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ORIGINAL REPORT

Shear characteristics of granular materials with different friction coefficients based on ring shear test

Wenqing Niu[1] · Hu Zheng[1,2,3] · Changju Yuan[1] · Wuwei Mao[1,2] · Yu Huang[1,2]

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Abstract
Interparticle friction is an intrinsic property of particles, which plays an important role in the macroscopic and microscopic shear mechanical properties of granular materials. In this research, we investigate the shear behavior of granular materials with different friction coefficients using ring shear tests. The particle image velocimetry (PIV) technique was also used to analyze the shear flow characteristics. The results indicate that the peak shear strength of granular materials increases with the increase in shear rates, especially for granular materials with high friction coefficients. The shear stress fluctuation difference is smaller under low normal stress. Under high normal stress, the shear stress fluctuation of granular materials with high friction coefficient is higher than that of granular materials with low friction coefficient. In addition, the shear stress fluctuation shows a trend of increasing with the increase of shear rates. The range of the liquid phase flow region of granular materials decreases with the increase of friction coefficient and normal stress. This work reveals the shear flow characteristics of granular materials under different conditions, which can provide reference for the flow processes of geological disasters such as landslides and debris flows.

Keywords Granular materials · Ring-shear test · Shear characteristic · Friction coefficients

1 Introduction

Granular materials are widely exist in nature [1, 2]. Geotechnical particle aggregates are complex disordered systems composed of a large number of discrete particles. It exhibits solid properties when stacked and behaves like a liquid when flowing. However, there are significant differences between its liquid and solid properties compared to continuum systems such as Newtonian fluids and elastic solids [3]. The complex macroscopic mechanical behavior of granular materials is influenced by a variety of factors, including particle shape, particle gradation, and inter-particle friction coefficient [4]. Among these factors, the inter-particle friction coefficient is one of the key factors determining its macroscopic mechanical properties [5–8]. The energy of the granular system is dissipated mainly through friction and collision [9–11], and the friction between the particles is also an intrinsic dominant controlling factor in geotechnical deformation and damage. Therefore, it is of great significance to study the effect of inter-particle friction on the macro-mechanical behavior of geotechnics based on particle mechanics.

Many natural disasters are triggered by shear damage of geotechnical granular materials [12–14]. Granular systems undergo dilatation or contraction during shear, however, its shear properties are controlled by a combined effect of stress ratios and inter-particle friction [15]. The rearrangement of particle scales is mainly controlled by sliding and rolling friction between particles which in turn affects the volume deformation of the particle system [16, 17]. Volume change affects the volume fraction of the granular system, while a decrease in volume fraction alters the mechanical stability of the granular system [18]. In the biaxial compression experiments of the particle system, the stress-strain switched from hardening to softening as the inter-particle

✉ Hu Zheng
zhenghu@tongji.edu.cn

1 Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

2 Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China

3 State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

friction increased, along with an increase in the stress ratio and peak strength [19]. Particle friction is also the main cause of the inconsistency between the p-plane stress tensor and the Lode angle of the incremental strain tensor under a three-dimensional non-axisymmetric loading path [20]. In the Taylor-Couette model, the friction coefficient significantly affects the force chain network and mechanical properties of the particle system. With the increase in the coefficient of friction, the shear stresses, normal stresses, average contact force and unbalance force increase accordingly [21]. Wu et al. [22] investigated the macroscopic and microscopic response of a two-dimensional granular shear system to changes in rolling friction by employing numerical simulations. The results show that the evolutionary properties of the force chain are significantly affected by the magnitude of rolling friction. The inter-particle friction coefficient not only has an effect on the macroscopic mechanical properties of the particle system, but also on the microscopic mechanical evolution process. Currently, studies on the mechanical properties of granular materials with different friction coefficients are mainly focused on small deformation damage. However, we still need to conduct more in-depth research on the effect of friction coefficient on the mechanical properties of granular materials in large deformation flow shear after reaching steady state.

Ring shear experiment is an important method to study the shear deformation characteristics of geotechnical granular materials. With respect to large deformation geotechnical flow problems, direct shear tests and triaxial tests provide only limited deformation information and have limitations in the research of such problems [23, 24]. However, the ring shear test can theoretically provide infinite shear deformation. Wang and Huang [25] studied the shear properties of geotechnical soils, analyzed the shear stress and shear stress fluctuation of the specimens, and explored the shear expansion and compaction mechanism of the samples under large-displacement shear. Jiang et al. [26]studied the shear properties of breccia silica sand and spherical glass microspheres at different shear rates. The researchers have studied the shear stress-strain relationship, particle breakage and other mechanical properties of geotechnical materials through ring shear tests [27–30], providing new insights into the shear damage mechanisms of landslides and other geologic hazards.

In this research, we select granular materials with different friction coefficients for ring shear tests to investigate the effect of friction coefficient on their shear mechanical properties and flow characteristics. We analyzed the effect of friction coefficient on the peak strength, shear stress and shear stress fluctuation of granular materials, and used particle image velocimetry technology to study the flow characteristics of granular materials, elucidating the influence of friction coefficients on the shear properties of granular materials.

Table 1 Basic physical parameters of granular materials

Order number	Materials type	Density(g/cm^3)	friction coefficient	Young's modulus (GPa)
RS1	steel	8.03	0.16	200
RS2	Polyoxymethylene (PP)	1.41	0.35–0.45	3.15
RS3	Polypropylene (POM)	0.89	0.50	1.6
RS4	aluminum	2.7	0.73	70

2 Materials and methods

2.1 Materials

In this research, we performed ring shear tests with four different types of granular materials: steel balls, polypropylene (PP), polyoxymethylene (POM), and aluminum balls. The diameters of granular materials are 1.5 and 2.0 mm respectively, and they are mixed 1:1 to generate uniform samples. To avoid the influence of the initial sample preparation of particles on the experimental results, we kept the height of each group of initial samples are the same. The properties of these materials are summarized in Table 1. The effect of granular material density on the shear properties is negligible due to the large normal stress applied in the experiments, and we have also verified this result by numerical simulations. Since the Young's modulus of the material selected for the experiment is above $10^8 Pa$, the deformation of the granular material within the applied normal stress range is relatively small, and the impact on the test results is negligible. Nguyen et al. [32] also investigated the effect of particle material properties on particle flow characteristics through numerical simulations and found that the effect of density and Young's modulus on granular flow was negligible. Therefore, this experiment focuses on the effect of the friction coefficient of the particles on shear flow characteristics.

2.2 Test equipment and test programs

The test device used in this research is the SRS-150 annular shear test device produced by Geotechnical Consulting & Testing Systems (GCTS) company, and purchased by the key laboratory of Geotechnical and underground engineering of the Ministry of Education of Tongji University (Fig. 1). SRS-150 ring shear instrument is fully automatic servo control, which can realize unlimited shearing displacement. The shear speed range is 0.001-360°/min, and the peak torque is 820Nm, the maximum normal stress and

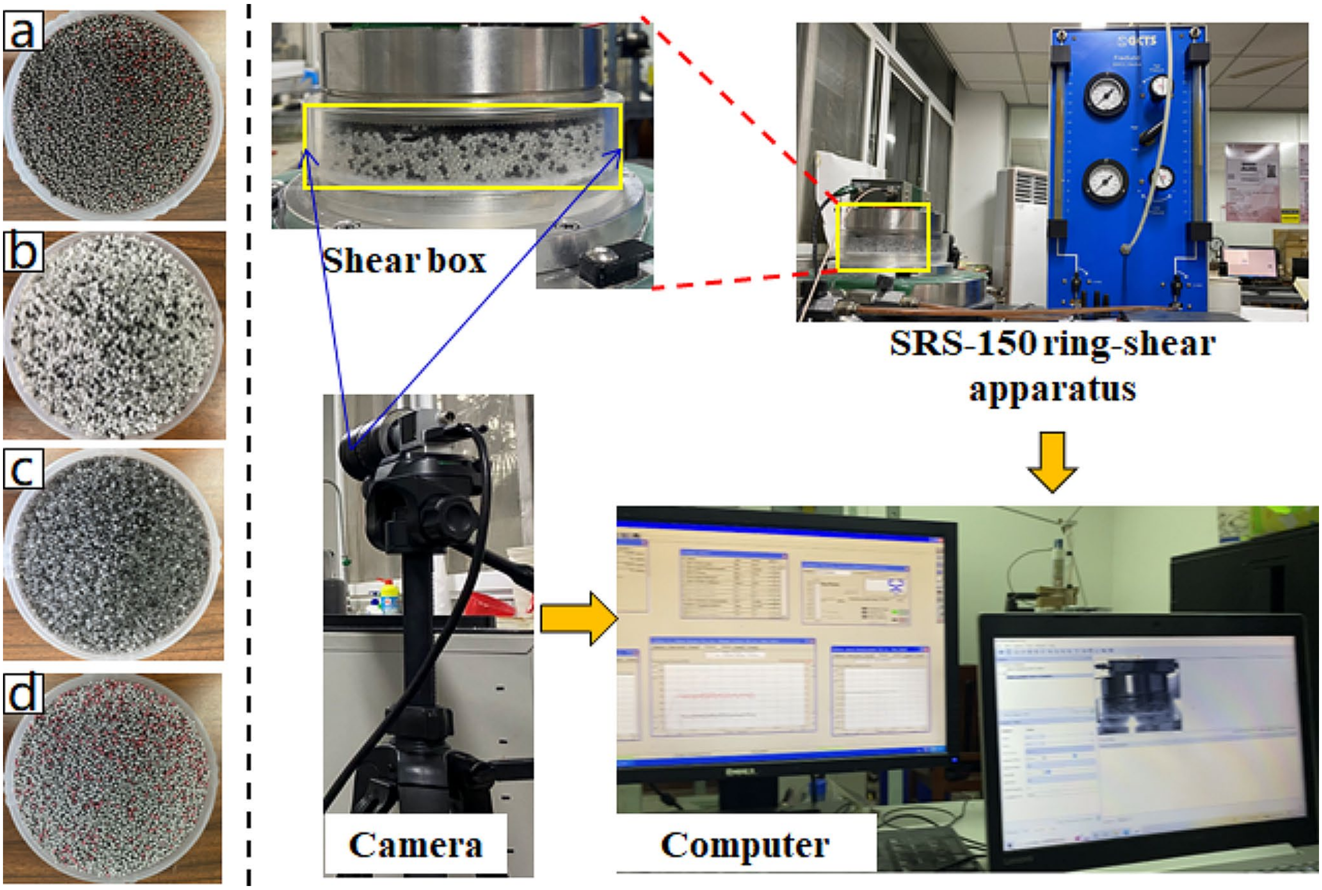


Fig. 1 GCTS SRS-150 ring-shear apparatus and images of test materials. (**a**) steel balls; (**b**) polyoxymethylene balls; (**c**) polypropylene balls; (**d**) aluminum balls

