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Influence of the thermal effect on quasi-static shear characteristics of calcareous soil: an experimental study

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Abstract
In principle, the mechanical properties of soil particles are irreversibly changed after particles are subjected to heating. Accordingly, this study performed ring-shear tests on calcareous sand samples subjected to high temperatures to qualitatively investigate the influence exerted by the degradation of the calcareous sand, caused by the thermal effect, on the large displacement shear characteristics of the samples. The effects of the shear velocity and normal stress on the quasi-static shear behavior of the calcareous sand samples were analyzed. The influence of the thermal effect on the quasi-static shear flow behavior of the samples is primarily reflected in the change in the particle mineral composition, particle hardness, and sample density. These variations result in changes in the shear strength, residual shear stress, macroscopic friction coefficient, and other shear characteristics of the calcareous sand samples. Both the shear velocity and the high temperature affect the fluctuation amplitude of the residual shear stress. The results have great theoretical and practical significance in terms of explaining the instability mechanism of a slope. Moreover, a feasible and effective technique is proposed to investigate the large-displacement shear behavior of soil subjected to the thermal effect exerted by a long-runout landslide.

Keywords: Ring-shear test, Shear characteristics, High temperature, Calcareous soil

Introduction

Landslides can cause enormous loss of life and financial damages. Since the 1960s, many long-runout landslides have occurred worldwide. In general, such landslides are characterized by high-speed movement, wide disaster ranges, and great destructive ability (Tika and Hutchinson 1999; Xu et al. 2017). Therefore, the movement and disaster-inducing mechanism of long-runout landslides have become a focus of researchers worldwide. The physical and chemical changes caused by the thermal effect induced by high-velocity sliding friction are among the main causes of long-runout landslides (Noda et al. 2011; Pinyol et al. 2018). The cause of the thermal effect and its influence on particles of geotechnical materials are of particular interest.

In large-displacement shear behavior, the soil has partial flow characteristics. To enable the accurate prediction and analysis of the kinetic characteristics of the shear behavior of landslides, it is important to explain the dynamic mechanism of long-runout landslides. Multiple field investigations and laboratory experiments on landslides and debris flows have shown that Newtonian and non-Newtonian fluid models, such as the Bingham fluid, pseudoplastic flow, expansion flow, and Coulomb viscous flow, can be used to describe the constitutive behavior of landslide soil (Johnson 1970; Hungr 1995; Uzuoka et al. 1998; Wang 2006; Huang and Dai 2014). However, previous studies did not consider the influence of the thermal effect on the motion state, which is necessary for an accurate description of the dynamic characteristics. Luo et al. (2016) summarized recent

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thermal-hydro-mechanical-coupled physical models of long-runout landslides. Some studies have focused on the friction behavior of the sliding surface, while other studies have focused on establishing thermal-hydro-mechanical-coupled physical models of long-runout landslides by introducing the depth-averaged hydrodynamic theory into the sliding block model. However, the results obtained thus far have not explained the kinetic mechanism of the thermal effect response and an accurate and effective kinetic model has not yet been established. Therefore, considering the thermal effect on the shear characteristics of soil is important to accurately describe the shear mechanism and the characteristics of large-displacement-sheared soil.

Regarding the shear thermal effect, Hu et al. (2018) was the first to obtain field and experimental evidence for the high-temperature thermal decomposition of a long-runout landslide belt and accurately estimated a bottom friction temperature of 790 °C during the high-velocity sliding process in the Jiweishan long-runout landslide. Hu et al. (2019) used a thermogravimetric method to estimate a bottom temperature of 850 °C for the sliding surface of the Daguangbao landslide. Using a ring-shear test, they obtained the microstructural variation after the thermal effect and the variation relationship between the friction coefficient and the shear displacement. Their results revealed that friction between the particles produces a dynamic recrystallization layer and carbon dioxide, which reduces friction. These studies confirmed that the thermal effect between the sliding particles is strongly related to the large displacement and fluidization of long-runout landslides.

