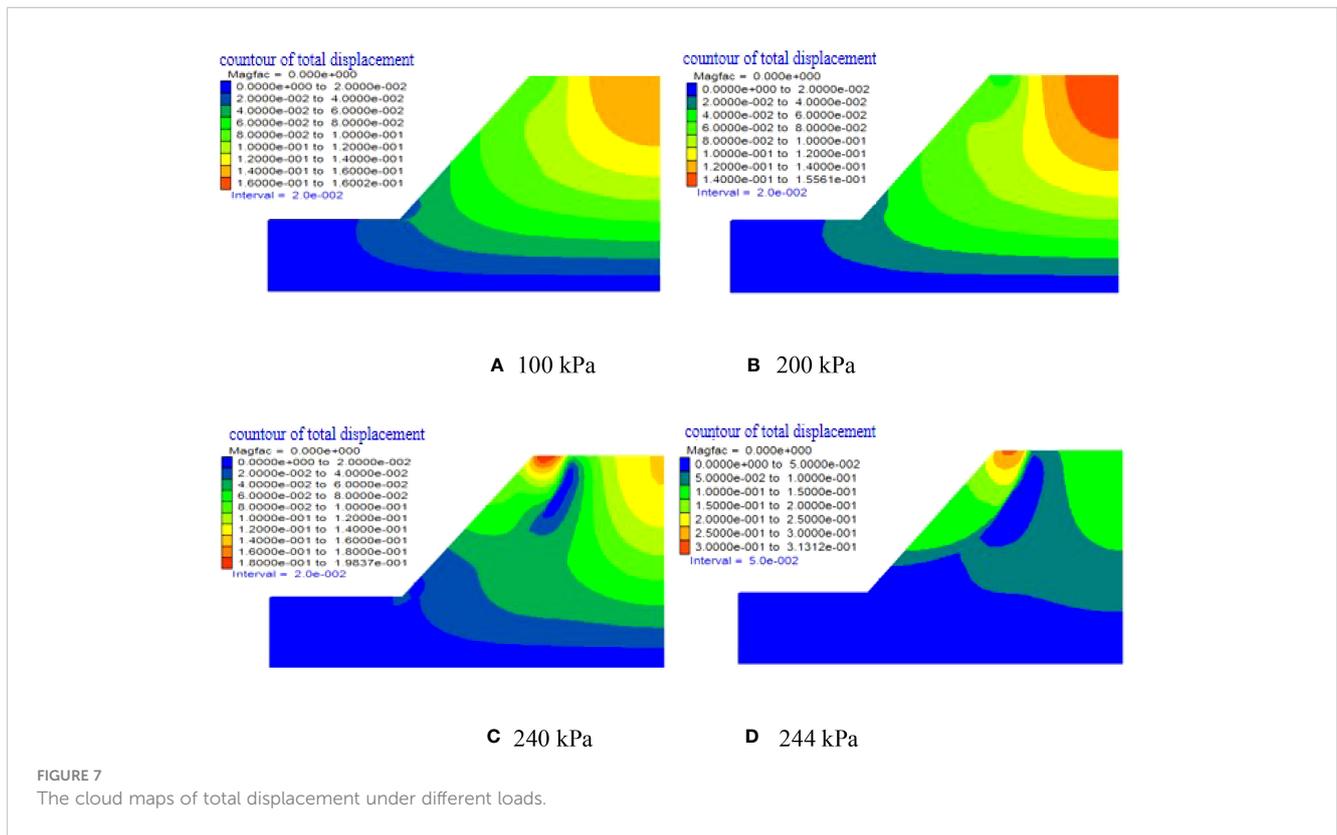
Figure 8 exhibits the cloud maps of the structural parameter changes of the progressive failure of the slope under the action of top loading and a water content of 15%. The change law of the structural parameters was found to be basically consistent with the change law and trend of the shear strain increment of the slope body. After the appearance of the slope shear zone, the structural parameters in the shear zone are close to 1. Different from the humidification model findings, the shear band generated by loading has an obvious zonal feature, i.e., there is a typical slip surface during the sliding process. Under the load on the top of the slope, when the whole slope slides, the top of the slope is partially destroyed.