shear stress are 1000 kPa and 1300 kPa respectively; the outer diameter, inner diameter, and height of the shear box are 150 mm, 100 mm, and 25 mm respectively. During the tests, we kept the height of the samples in each group of tests about 20 mm, and controlling the sizes of the test system could minimize the errors of the experimental results caused by the changes of the system sizes.

Data such as shear stress, normal stress, and shear displacement can be obtained by calculating the rotational couple moment M, normal load F, and angular displacement θ parameters.

$$\text{Moment of couple}: \ M = \int_{R_1}^{R_2} \tau \times 2\pi R^2 \mathrm{d}R \tag{1}$$

$$\text{Shear stress}: \ \tau = \frac{3M}{2\pi(R_2^3 - R_1^3)} \tag{2}$$

$$\text{Normal stress}: \ \sigma = \frac{F}{\pi(R_2^2 - R_1^2)} \tag{3}$$

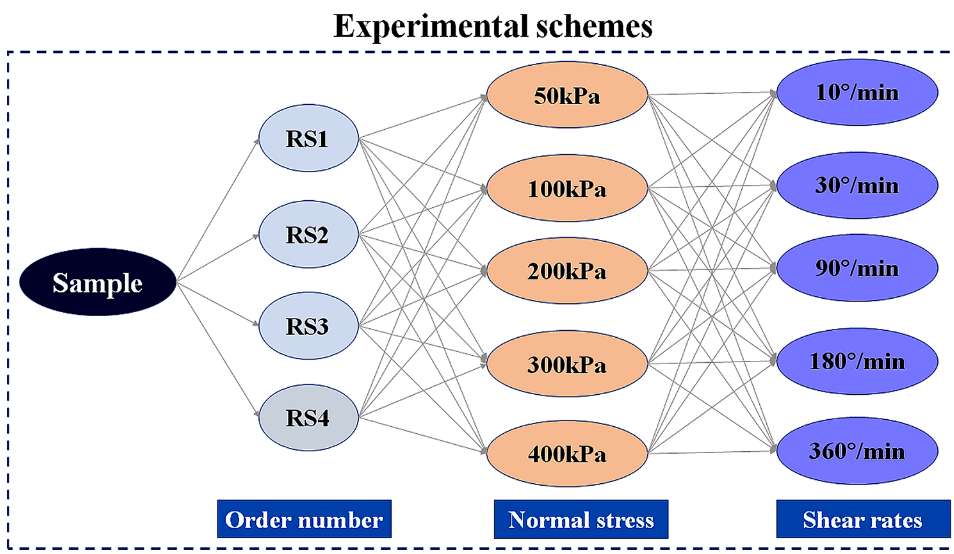
$$\text{Shear displacement}: S = \pi D \times \mathrm{n} \times t = \frac{D}{2}\theta = R\theta \tag{4}$$

$$\text{Average diameter}: D = 2R = 2 \times \frac{2\left(R_2^3 - R_1^3\right)}{3\left(R_2^2 - R_1^2\right)} = \frac{2\left(D_2^3 - D_1^3\right)}{3\left(D_2^2 - D_1^2\right)} \tag{5}$$

Where R_1 is the inner radius, R_2 is the outer radius, n is the rotational speed (Revolutions/min), t is the time (min), and F is the normal load.

We conducted a total of 100 sets of shear tests on four types of granular materials under different normal stresses and shear rates. For convenience, we use the order numbers RS1, RS2, RS3, and RS4 to represent steel balls, polypropylene (PP), polyoxymethylene (POM), and aluminum balls respectively. The specific implementation of this experiment is shown in Fig. 2. The change of normal stress with time is shown in Fig. 3(a). After the loading reaches the target normal stress, it stays for one minute and starts to enter the shear phase. The shearing rates are constant shearing speed is maintained during the shearing process. The change of shear angle with time is shown in Fig. 3(b).

Fig. 2 Specific implementation of this experiment



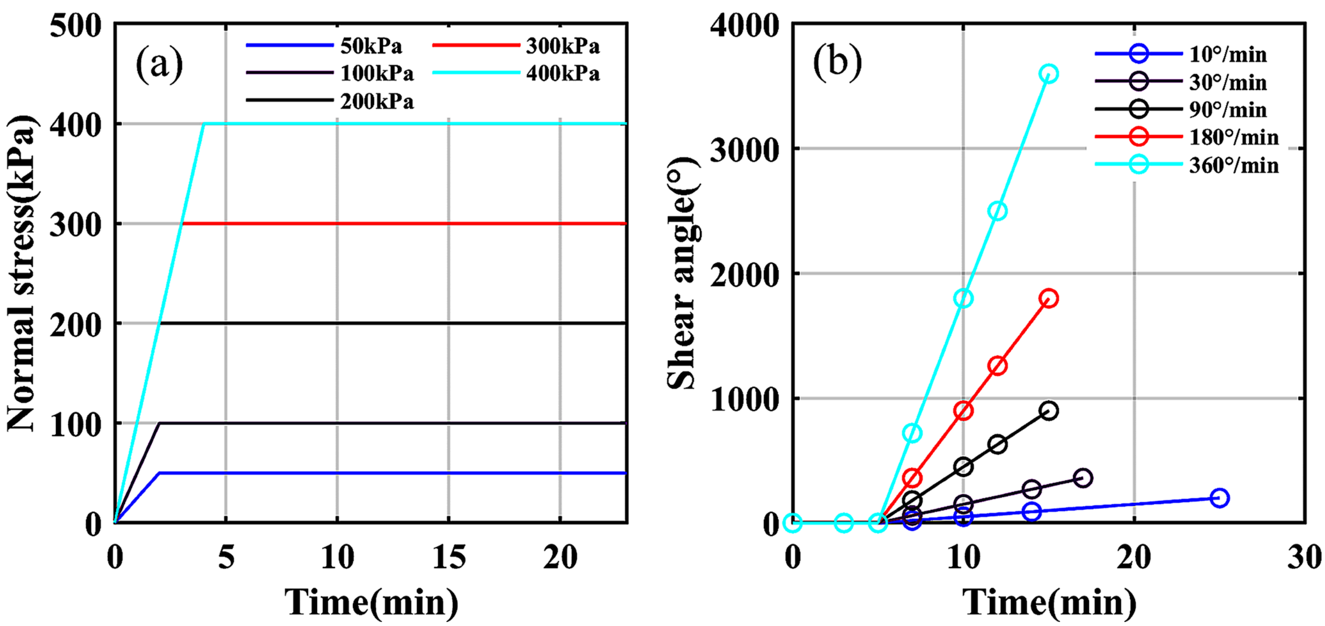


Fig. 3 Parameter settings for ring shear test. (**a**) load condition; (**b**) shear condition

2.3 Image processing

To observe the particle shear flow characteristics, we designed a transparent plexiglass shear box (Fig. 1). A video camera is used to capture continuous multi-frame images of the shearing process of the granular material. Then, the obtained image is processed by particle image velocimetry (PIV) to study the shear flow characteristics of granular materials. Before image PIV analysis, the original image needs to be preprocessed to increase the accuracy of the acquired data (Fig. 4). Image preprocessing includes histogram equalization, intensity high-pass, and intensity capping [31]. Histogram equalization can improve the contrast and visual effect of the image. By redistributing the gray value of the image pixels, the histogram of the image is evenly distributed throughout the gray range, and the dark and bright areas are more balanced. Intensity high-pass is used to highlight high-frequency information in an image while suppressing low-frequency information (the overall brightness variation of the image). It can help extract details in the image and enhance the sharpness of the image. Bright particles in the image area contribute more to the correlation signal, biasing the results from the non-uniform flow. Intensity capping avoids this problem and improves the detection probability of valid vectors in experimental images.