Owing to limitations in the design of conventional geotechnical test equipment, the shear failure and mechanical behavior of soil cannot be completely obtained, particularly in studies concerned with the mechanical properties of soil subjected to large-displacement shear. One such limitation is that the shearing surface of conventional direct shear test equipment is not sufficiently long. Therefore, the long-term shear mechanical properties of soil cannot be fully monitored during a test (Hong et al. 2009). The ring-shear test is primarily used to investigate the post-peak stress–strain relationship and the shear stress variation of geotechnical materials with large shear displacement and complex stress. The shear flow behavior of different rocks and soil with large displacement under different conditions has been investigated (Skempton 1985; Kamai 1998; Agung 2004). In the research field of coseismic faults with high-speed friction activity, a rotary-shear high-velocity friction apparatus is used to investigate high-speed friction with large displacement and obtain the mechanical properties of rock under the friction heat produced by high-velocity sliding (Shimamoto et al. 1994; Smith et al. 2013; Ujiie et al. 2013; Ma et al. 2014). Owing to the different characteristics between the rock and the soil, it is difficult to test the soil by carrying out high-velocity friction tests at temperatures of approximately 800 °C. Therefore, other methods have been used to investigate the shear characteristics of soil subjected to high temperatures. In principle, the mechanical properties of soil particles are irreversible after heating. Accordingly, calcareous soil was first subjected to a heat treatment and then ring-shear tests were carried out on the samples. In this way, the influence of the thermal effect on the physical and mechanical properties of the soil can be investigated. Moreover, the influence of this change on the shear characteristics of the soil can also be determined.

Based on previous studies, a ring-shear test was carried out on calcareous sand samples subjected to high temperature using a GCTS ring-shear apparatus to examine the shear characteristics of calcareous sand with large-displacement shear flow. The experimental results have great theoretical and practical significance with respect to explaining the flow mechanism and conducting instability analyses.

Methods and materials

Specimen preparation

To investigate the variation in the large-displacement shear characteristics of calcareous soil samples subjected to high temperature, a single mineral composition soil sample was used in this test. The sample consisted of calcareous sand obtained from the Guangdong Province, China. The specific composition of the soil is presented in Table 1, and the mechanical properties of sample is presented in Table 2.

Test equipment and procedure

The SMF1900-50 box resistance furnace at the University of Shanghai for Science and Technology was

Table 1 Material composition

Composition	Percentage (%)
IL(Loss on Ignition)	43.67
Al_2O_3	< 0.01
SiO_3	0.4
Fe_2O_3	0.0086
CaO	55.5
MgO	0.19
K_2O	0.0085
Na_2O	0.072
TiO_2	< 0.01

Table 2 Dry density of the samples (kg/m^3)

Temperature	Minimum dry density	Maximum dry density
20 °C	1363.8	1496.5
800 °C	826.0	882.1

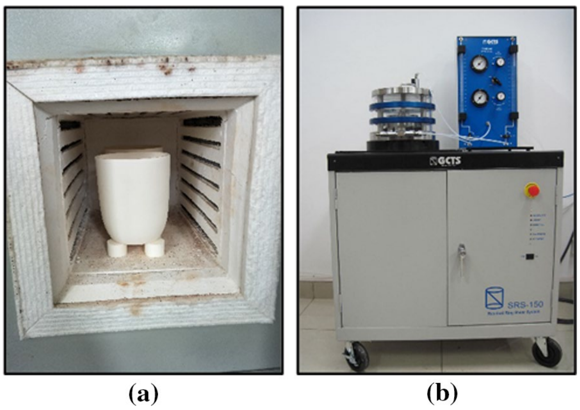

Fig. 1 Test equipment: **a** SMF1900-50 box resistance furnace and **b** GCTS SRS-150 ring-shear apparatus

used to conduct a high-temperature test (Fig. 1a). The maximum temperature was 1000 °C. The heating rate and the cooling rate were set to 4 °C/min, and the temperature was maintained at 800 °C for 24 h and finally reduced to 20 °C (Zhang et al. 2015; Chen et al. 2017; Wang et al. 2022a). The sample was placed in a corundum crucible, which was raised by a corundum gasket to ensure uniform heating.

