

Responses to the Comments by Editors and Reviewers

Dear Professor Parise:

Upon your recommendation, we have carefully revised Paper nness-2019-156 entitled “Shear rate effect on the residual strength characteristics of saturated loess” after considering all the comments made by the reviewers.

We thank Professor Parise, Editor and anonymous reviewers for their constructive comments. The manuscript has been significantly improved by incorporating their suggestions. The following are our point-to-point responses to their comments.

Responses to the Comments from Editor and reviewers

Comments from the editors and reviewers:

1. As indicated by the reviewer, there are some technical issues with formatting (tab.2, text justification, use of different font for references). Authors are kindly asked to adjust all these incongruences.

Reply: Implemented.

With regards to technical issues with formatting (Table 2), we have adjusted Table 2 according to the review’s suggestion, see details in Table 2 (lines 455-456) of the revised manuscript.

With regards to technical issues with formatting (text justification), we have adjusted text, see details on lines 44-49, 90-100, 130-144, 154-167, 197-214, 219-259, 381-387, 402-424, 434-443, 459-474 and 484-522 of the revised manuscript.

With regards to technical issues with formatting (use different font for references), we have used the same font for references, see details on lines 568-570 of the revised manuscript.

2. Please also have a careful look at the text, where I have noticed there are many points where you need to separate words.

Reply: Implemented. See details on lines 33, 255, 261,283, 371, 373, 383, 394, 427, 440, 461, 496 of the revised manuscript.

1 Shear rate effect on the residual strength characteristics of saturated loess in naturally
2 drained ring shear tests

3

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19 **Abstract**

20 Residual shear strength of soils is an important soil parameter for assessing the
21 stability of landslides. To investigate the effect of the shear rate on the residual shear
22 strength of loessic soils, a series of naturally drained ring shear tests were carried out
23 on loess from three landslides at two shear rates (0.1 mm/min and 1 mm/min).
24 Experimental results showed that the shear displacement to achieve the residual stage
25 for specimens with higher shear rate was greater than that of the lower rate; both the
26 peak and residual friction coefficient became smaller with increase of shear rate for
27 each sample; at two shear rates, the residual friction coefficients for all specimens
28 under the lower normal stress were greater than that under the higher normal stress.
29 Moreover, specimens with almost the same low fraction of clay (CF) showed similar
30 shear rate effect on the residual friction coefficient with normal stress increasing,
31 whereas specimen with high CF (24%) showed the contrast tendency, indicating that
32 such effect is closely associated with CF. The tests results revealed that the difference
33 in the residual friction angle ϕ_r at the two shear rates, $\phi_r(1) - \phi_r(0.1)$, under each
34 normal stress level were either positive or negative values of which the maximum
35 magnitude is about 0.8° . However, the difference $\phi_r(1) - \phi_r(0.1)$ determined under all
36 normal stress levels was negative, which indicates that the residual shear parameters
37 reduced with the increasing of the shear rate in loess area. Such negative shear rate
38 effect on loess could be attributed to a greater ability of clay particles in specimen to
39 restore broken bonds at low shear rates.

40 **Keywords:** Loess; Residual shear strength; Ring shear test; Shear rate; Residual shear
41 parameter

42

43 **1. Introduction**

44 Residual shear strength of soil is of great significance for evaluating the stability
45 for the slip surface of first-time landslides as well as reactivated landslides (Bishop et
46 al., 1971; Mesri and Shahien, 2003; Tiwari and Latha, 2019; Li et al., 2017). The
47 residual strength of soils is defined as the minimum constant value of strength along
48 the slip plane, in which the soil particles are reoriented and subjected to sufficiently
49 large displacements in relatively low shear rate (Skempton, 1985).

50 Numerical studies have been done to assess the residual strength through the
51 laboratory tests using ring shear tests and reversal direct shear tests (Vithana et al.,
52 2012; Summa et al., 2018; Moeyersons et al., 2008; Chen and Liu, 2013; Summa et al.,
53 2010). It is a generally accepted fact that the measurement of the residual strength is
54 most preferred done with a ring shear test since it allows the soil specimen be sheared
55 at unlimited displacement which can simulate the field conditions more accurately
56 (Sassa et al., 2004; Tiwari and Marui, 2005; Lupini et al., 1981; Bhat, 2013). Until now,
57 great efforts have been paid to the study of the shear rate effect on the minimum value
58 of clay or sand strength at residual states (Li et al., 2017; Tika and Hutchinson,
59 1999; Suzuki et al., 2007; Grelle and Guadagno, 2010; Lemos, 1985; Tika,
60 1999; Morgenstern and Hungr, 1984). As a result, the residual strength of clay or sand
61 under the effect of shear rate has been made relatively clear. However, compared with
62 the results of tests on clay or sand, understanding of the shear characteristics of silty
63 soil, such as loess, is not yet complete. As pointed out by Ding (2016), some drained
64 ring shear tests have concluded that the increase in shear rate causes the residual

65 strength of loess to increase. On the contrary, Kimura et al. (2014) reported that the
66 residual strength of Malan loess decreases with the increase of shear rate. Furthermore,
67 Wang et al. (2015) found that the effect of shear rate on residual strength of loess is
68 closely associated with the normal stress levels, and the change in residual strength of
69 loess samples under high normal stress levels is small in ring shear tests.