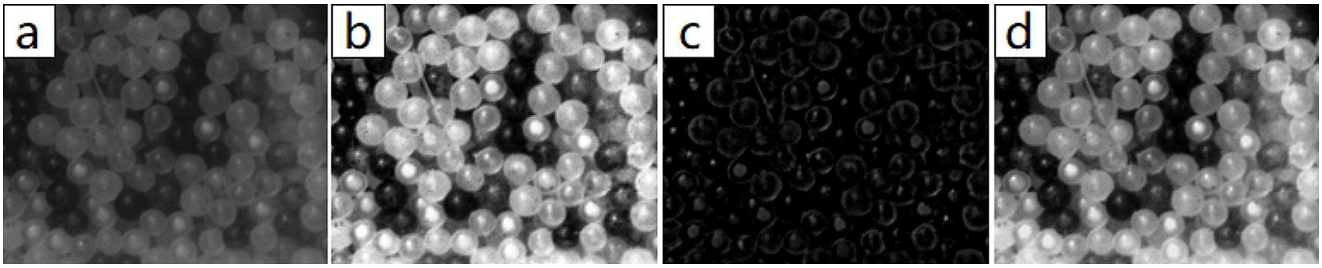


Fig. 4 Image preprocessing process. (**a**) Original. (**b**) CLANE. (**c**) High-pass. (**d**) Intensity capping

3 Results

3.1 Shear stress

Under different shear rates (normal stress 200 kPa), the effect of different friction coefficients on the shear stress of granular materials is compared through the shear stress and shear displacement relationship curve shown in Fig. 5. To reduce the influence of shear stress fluctuations, the moving average method is used to filter the data to obtain smooth shear stress and shear displacement curves (thick solid line). The results indicates that the friction between the granular materials plays an important role in the magnitude of the shear stress. A larger friction coefficient leads to an enhanced interaction between particles, which hinders the relative sliding of particles during shearing, resulting in higher shear stress.

During the shearing of granular materials, we define the value of the shear stress when it first reaches its peak as the peak shear stress. The peak shear stress of the low friction particle system is less affected by the shear rate, while the peak shear stress of the high friction system is significantly affected by the shear rate. The peak strength of the granular material (RS4) reaches 100 kPa at high shear rates of 90°/min, 180°/min and 360°/min (Fig. 5d and e). However, at low shear rates of 10°/min and 30°/min, the peak strength of the granular material was approximately 90 kPa (Fig. 5a and b). The effect of shear rate on the peak shear stress of particulate systems with different friction coefficients will be further analyzed later.

The shear stress and shear displacement curves of the granular materials under different normal stress conditions (shear rate of 90°/min) are shown in Fig. 6. At low normal stresses, except for the steel ball with the smallest friction coefficient (RS1) which exhibits lower shear stress, the granular materials with higher friction coefficients, the differences in shear stresses between them are not significant (Fig. 6a and b). The shear stresses of the particle systems with high and low friction coefficients show two extreme trends when the normal stresses are increased to 200 kPa and 300 kPa. The shear stresses of steel balls (RS1) and POM balls (RS2) with lower friction coefficients were approximately equal, and the shear stresses of PP balls (RS3) and aluminum balls (RS4) with higher friction coefficients were also approximately the same (Fig. 6d). The effect of the friction coefficient on the shear stress of the particle system is more significant at high normal stresses.

Under different normal stress and shear rate conditions, we analyzed the variation of the average shear stress of the granular material (Fig. 7). The average shear stress is calculated by averaging multiple data points after the shear stress reaches the residual strength. By linear fitting the average shear stress of granular materials under different shear rates and different normal stress conditions, the average shear stress of granular materials with larger friction coefficients is larger when the normal stress exceeds 100 kPa. This shows that the frictional resistance between particles has a significant effect on the average shear stress. With the increase of the normal stress, the slope of the increase of the average shear stress is also different. The average shear stress of granular materials with a larger friction coefficient increases faster with the increase of normal stress. Under the condition of low normal stress, the effect of collision between particles exceeds the effect of friction coefficient on shear stress.

The variation of peak shear strength of granular materials at different shear rates is shown in Fig. 8. The effect of shear rate on the peak shear strength of the low friction coefficient particulate system is small. In the range of normal stress from 50kpa to 400kpa, the peak shear stress of steel balls with the lowest coefficient of friction hardly varies with the change of shear rate (Fig. 8a). The peak shear stress of PP ball granular materials in the range of normal stress from 50kpa to 200kpa is not affected by the shear rate (Fig. 8b). When the normal stress exceeds 200kpa, the peak shear stress shows a tendency to increase with the shear rate. However, for granular materials with high friction system, the peak shear stress almost increases with the increase of shear rate from the range of low normal stress to high normal stress.

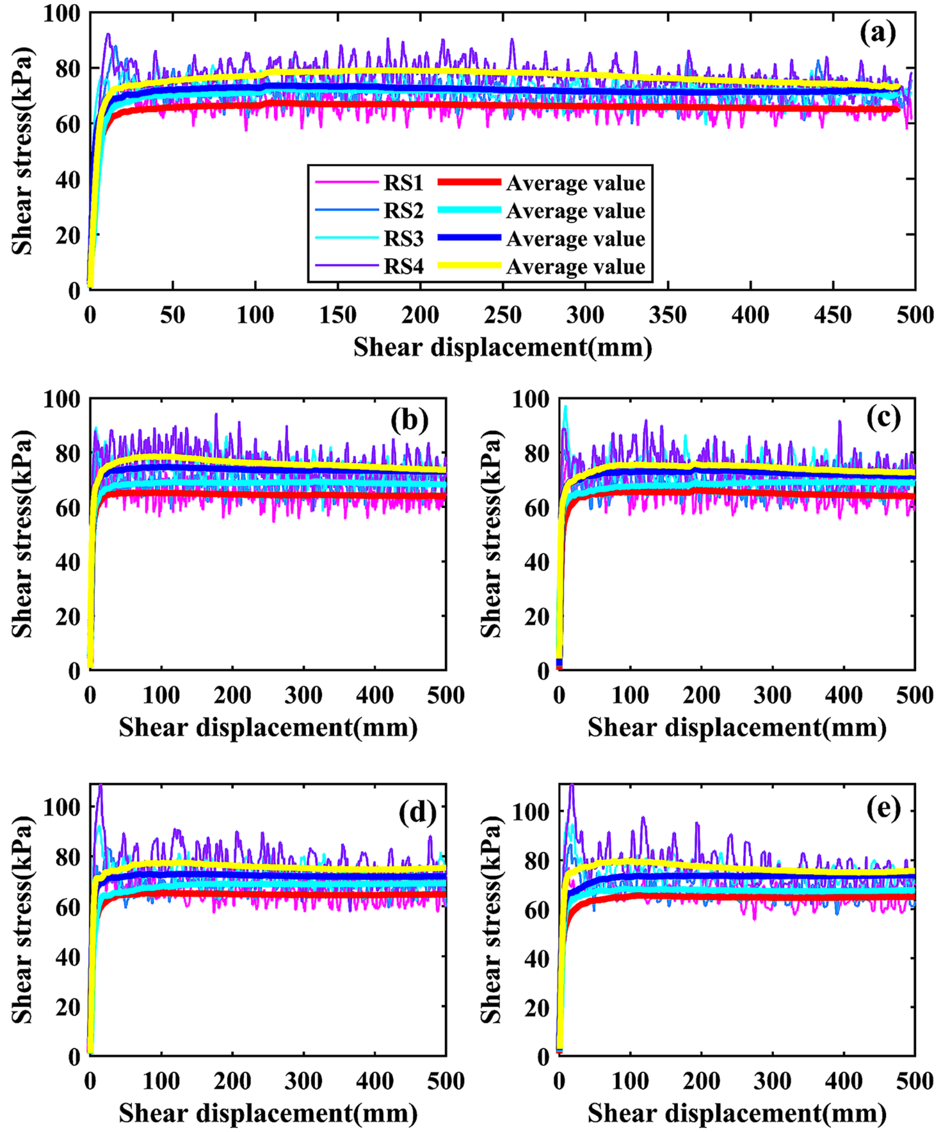


Fig. 5 The relationship between shear stress and shear displacement of granular materials under normal stress of 200 kPa. Shear rates: (**a**) 10°/min; (**b**) 30°/min; (**c**) 90°/min; (**d**) 180°/min; (**e**) 360°/min. RS1, RS2, RS3 and RS4 represent steel, polypropylene, polyoxymethylene and aluminum balls, respectively

3.2 Shear stress fluctuations

The shear stress fluctuations and shear displacements of granular materials at different shear rates under 200 kPa normal stress conditions are shown in Fig. 9. From the peak value of shear stress fluctuation, the stress fluctuation of high friction particle systems is larger than that of low friction particle system under different shear rates, especially the highest friction coefficient of granular material (RS4) has a significantly higher fluctuation than the other granular materials with three relatively low friction coefficients. Meanwhile, the effect of shear rate on the stress fluctuation range of the granular system is small, and the stress fluctuation range is approximately between 0 and 15 kPa.

The normal stress has a great influence on the shear stress fluctuation of granular materials, which increases with the increase of normal stress (Fig. 10). The shear stress fluctuations of the relatively low friction coefficient PP balls (RS2) were more obvious than those of the high friction coefficient aluminum balls at 50 kPa and 100 kPa normal stresses (Fig. 10a and b). When the normal stress was increased to 300 kPa (Fig. 10c), the shear stress fluctuation of the high friction coefficient aluminum ball (RS4) was significantly larger than that of the low friction coefficient granular material. The maximum shear stress fluctuation of the aluminum balls increased from 6 kPa to 30 kPa when the normal stress was increased from 50 kPa to 400 kPa. Stress fluctuations in granular systems occur mainly due to the breaking and reconstruction of internal force chains and collisions between particles during granular flow. Under low normal stress conditions, granular materials with low friction coefficients have fast flow rates and intense inter-particle collisions that produce large stress fluctuations. Under high normal stress, the collision effect between particles