The GCTS SRS-150 ring-shear apparatus in the key laboratory of the Ministry of Geotechnical and Underground Engineering of Tongji University was used to conduct the ring-shear test (Fig. 1b). In the test, the displacement was continuous and the equipment automatically obtained the shear stress of the samples. Details regarding the instrumentation and the test process are provided in Wang et al. (2022b).

Results and analysis

Appearance of samples

The calcareous sand was obviously different after the high-temperature treatment (Fig. 2), and its particles changed from translucent gray white crystals to pure white opaque crystals, indicating that the calcareous sand was completely converted from calcium carbonate to calcium oxide. The content of the remaining components was negligible.

Fig. 2 Appearance of the calcareous sand before (left) and after (right) heat treatment

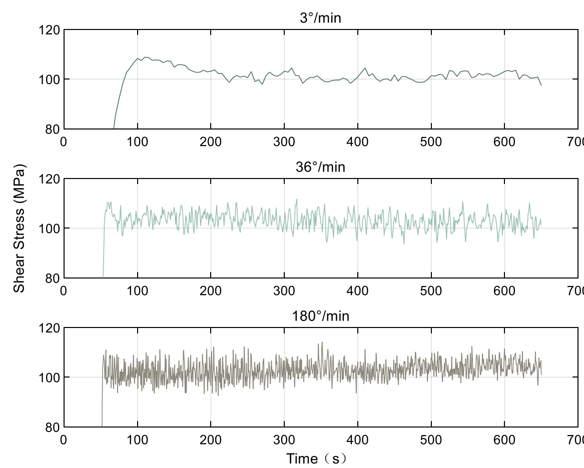

Fig. 3 Relationship between time and the shear stress for different shear velocities

Effect of shear velocity on the shear strength, residual shear stress, and apparent viscosity

Under the same conditions, the mechanical behavior of the calcareous sand samples sheared at different shear velocities was different. Figure 3 shows the relationship between time and the shear stress for different shear velocities. In Fig. 3, the shear strength and the residual shear stress can be clearly observed. The average, maximum, and minimum residual shear stresses were obtained separately, as plotted in Fig. 4. With shear velocities of 3°/min, 36°/min, and 180°/min, the shear strengths of the calcareous sand samples were 108.3 kPa, 110.4 kPa, and 108.9 kPa, respectively;

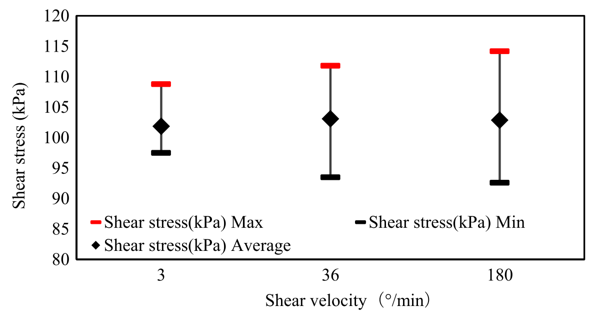

Fig. 4 Relationship between the average, maximum, and minimum residual shear strains and the shear velocity

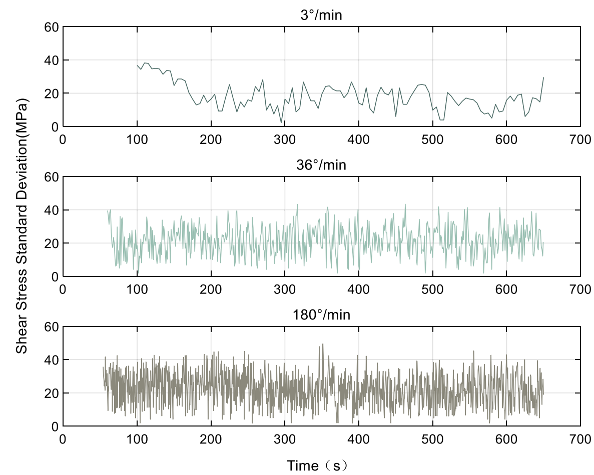

Fig. 5 Standard deviation of the shear stresses of the samples with time

the average residual shear stresses were 101.8 kPa, 103.1 kPa, and 102.8 kPa, respectively; the maximum residual shear stresses were 108.8 kPa, 111.8 kPa, and 114.2 kPa, respectively; and the minimum residual shear stresses were 97.5 kPa, 93.5 kPa, and 92.6 kPa, respectively.