70 Therefore, some inconsistent or even opposite results have been reported in the
71 ring shear tests on loess above, which maybe attributed to the differences in the grain
72 size distribution and mineral composition of the different material tested in previous
73 studies (Ajmera et al., 2012). Particularly, this discrepancy maybe due to the
74 difference in quantity and mineralogy of clay fraction (Nakamura et al., 2010;Li et al.,
75 2013). Therefore, the previous studies on the effect of shear rate on residual strength
76 of loess implied that there is still a lack of experimental data on this topic. From the
77 above investigations, it can be concluded that the effect of the shear rate on the
78 residual strength of the loess is not fully understood and needs further scrutiny.
79 Moreover, it should be noted that the residual strength parameters (friction angle)
80 obtained from using different shear rates may be adopted to provide a guide for
81 designing some precision engineering which require high accuracy of the design
82 parameters, thus, the effect of the shear rate on the residual strength of soils should be
83 fully investigated to determine the parameters with high reliability. In addition,
84 residual strength parameters of soil play a key role in assessing the stability analysis
85 of landslides (Xu et al., 2018;Wesley, 2018). Therefore, accurate determination of the
86 residual strength parameters and their dependence on the shear rate may affect the

87 stability evaluation of landslides. Thus, it is necessary to study the change of residual
88 strength of loess with shear rate in order to have a good understanding of the suitable
89 approach for the residual strength parameters measurement.

90 In this backdrop, to clarify the residual shear characteristics of loess under the
91 effect of the shear rate, a series of naturally drained ring shear tests were conducted on
92 loess obtained from three landslides on the Loess Plateau in China at two shear rates
93 (0.1 mm/min and 1 mm/min). The residual shear characteristics of loess at the
94 residual state was examined. Considering that shear strength of loess reduces with
95 moisture content (Picarelli, 2010;Zhang et al., 2009;Dijkstra et al., 1994), ring shear
96 tests were conducted on saturated loess samples corresponding to the worst condition
97 in field engineering. Furthermore, this study investigated the change in the residual
98 strength parameters of loess at different shear rates and the relationship between the
99 residual strength parameters with the normal stress in naturally drained ring shear
100 tests as well.

101

102 **2. Geological setting of landslide sites**

103 Soil samples from three landslides in the northwest of China were selected in this
104 study. Soil samples used for the ring shear tests and index measuring tests
105 predominantly consist of loess deposits and were collected in a disturbed condition.
106 For convenience, the names of landslide sites were abbreviated into Djg, Ydg and
107 Dbz. Fig. 1 shows the study sites and some views of the landslides.

108 **Dingjiagou landslide (Djg)**

109 The Djg landslide, located at the mouth of Dingjia Gully in Yan'an of China, is

110 geologically composed of upper loess and lower sand shale in the Triassic Yanchang
111 formation (She, 2015). The dustpan-shaped landslide is inclined to the east, with its
112 inclination 75.85° . The landslide is 350 m in width, 180 m in length, 70 m in elevation.
113 The average thickness of slip mass is around 20 m, and the volume of landslide
114 totaled approximately $105 \times 10^4 \text{ m}^3$. The slip mass is mainly constituted by loess,
115 whereas the sliding bed consists of sand shale in Yan-chang formation. The thickness
116 of the sliding zone varied from 30 to 50 cm. The front lateral region of the main slide
117 section of the Djg landslide, where the sampling was performed, was found to be silty
118 clay.