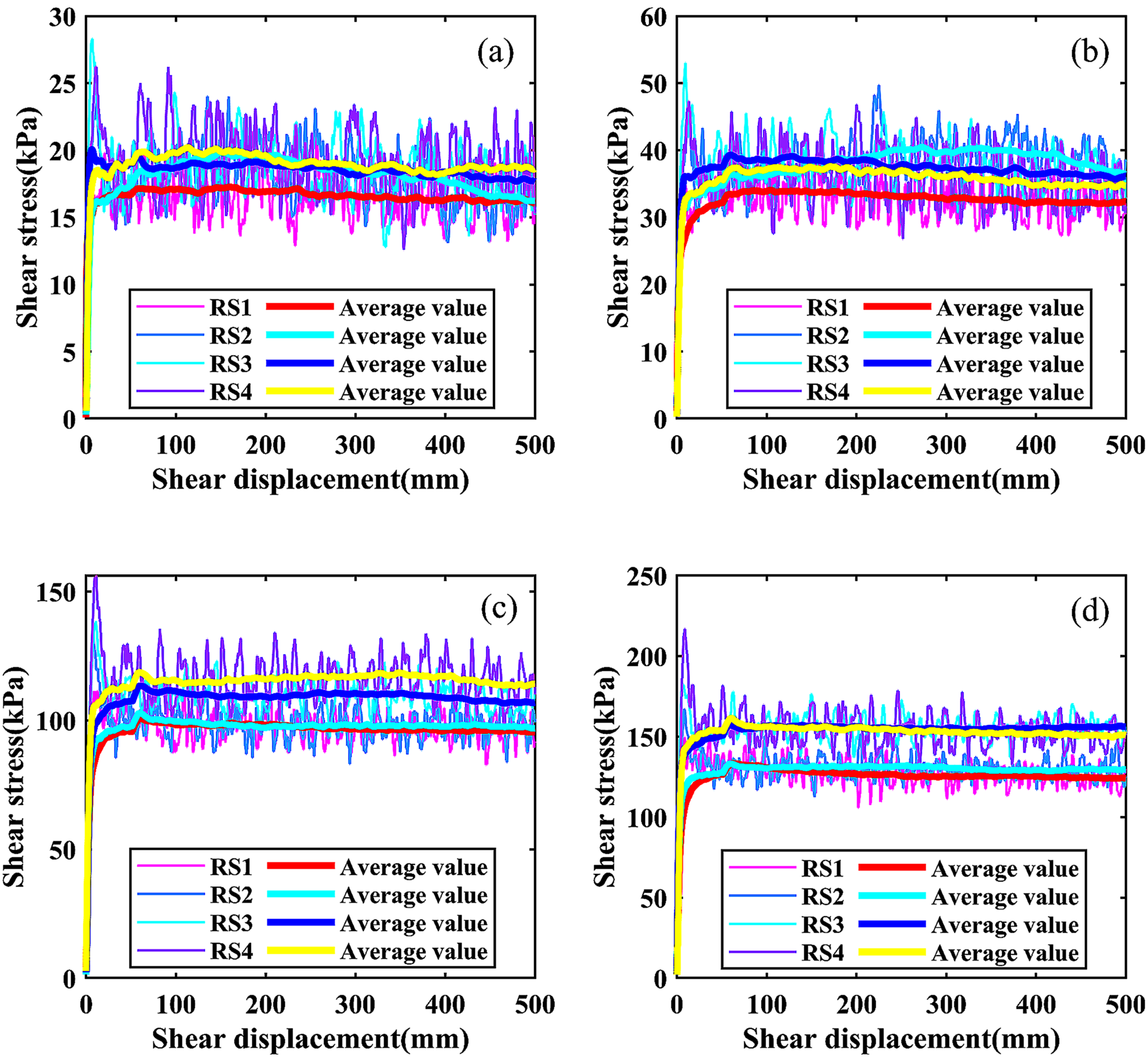


Fig. 6 The relationship between shear stress and shear displacement of granular materials under shear rates 90°/min. Normal stress: (**a**) 50 kPa; (**b**) 100 kPa; (**c**) 300 kPa; (**d**) 400 kPa

is weaker, and the particle system with high friction coefficient has larger stress fluctuation due to the breakage of force chain.

Figure 11 shows the average shear stress fluctuation (ASSF) of granular materials under different normal stress and shear rate conditions. The shear stress fluctuations of the granular materials increase with the increase of normal stress, except for POM balls (RS3) and PP balls (RS2) which show a discontinuous increase at 300 kPa and 100 kPa normal stresses, respectively. This indicates that the shear stress fluctuation of granular materials is greatly influenced by the normal stress. The average shear stress fluctuations of the high friction coefficient aluminum spheres (RS4) ranged from 2 to 11 kPa, while the average shear stress fluctuations of the other three materials ranged from 1 to 6 kPa. Therefore, the shear stress fluctuations increase significantly only after the friction coefficient increases to a certain value.

3.3 Shear flow characteristic

We use particle image velocimetry to analyze particle flow field information of granular materials. Granular material with a low friction coefficient flows more easily during shearing, and a large area of granular material in the upper middle region of the sample. From the information on the particle flow field (the yellow curve is the streamline), it can

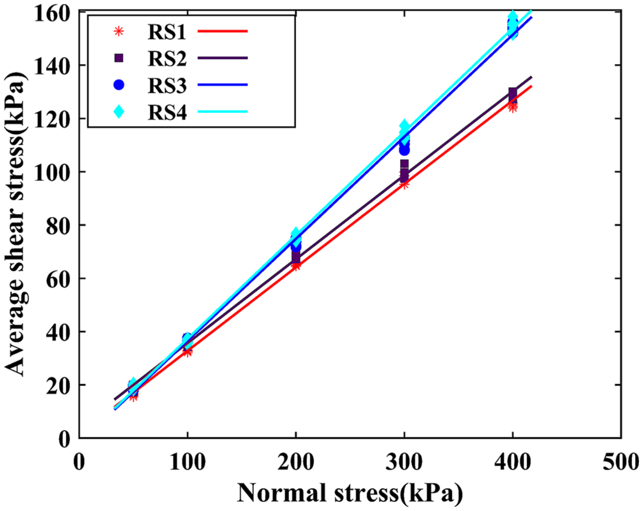


Fig. 7 Average shear stress and normal stress relationship curves of granular materials at different shear rates

be seen that the particle material forms a relatively uniform flow field from the left to the right (Fig. 12a). However, due to the large contact friction force between the particles during the shearing process, the fluidity of the granular material with a large friction coefficient is relatively weak (Fig. 12b). Granular materials with a high friction coefficient mainly form a local area flow field, and the shape of the flow field is complex.

To further quantitatively analyze the variation of particle flow velocity along the height of the sample, we obtained the velocity profile curves of the particle material under different normal stress conditions (Fig. 13). The experimental results show that the velocity profile curve increases exponentially along the direction of the sample height. Under the condition of low normal stress, the difference in velocity profile curves of granular materials with different friction coefficients is small (Fig. 13a). With a gradual increase in the normal stress, the flow velocity of the granular material decreases with an increase in the friction coefficient. Especially when the normal stress reaches 400 kPa, as the friction coefficient increases, the flow velocity of the granular material tends to decrease in turn.

The main reason why the velocity profile of polypropylene spheres (RS2) does not show a regular change with the coefficient of friction is that the electrostatic attraction between the particles affects the flow characteristics of the granular material. The electrostatic attraction between the particles weakens the flowability of the particles due to the presence of weak electrostatic attraction inside the PP balls. Under low normal stress conditions, the flowability of particles is very strong and the electrostatic attraction has an important effect on the flow of particles. Therefore, at 100 kPa, 200 kPa and 300 kPa normal stresses, the velocity profiles of PP balls are lower than those of POM and aluminum balls with high coefficients of friction. At a normal stress of 400 kPa, the flow velocity of the granular material decreases almost sequentially with increasing friction coefficient (Fig. 13e). At high normal stress, the electrostatic attraction between particles has little effect on the particle flow, and the friction coefficient between particles mainly controls the flow behavior of granular materials.

We analyzed the flow velocity distributions of granular materials under different normal stresses and found that for granular systems with low friction coefficients, the effect of normal stress on the flow velocity is small. In the range of 50kpa ~ 400kpa normal stress, the flow velocity distribution shows a decreasing trend, but the decreasing trend is not obvious (Fig. 14a). However, with the increase of the friction coefficient of the granular material, the effect of normal stress on the flow velocity is significant. With the increase of normal stress, the velocity of the granular material decreases as a whole (Fig. 14c, d), and the range of liquid phase flow area becomes smaller and smaller. In addition, the particle flow velocity at the top of the sample may be greater under high normal stress conditions than under low normal stress conditions (Fig. 14b), which is mainly due to the effect of the shear disk on the particle velocity at the sample surface.