At lower shear velocity (3°/min), the initial peak shear strength of the sample appeared later compared with those of samples with higher shear velocities. The fluctuation amplitude of the residual shear stress was small and gentle. At higher shear velocities (36°/min and 180°/min), the initial peak shear strength of the samples appeared faster and the residual shear stress fluctuated significantly. In this unsteady state, the residual shear stress was greater than the shear strength. As the shear velocity increased, the residual shear stress fluctuation of the samples with a large displacement shear became more intense and even exceeded the shear strength. This is related to the shear breakage and rearrangement of the soil particles in the shear box. Therefore, the residual shear stress of calcareous sand may exceed the shear strength and increase with the shear velocity when the other experimental conditions remain the same. Moreover, the residual shear stress of the sample with a shear velocity of 180°/min kept increasing, which indicates that the residual shear stress of the sample increased with the particle breakage. To quantify the shear stress fluctuation, the standard deviation of the shear stress was used to measure the fluctuation amplitude of the shear stress, as shown in Fig. 5. The results indicate that a higher shear velocity led to an increase in the sample's shear fluctuation amplitude. The shear behavior of the calcareous sand exhibited the phenomenon of shear stress fluctuation, which is related to the continuous formation and reconstruction of the force chain structure (Sun and Wang 2008). Existing studies on dense granular flow consider the shear stress to be independent of the shear rate; however, this conclusion was reached considering simple particles and clay particles with large moisture contents (Forterre 2008). The results obtained via the ring-shear test in this study differ from the theoretical results. Even though the shear flow in the ring-shear test belongs to the quasi-static flow regime, the shear stress and shear rate are not completely independent; this is strongly related to the unsteady state of the soil under large-displacement shear.

The shear rate can be calculated as follows:

$$\dot{\gamma} = \frac{vD_m}{2h},$$

where v is the shear velocity [°/s]; D_m is the average diameter of the ring-shear sample [mm]; h is the thickness of the ring-shear sample [mm].

The apparent viscosity η can be expressed by the relationship between the shear stress and the shear rate:

$$\tau = \eta\dot{\gamma}.$$

Accordingly, the specific value of the apparent viscosity can be calculated.

Because the residual shear stress fluctuated continuously as the shearing progressed, the average, maximum, and minimum residual shear stresses were calculated as shown in Fig. 6. The approximate shear flow characteristics of the calcareous sand samples were obtained under a normal stress of 200 kPa. Here, the rheological curve does not pass through the origin point and is concave to the shear rate axis. The sample has both yield characteristics and pseudoplastic fluid characteristics and can therefore be thought of as a yield pseudoplastic fluid. In Fig. 7, the curve of the average value of the apparent viscosity is slightly different from the curve drawn according to