5 Conclusion

It was found that when the water content is 10%, the maximum load on the top of the slope reaches 500 kPa. At this time, the value of slope failure appears at the top of the slope, and there is no continuity of the slip surface throughout the entire slope. With the

increase of the water content, the load that the slope top can bear decreases correspondingly, and the slope sliding surface begins to move downward. When the water content reaches 15% and the load on the top of the slope reaches 224 kPa, the sliding surface of slope failure begins to penetrate, but it does not pass the toe of the slope. However, with the further increase of the water content, the load on the top of the slope decreases sharply, and the sliding surface of the slope gradually becomes close to the slope toe. When the water content reaches 17.5%, the slope top slips without any load. The following conclusions can be drawn from the findings:

- (1) In previous soil slope stability analysis, it was assumed that the strength of the soil in the assumed sliding surface of the soil slope reaches its peak value simultaneously; in this case, the asymptotic process of slope failure was not considered. The viewpoint that the failure of the slope begins from the slope toe at a certain time and finally develops to the top of the slope to form a slip is one-sided. In theory, the strength of the soil in the slip zone is fully exerted when the slope is subject to sliding failure.
- (2) When the water content is 10%, the attenuation of the structural parameters caused by the top loading of the slope mainly occurs at the top of the slope. Moreover, the attenuation of the structural parameters is mainly caused by loading, which exhibits regional characteristics rather than a zonal distribution during humidification. With the increase of the water content, the attenuation of the structural parameters caused by humidification increases and begins to expand in a band to the slope bottom.



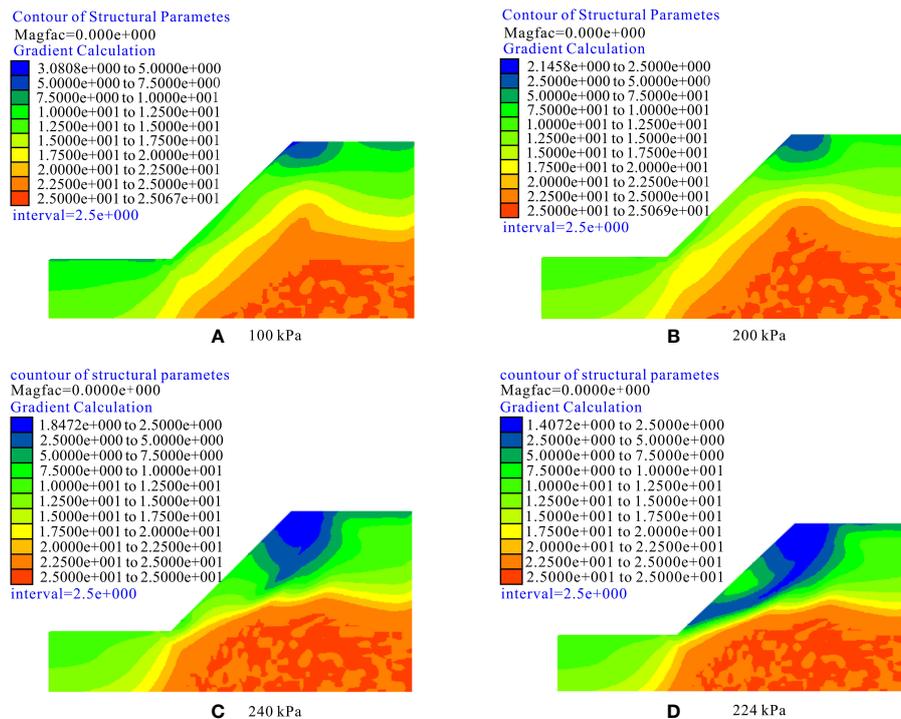


FIGURE 8
The cloud maps of the stress ratio structural parameters under different loads.

- (3) Under the action of humidity and loading, the attenuation of the structural parameters becomes increasingly more obvious, and the attenuation band is the slip band corresponding to the shear strain increment; this also shows that the structural parameters can be used as some of the criteria for the progressive failure of structural loss slopes.
- (4) For the slope investigated in this study, with the increase of the water content of the slope, the load that the slope top can bear was found to decrease gradually, and the load decreased sharply after the water content reached 17%. This phenomenon provides a certain criterion for the relationship between the magnitude of the slope top surcharge and slope stability in engineering construction.

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Conflict of interest

Author SS is employed by Institute of Geotechnical Engineering, Xi'an University of Technology.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JF: Formal Analysis, Writing – review & editing, Writing – original draft. AL: Funding acquisition, Writing – original draft,

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