4 Discussion

4.1 Effect of friction coefficient on mechanical properties

Inter-particle friction promotes the contribution of strong contact normal stresses to the major principal stresses and reduces the contribution of strong contact normal stresses to the minor principal stresses [32, 33]. As a result, the increase in friction coefficient of the particle system as a whole promotes the increase in deviatoric stress, showing a trend that the peak shear stress of the particle system increases with the interparticle friction coefficient. However, the characteristics of shear stress and peak shear stress for different friction particle systems are also affected by the shear rate. Shear stress can exhibit positive, negative and neutral shear rate effects [34–36], i.e., shear stress exhibits an increasing, decreasing or no change with increasing shear rate. The results of our peak shear stress tests show that low friction granular systems exhibit a neutral shear rate effect at low normal stresses and a positive shear rate effect at high normal stresses. The magnitude of shear stress can also be reflected by the fluidity difficulty of the granular material. The particles of the low friction particle system are highly mobility, and at lower normal stress, the shear rate has less influence on the steady flow state of the particles, thus exhibiting a neutral shear rate effect. As the normal stress

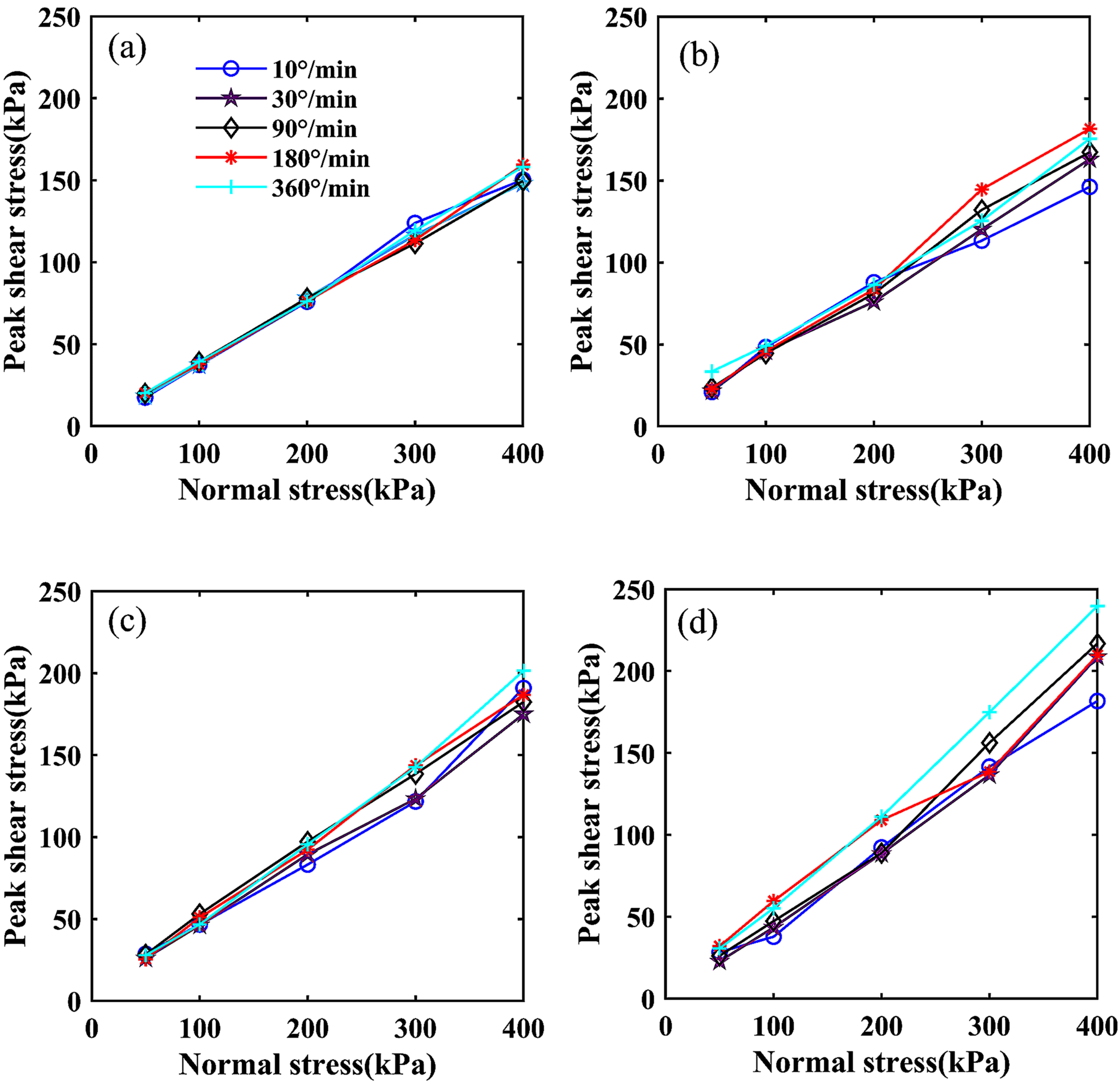


Fig. 8 Variation of peak shear stress of granular materials at different shear rates. Materials: (**a**) RS1: steel balls; (**b**) RS2: polypropylene (PP); (**c**) RS3: polyoxymethylene (POM); (**d**) RS4: aluminum

increases, the particle flow velocity decreases and the shear rate effect become apparent, exhibiting a positive shear rate effect. However, the slow flow rate of the particulate material in the high friction system is strongly influenced by the shear rate, and the peak shear stress exhibits an overall positive shear rate effect. The results of the high friction system tests are consistent with the results of previous studies in the geotechnical shear process [37–39], where there is a positive correlation between the shear rate and the peak shear strength.

After averaging the peak shear stresses of granular materials at different shear rates (Fig. 15), the peak shear strength of the low friction coefficient granular materials (RS1, RS2) increases linearly with the normal stress. However, the peak shear strength of high friction coefficient granular materials (RS3, RS4) increases at a higher rate with increasing normal stress. The error bars in the figure represent the effect of shear rate on the peak shear strength of the granular material, characterizing the extent of fluctuation in peak shear stress at different shear rates. The error bars also show that the shear rate has a large range of influence on the peak

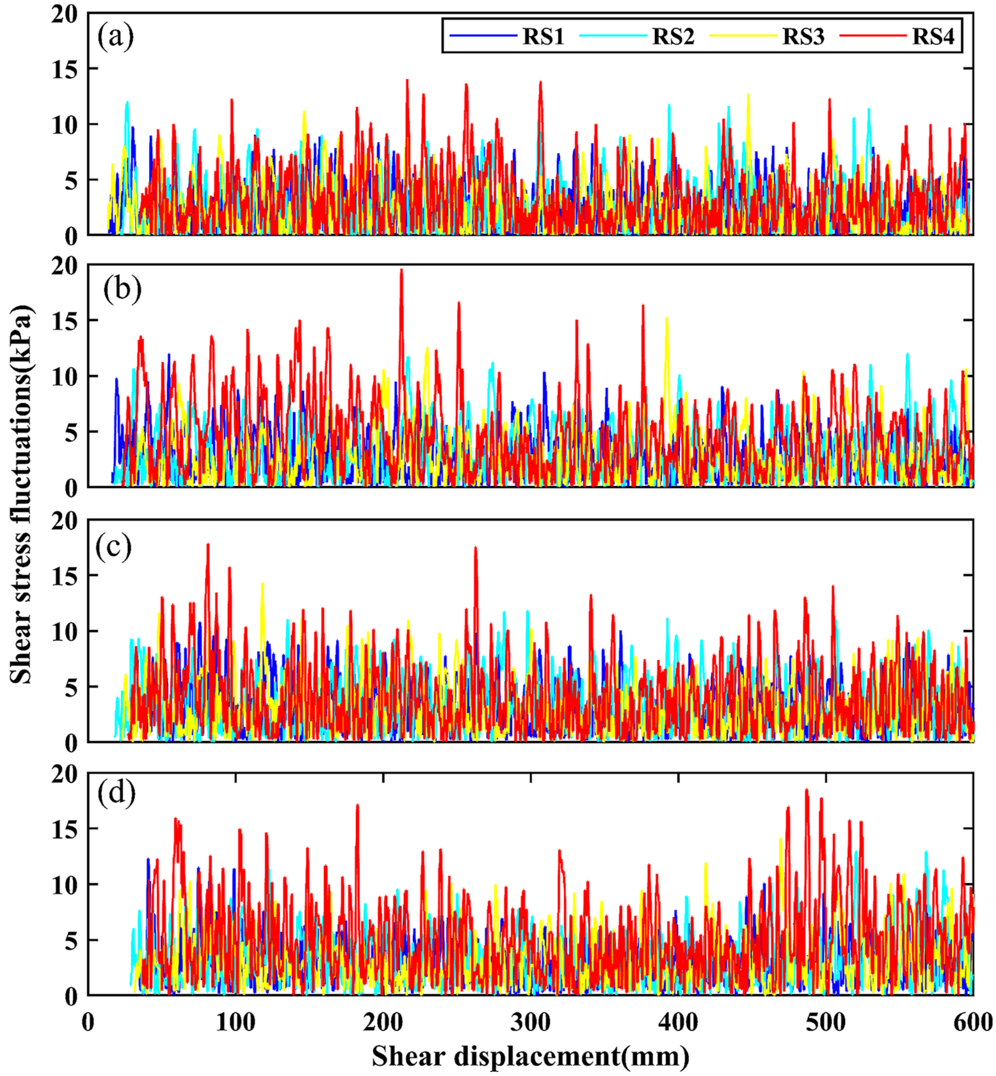


Fig. 9 The relationship between shear stress fluctuations and shear displacement of granular materials under normal stress of 200 kPa. Shear rates: (**a**) 10°/min; (**b**) 30°/min; (**c**) 90°/min; (**d**) 180°/min

shear stress of the high friction particle system, i.e., the high friction system exhibits the high-rate dependency.

The shear stress of granular materials is affected by various factors such as normal stress and shear rate. Therefore, the shear stress of granular materials as a whole does not increase with increasing friction coefficient, but presents different shear mechanical properties at low and high normal stresses. Wei et al. [17] found in triaxial compression experiments that the friction coefficient has a small effect on the bias stress-axial strain and axial strain-volume strain curves of the granular system at low normal stresses, whereas the friction coefficient exerts a large effect on the mechanical response of the granular system at high normal stress conditions. The results of our ring shear tests are similar, the average shear stresses of the granular materials for the low and high friction systems are almost the same under low normal stress conditions, whereas the influence of the friction coefficient on the shear properties of the granular materials dominates under high normal stress conditions, and the shear stresses show a tendency to increase with increasing friction coefficients. There are two main reasons for this, firstly, the difference in shear resistance caused by the friction coefficient increases significantly for the particle system with high normal stress. Secondly, the high normal stress effectively limits the shear dilatancy phenomenon of the granular material [27], and the increase of the friction coefficient leads to the difficulty of inter-particle rearrangement in the shear process, and the particle sliding contact ratio of the high-friction system is significantly larger than that of the low-friction granular system, which exhibits a large shear stress value.