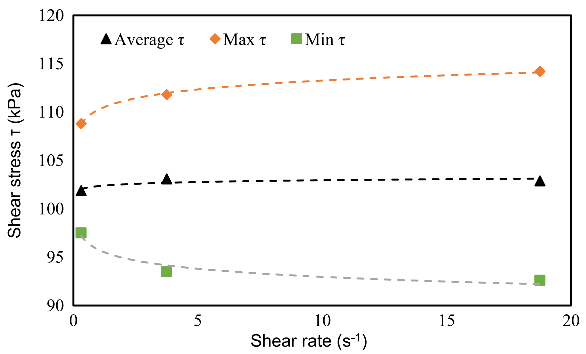

Fig. 6 Relationship between the shear rate and the residual shear stress

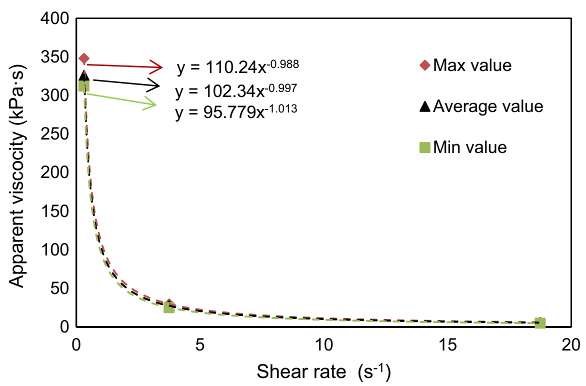

Fig. 7 Relationship between the shear rate and the apparent viscosity

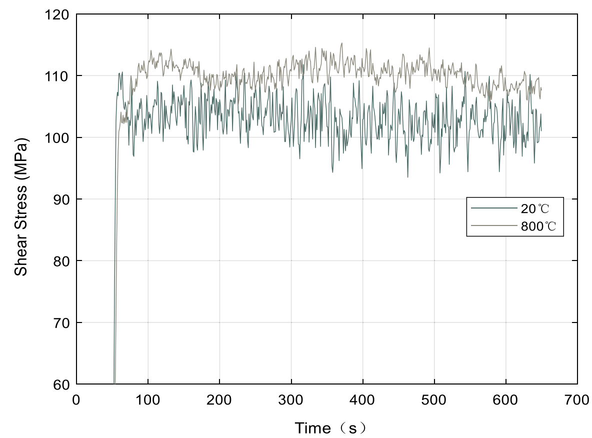

Fig. 8 Relationship between time and the shear stress of the calcareous sand before and after heat treatment

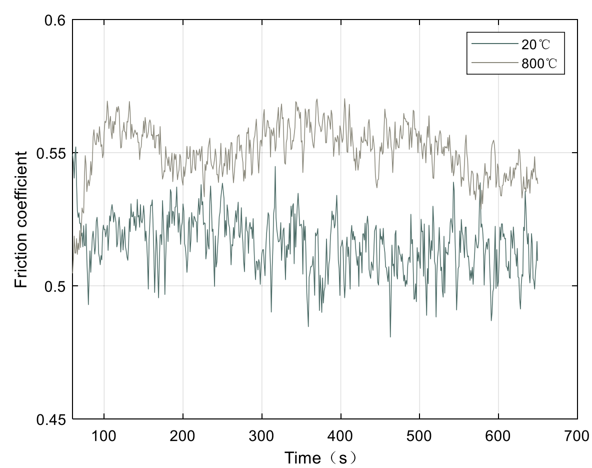

Fig. 9 Relationship between time and the friction coefficient of the calcareous sand before and after heat treatment

the maximum and minimum values; however, the overall trends of the two are essentially identical. The apparent viscosity decreased as the shear rate increased; therefore, the viscosity of the calcareous sand decreased as the shear rate increased and the relationship between the shear stress and the shear rate is nonlinear, with a certain degree of shear dilution.

Variation of the shear strength, residual shear stress, and friction coefficient caused by high temperature

The ring-shear tests on the calcareous sand samples before and after heat treatment were performed under the same normal stress and shear velocity conditions. The shear characteristics of the samples were obtained before and after the heat treatment, and the shear stress curves are shown in Fig. 8. The shear strengths of the samples before and after heat treatment were 110.4 kPa and 104.1 kPa, respectively. This indicates that the shear strength of the calcareous sand decreased after the calcareous sand was subjected to high temperature and that the calcareous sand became more prone to shear failure. The average residual shear stresses were 103.1 kPa and 110.2 kPa before and after heating, respectively. Hence, the residual shear strength of the sample increased after the high-temperature treatment. A comparison of the friction coefficient of the sample before and after heat treatment (Fig. 9) indicated that the average friction coefficient increased from 0.51 to 0.55. After the heat treatment at 800 °C, the friction coefficient of the sample was obviously higher compared with that prior to the heat treatment. Figure 10 shows the state of the calcareous sand sample particles after heat treatment at different temperatures. Considering Fig. 10 in conjunction with the sample images captured after the ring-shear tests (Fig. 9), it was determined that the variation behavior of the shear flow was primarily influenced by the change in the sand particles

Fig. 10 Calcareous sand samples after being subjected to different temperatures

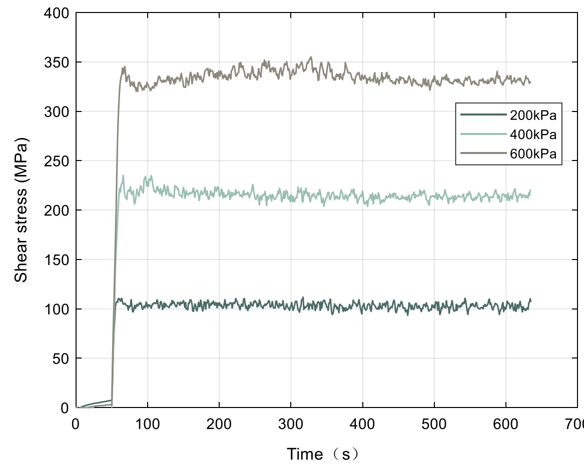

Fig. 11 Relationship between time and the shear stress under different normal stresses

subjected to high temperature, after which the calcareous sand particles were smaller and more brittle and capable of being crushed with greater ease. After the heat treatment, the sand particles could more easily be destroyed and the sample became denser. This eventually led to an increase in the friction coefficient and the residual shear strength. The calcareous sand subjected to heat treatment had smaller particles, and its residual shear stress fluctuation amplitude was relatively reduced, which affects the stability of the soil to large-displacement flows. From the above discussion, it is understood that the amplitude of the shear stress fluctuation in the calcareous sand shear flow behavior is related to the particle size and the particle hardness. Hence, the increase in the residual shear stress and the decrease in the friction coefficient and residual shear stress fluctuation amplitude following the high-temperature treatment were caused by the decrease in the particle size.

Effect of normal stress on the shear stress and friction coefficient of calcareous sand

The variation in the shear characteristics of the calcareous sand subjected to different normal stresses is similar to that obtained in other studies. The shear stresses of the calcareous sand samples under different normal stresses are shown in Fig. 11. The shear strengths of the calcareous sand samples under normal stresses of 200 kPa, 400 kPa, and 600 kPa were 110.4 kPa, 221.8 kPa, and 323.7 kPa, respectively, and the average residual shear stresses were 199.8 kPa, 215.2 kPa, and 334.4 kPa, respectively. The shear strength and residual shear stress increased with the normal stress. The fluctuation amplitude of the residual shear stress increased, particularly when the normal stress reached 600 kPa, and the fluctuation amplitude of the residual shear stress of the calcareous sand obviously increased. The average residual shear stress exceeded the shear strength and was similar to that of the calcareous sand sample at high shear velocity.

Figure 12 shows the variation in the friction coefficient of the calcareous sand samples under different normal stresses. The average friction coefficients of the samples under normal stresses of 200 kPa, 400 kPa, and 600 kPa were 0.51, 0.53, and 0.55, respectively. Therefore, the friction coefficient of the samples increased as the normal stress increased. This indicates that, as the normal stress increased, the friction coefficient increased and the fluctuation amplitude of the friction coefficient obviously decreased. The shear characteristics of the calcareous sand samples under different normal stresses are

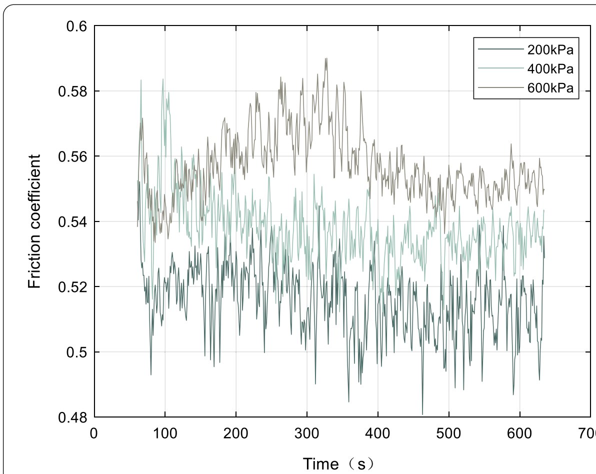

Fig. 12 Relationship between time and the friction coefficient under different normal stresses

essentially the same as those of other sand types, such as quartz sand. Therefore, as the normal stress increased, the particle breakage and the residual shear stress increased.