The rearrangement of internal particles during shearing of granular materials causes fluctuations in shear stress. In the low-friction granular regime, the major force chain

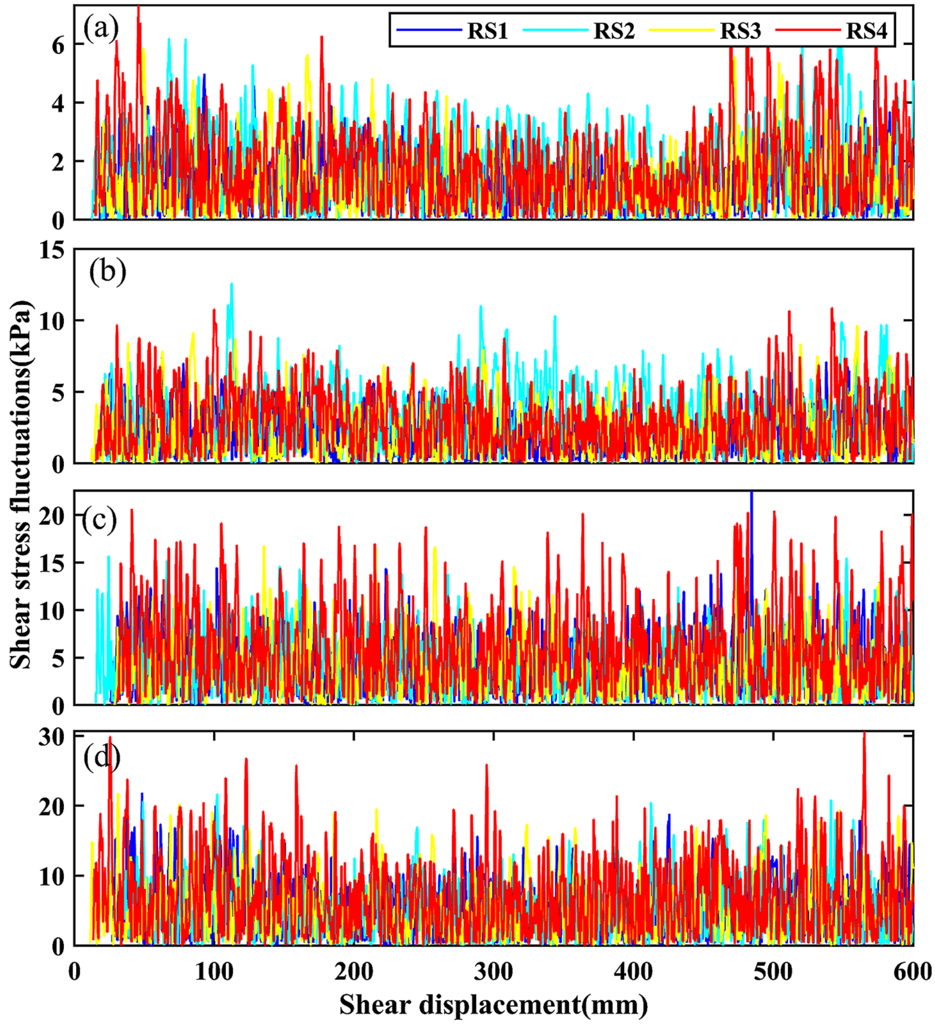


Fig. 10 The relationship between shear stress fluctuations and shear displacement of granular materials under shear rates of 90°/min. Normal stress: (**a**) 50 kPa; (**b**) 100 kPa; (**c**) 300 kPa; (**d**) 400 kPa

network can collapse gradually, whereas in the high-friction granular regime, the major force chains can collapse almost suddenly when the tangential force reaches a limiting value for most of the strong contacts [40]. Therefore, the friction coefficient induces different ways of force chain network evolution in the granular system on the microscale, which in turn exhibits different magnitudes of stress fluctuations. However, our experimental results show that the effect of the friction coefficient on the shear stress fluctuation is only obvious when the friction coefficient reaches a certain limit value. The shear rate affects the particle rearrangement process in the granular system and therefore also affects the magnitude of the shear stress fluctuations. When the shear rate increases to a certain limit value (360°/min), the stress fluctuation of the particle system with low friction system shows a rate weakening phenomenon, and below this shear rate, the shear stress fluctuation shows a positive shear rate effect. However, for the particle system with high friction system, the shear stress fluctuation shows a positive shear rate effect in the range of shear rates we tested.

We analyze the average shear stress fluctuation of granular materials at different shear rates and normal stresses, and characterize the extent of fluctuations in the average shear stress of granular materials at different shear rates and normal stresses using error bars (Fig. 16). In the low normal stress state, the shear stress fluctuation of the high friction coefficient particle system is higher than that of the low friction particle system. Under the low normal stress condition, the particle flow rate is fast, the force chain within the particle system undergoes frequent breakage and reorganization, and the friction coefficient has a significant effect on the force chain evolution process. However, under the high normal stress condition, the particle flow process is very slow, and the breakage and reorganization of the force chain inside the particles are infrequent, and the stress fluctuation generated at this time is related to the breakage of the major force chain. Therefore, the obvious shear stress fluctuation under high normal stress occurs only after the friction coefficient increases to a certain value.

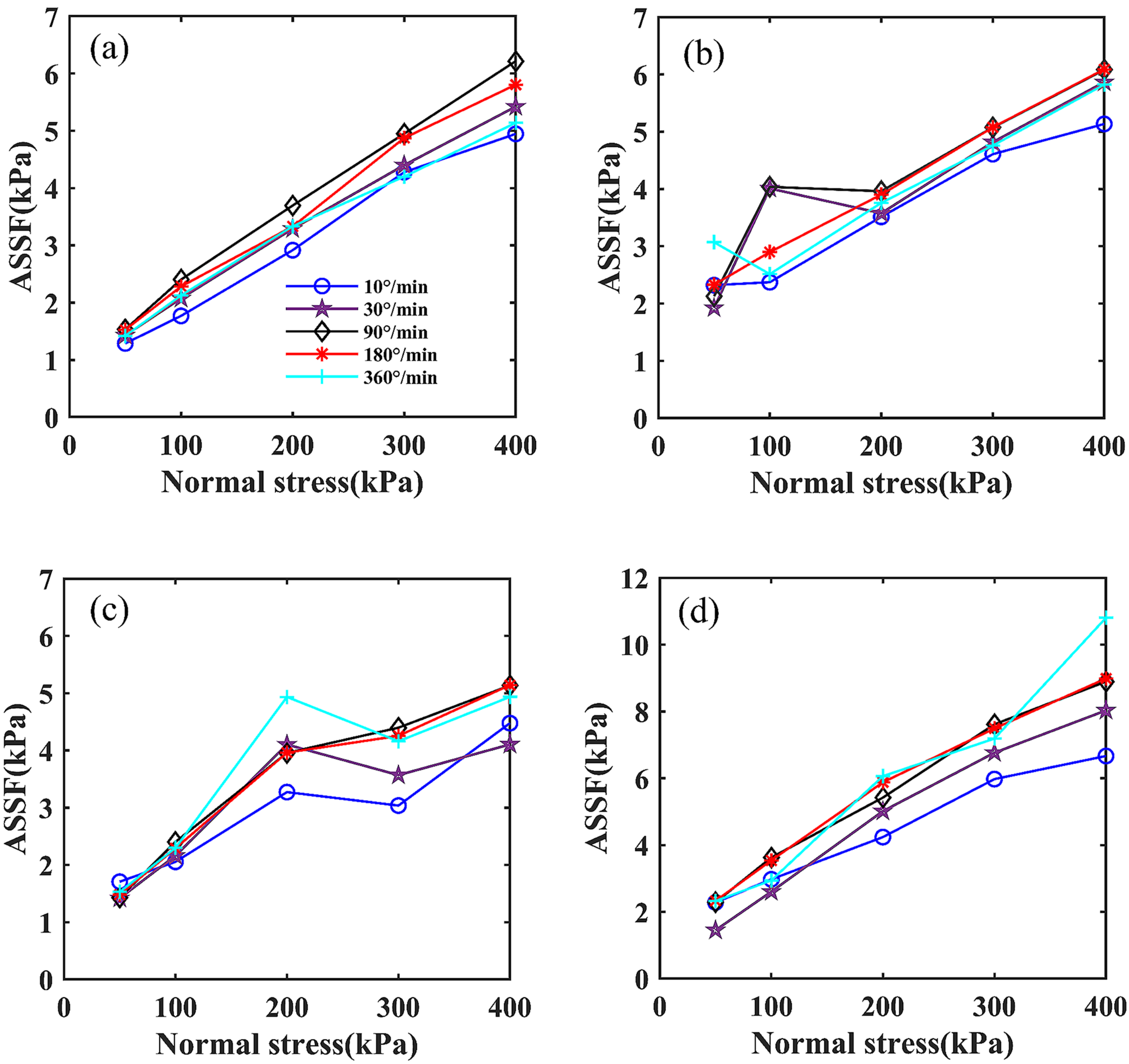


Fig. 11 Variation of average shear stress fluctuations of granular materials at different shear rates. Materials: (**a**) steel balls; (**b**) polypropylene balls; (**c**) polyoxymethylene balls; (**d**) aluminum balls

4.2 Effect of friction coefficient on granular flow

During the sliding phase of the landslide, the granular material behaves as a solid phase or a liquid phase, which is a typical phenomenon of the shear flow of granular materials [41]. Particle flow can be divided into quasi-static flow, inertial particle flow, and fast particle flow according to the inertia number [3]. The friction coefficients of granular materials are the essence that affects their macroscopic flow behavior. In the shear particle system, the shear stress of the particle material with different friction coefficients is different, which leads to the difference of the effective friction coefficient $\mu = \tau / P$ (where τ and P are the shear stress and normal stress) of the granular system. There is a one-to-one relationship between the effective friction coefficient μ and the inertia number I in the local rheological model [42–44]. Therefore, macroscopic shear stress and normal stress directly determine the flow state of particles.

There exist force chain networks in frictional contact with each other within the particle system, and the solid-like phase has a certain resistance to deformation. The strength of the system is mainly determined by the stresses that these frictional contacts can withstand. When a sufficient number of contacts break under large stress conditions, the entire

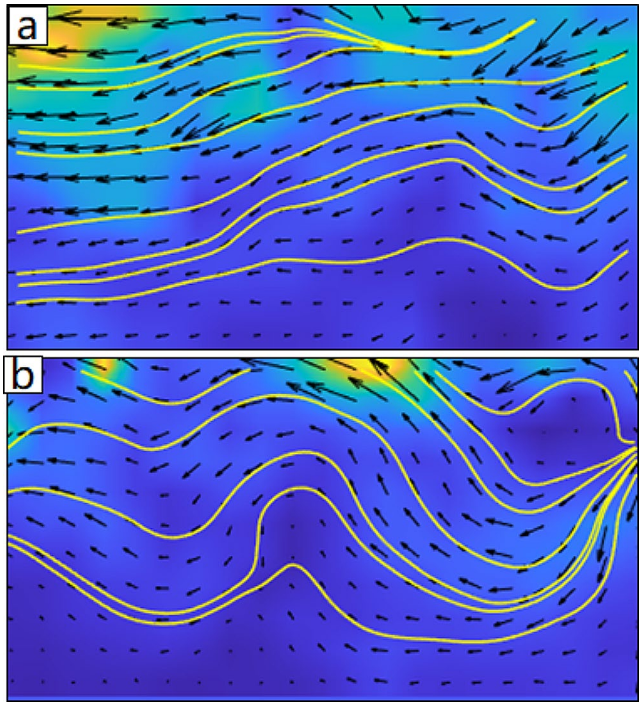


Fig. 12 The velocity field during shearing of granular material. Materials: (**a**) steel balls; (**b**) aluminum balls

internal structure exhibits a collapsing behavior, resulting in the granular system yielding to flow [45, 46]. The experiment results show that at low normal stresses, the difference in shear stresses between particles with different coefficients of internal friction is small, resulting in similar effective friction coefficients, and thus the particles with different coefficients of internal friction show similar flow states. However, at high normal stresses, the difference in shear stresses between the high and low friction particle systems is large, and the effective coefficients of friction of the particle systems are different at the same normal stresses, so that the particle systems show different flow states.

We averaged the velocity field of continuous multi-frame images after the granular material reaches a steady state, the overall granular material flows along the horizontal shear direction, and combined with the flow velocity profile of the granular system, the schematically of the flow system is shown in Fig. 17. During the shearing process of granular materials, the velocity of the particles increases sequentially from the bottom to the top. Along the direction of sample height, it can be roughly divided into three regions: the upper liquid phase region, the middle solid-liquid phase transition region, and the lower solid phase region. The widths of the three regions of granular materials with different friction coefficients are different, and the smaller the friction coefficient of granular materials, the larger the liquid phase flow region.

5 Conclusion

The friction force between particles is one of the important factors affecting the shear characteristic. The purpose of this research is to investigate the shear mechanical behavior of granular materials with different friction coefficients, and to study the effect of friction coefficient on the shear stress, peak shear strength, shear stress fluctuation, and shear flow characteristics of granular materials. The results can be summarized as follows:

(1) The difference in average shear stress between low and high friction systems with different shear rates is small under low normal stress conditions. As the normal stress increases, the shear stress increases at a higher rate for the high friction system than that of low friction particle system.
(2) At low normal stress conditions, the shear rate has less effect on the peak shear stress for low friction systems. In contrast, for high friction coefficient particulate materials, the peak shear stress of particulate materials shows a positive shear rate effect. At high normal stresses, the rate of increase of peak shear stress with normal stress is greater for high friction coefficient particulate materials than for low friction coefficient particulate systems.
(3) When the shear rate is increased to a certain limit (360°/min), the stress fluctuation of the particle system with low friction shows a rate weakening phenomenon, below which the shear stress fluctuation shows a positive shear rate effect. For the high friction particle system, the shear stress fluctuation always shows a positive shear rate effect within the range of shear rates in our experiments.
(4) At low normal stresses, the particle systems with different internal friction coefficients have small differences in shear stresses resulting in similar effective friction coefficients and exhibit similar flow regimes. With the increase of normal stress, the flow rate of particulate materials with high friction coefficient is significantly lower than that of low friction particulate systems, and the flow of particles mainly occurs in localized areas. The flow region of the granular system decreases with increasing normal stress and granular friction coefficient.

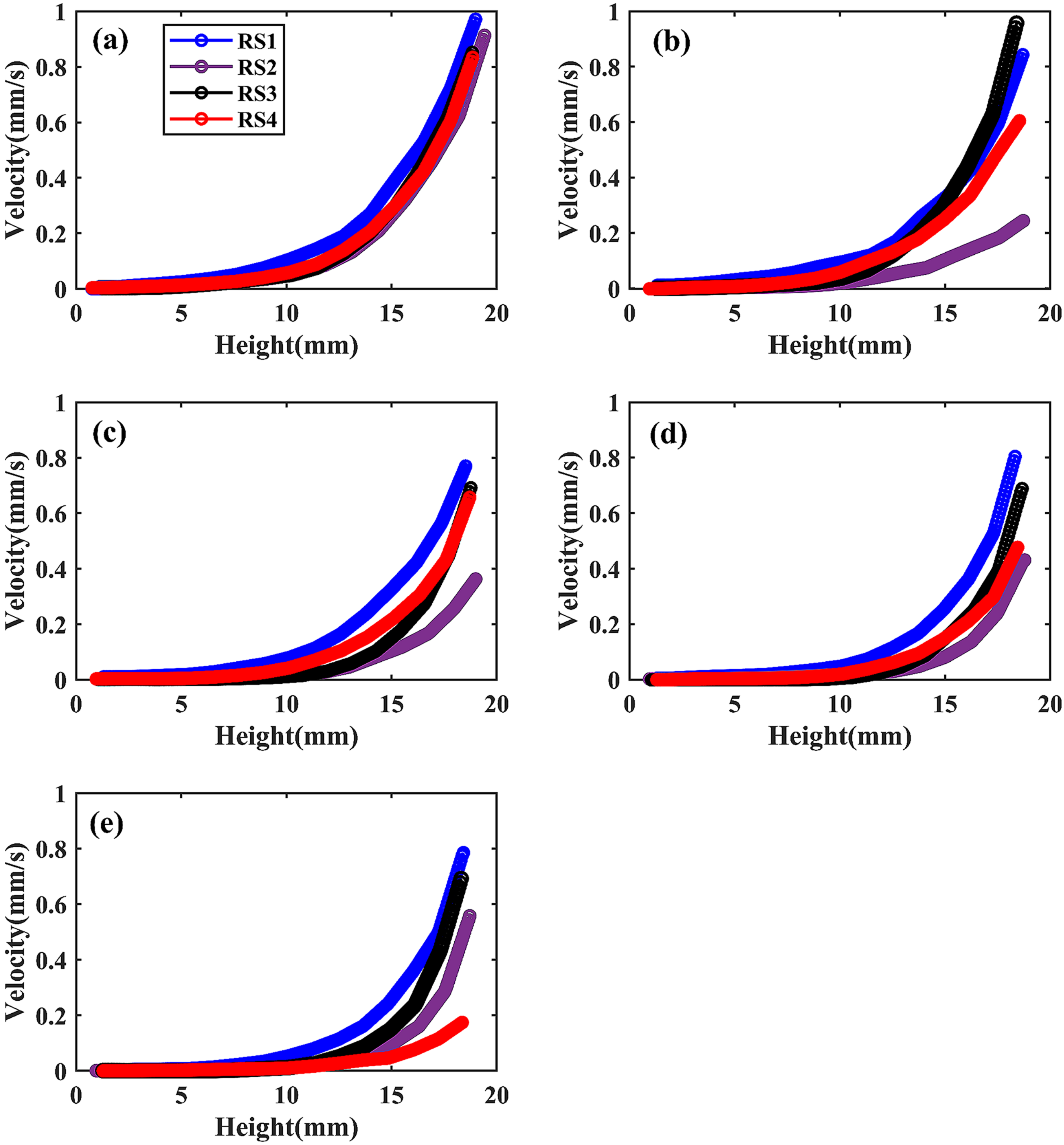


Fig. 13 Velocity profiles of granular materials with different friction coefficients. Normal stress: (**a**) 50 kPa; (**b**) 100 kPa; (**c**) 200 kPa; (**d**) 300 kPa; (**e**) 400 kPa