Discussion

The experiment conducted in this study confirmed the irreversible reaction of minerals in calcareous sand subjected to high-temperature treatment, and the heat treatment affected the shear flow behavior of the calcareous sand samples because of the variations in the mineral composition, particle hardness, and particle size. The reaction of the minerals in the calcareous sand following heat treatment at 800 °C proceeded as

$$CaCO_3 \xrightarrow{Heating} CaO + CO_2 \uparrow$$

Therefore, when investigating the influence of heating on the shear flow behavior, it is necessary to consider the effect of high temperatures on changes in the mineral composition of the landslide soil. In this test, the hardness of the calcareous sand particles after heat treatment was lower and the particles could break more easily. According to the variation in the hardness, the shear strength and residual shear strength of calcareous sand subjected to high temperature should be lower compared with those of calcareous sand without heat treatment. However, the test results indicate the opposite. Therefore, when the results are analyzed, it is necessary to consider both the particle size variation and the sample density at which the calcareous sand was crushed.

The calcareous sand particles were subjected to heat treatment and large displacement shear testing, and the particle size partially decreased, which led to an increase in the sample density. In addition, the contact between the particles increased, which led to an increase in the macroscopic friction coefficient of the samples. Finally, the shear strength and residual shear stress of the calcareous sand increased.

The results obtained in this study reveal that the fluctuation amplitude of the residual shear stress increases with the shear rate and that the maximum value of the residual stress exceeds the shear strength. Therefore, the frequency of the particle rearrangement and particle breakage increases with the shear rate. Moreover, the impact force between the particles increases. It is thought that the fluctuation amplitude of a sample's residual shear stress is proportional to the velocity in a certain range. In long-runout landslides, the soil has similar residual shear stress fluctuations; this may be one reason for the unsteady characteristics of the soil's shear flow behavior. This experiment resulted in multiple revelations. (1) In the process of landslide movement, decreasing overlying stress will lead to decreasing shear stress and increasing sliding velocity. (2) In the process of sliding, the breakage of the landslide mass will have a complex impact on the landslide. (3) The high temperature generated by a long-runout landslide will affect the rate of soil breakage through chemical reactions, which will then indirectly affect the landslide process.

Conclusions

Based on the principle of the mechanical properties of minerals being irreversible after heating, ring-shear tests were conducted on calcareous sand subjected to heat treatment. The variation laws of the shear characteristics of the calcareous sand were investigated. Based on the analysis of the experimental results, the following conclusions were drawn.

(1) The calcareous sand samples exhibited obvious non-steady quasi-static shear flow characteristics, and the fluctuation amplitude of the shear stress increased with the shear velocity. In the ring-shear test, the average residual shear stress was not affected by the increasing shear rate. The calcareous sand was identified as a yield-pseudoplastic fluid when subjected to large-displacement shear. The apparent viscosity decreased as the shear rate increased, and a certain degree of shear dilution was observed.

(2) The calcareous sand subjected to high temperature could be destroyed with greater ease, and the particles became smaller. The fluctuation amplitude of the residual shear stress decreased, which affected the stability in the large-displacement shear behavior. The fluctuation amplitude of the shear stress in the shear behavior may be related to the particle size and particle hardness. Moreover, the high temperature directly affected the shear behavior and induced unsteady characteristics by changing the mineral composition of the soil.

(3) The friction coefficient of the calcareous sand samples obviously changed under different normal stresses. As the normal stress increased, the shear strength of the calcareous sand increased while the friction coefficient decreased. Finally, the fluctuation amplitude of the friction coefficient obviously decreased.

Author contributions
Conceptualization, SW; formal analysis, SW; writing: original draft preparation, SW; writing: review and editing, YH; supervision, YH; funding acquisition, SW and YH All authors reviewed the manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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