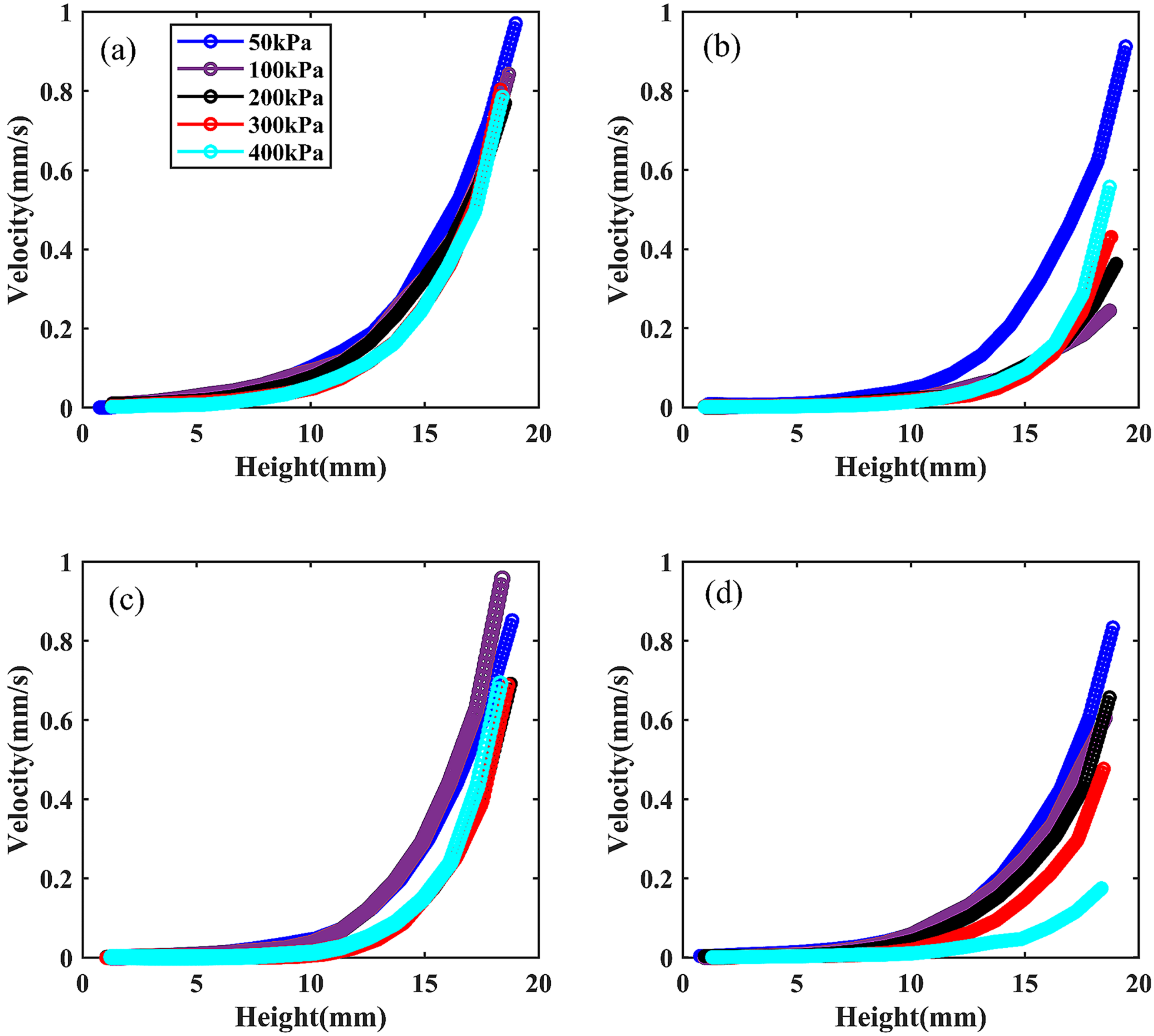


Fig. 14 Velocity profiles of granular materials with different normal stresses. (**a**) steel balls; (**b**) polypropylene balls; (**c**) polyoxymethylene balls; (**d**) aluminum balls

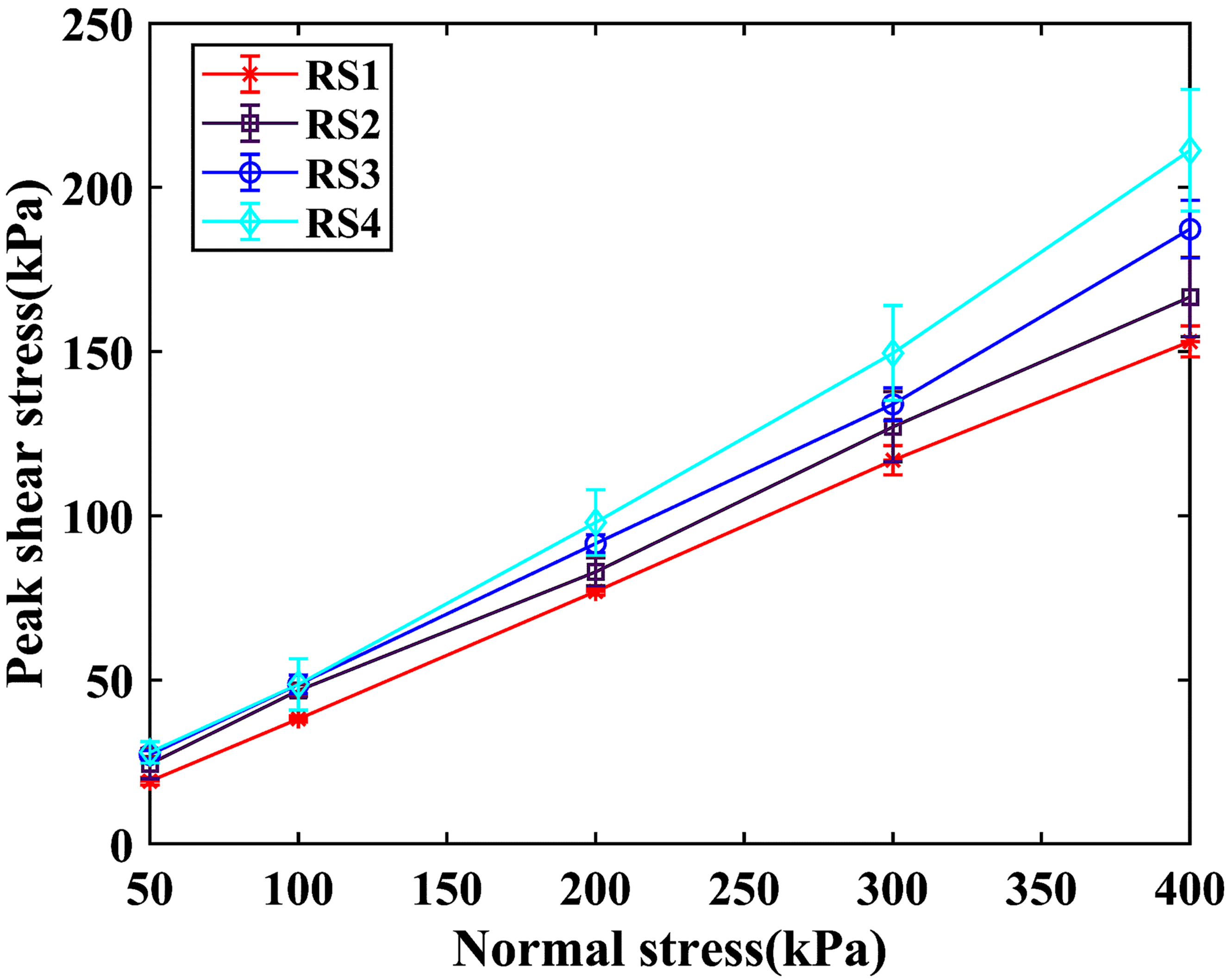


Fig. 15 The relationship between peak shear stress and normal stress of granular materials

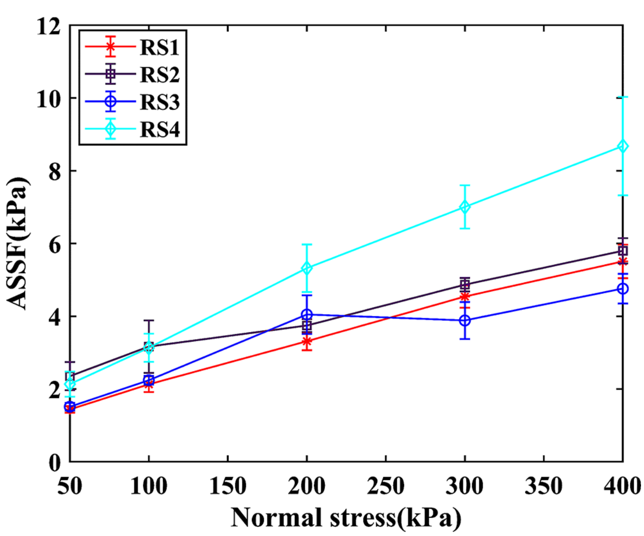


Fig. 16 Discrete variation of average shear stress fluctuation of granular materials at different shear rates

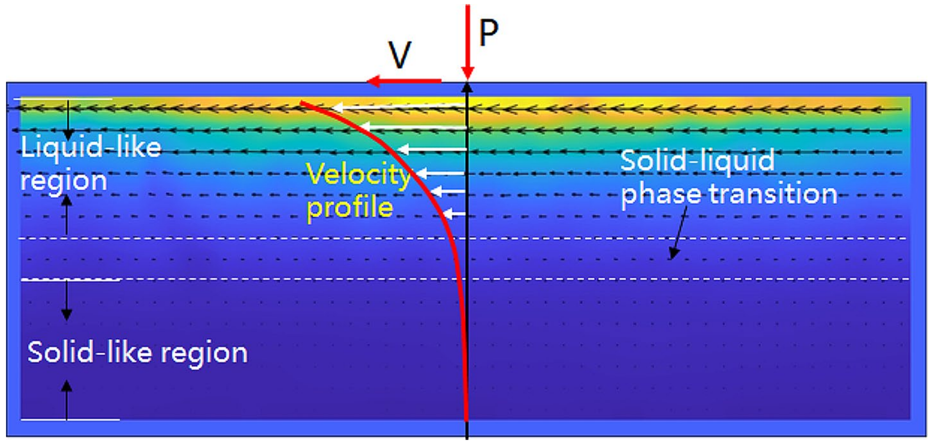


Fig. 17 Schematically of granular material during shearing

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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