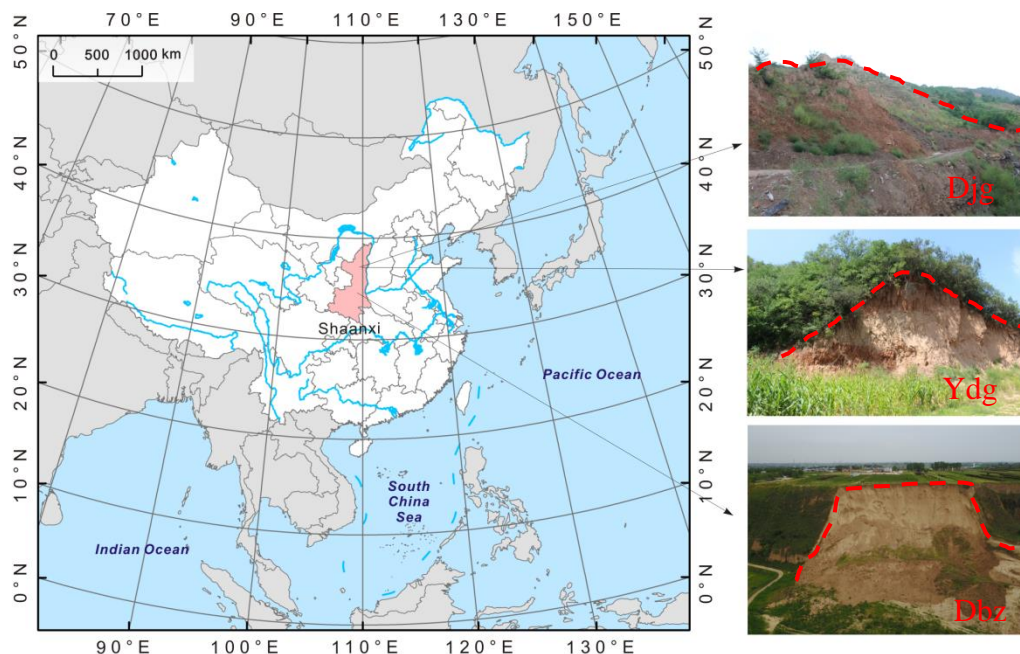
119 **Yandonggou landslide (Ydg)**

120 The Ydg landslide, located in the Qiaogou town of Yan'an in Shaan xi province of
121 China. The top and the toe altitude of the landslide are about 1165 m and 1110 m
122 above the sea level, with the height difference between the toe and the top of landslide
123 about 55 m. The slides have well-developed boundaries with the main sliding
124 direction of 240° and slope angle of 30° . From the landslides profile, the sliding masses
125 from top to bottom were classified by late Pleistocene (Q_3) loess, Lishi (Q_2) loess and
126 clay soil, respectively (Zhang et al., 2006). Multiple landslides had occurred in this
127 site, and the soil samples used in this study were collected from Q_2 loess stratum
128 within the slide ranged from 4.5 m to 18 m in height.

129 **Dabuzi landslide (Dbz)**

130 The Dbz landslide located in the middle part of Shaanxi province (about E
131 $108^\circ 51' 36''$ and N $34^\circ 28' 48''$), China, which is a semi-arid zone dominated by loessic
132 geology (Yan et al., 2015). In this region, the investigated site is classified as a typical

133 loess tableland with Quaternary stratum (Ma et al., 2019). The sedimentary losses in
134 this area are grey yellow, and the exposure stratum in this area has been divided into
135 two stratigraphic units, namely, the upper Malan (Q₃) loess and the lower Lishi (Q₂)
136 loess, of which the Q₃ loess is younger. The Q₃ loess is closest to the surface and is up
137 to approximately 12 m thick, while the thickness of Q₂ loess may reach an upper limit
138 of about 50 m (Leng et al., 2018). The loess in this area have well-developed vertical
139 joints (Sun et al., 2009). The travel distance and the maximum width of the slip mass
140 are roughly estimated to be 122 m and 133 m, respectively. The armchair-shaped
141 landslide shows an apparent sliding plane, with an area of approximately 15,660 m²
142 and about 66.25 m maximum difference in elevation. The main direction of this
143 landslide is approximately 355°. The exposed side scarp of the landslide, where the
144 sampling was done, was found to be entirely in the Q₂ loess stratum.



145
146 Fig. 1. Location of study sites and some views of landslides (after Hu et al., 2018)

147 Notes: Red dashed lines in the Fig. 1 represent landslide boundary.

148 3. Experimental scheme

149 **3.1. Testing sample**

150 The fact that the residual shear strength is independent of the stress history has
151 been reported by many researchers (Bishop et al., 1971; Stark et al., 2005; Vithana et
152 al., 2012). Thus, disturbed loess samples from each landslide weighing about 25 kg
153 were collected to investigate the residual shear strength.

154 The soil samples were air-dried, and then crushed with a mortar and pestle as it
155 has been reported that crushing samples were suitable to determine the residual
156 strength of the remoulded soils (Stark et al., 2005). It was found that small lumps may
157 exist in air-dried samples, which may be too big for the cell, so lumps were crushed in
158 order to make sample uniform. This should be done with care so as not to destroy
159 silty-dominated loess. After that, soil samples were processed through 0.5 mm sieve.
160 Distilled water was then added to the soil samples until saturated water content were
161 obtained. The physical parameters such as natural moisture content (*in-situ* moisture
162 content), specific gravity, bulk density, plastic limit, and liquid limit were determined
163 in accordance with the Chinese National Standards (CNS) GB/T 50123-1999
164 (standards for soil test methods) (SAC, 1999), but clay size was defined to be less
165 than 2 μm followed ASTM, D 422 (ASTM, 2007). Each soil sample was separated
166 into clay (sub 0.002 mm), silt (0.002-0.075 mm), and sand (0.075-0.5 mm) fractions.
167 The physical indexes of the soil are listed in Table 1.

168 The grain size distribution of soil was measured using a laser particle size
169 analyzer Bettersize 2000 (Dandong Bettersize Instruments Corporation, Dandong,
170 China). The sieved soil samples were used to determine particle size distribution. In

171 this study, soil samples were treated with sodium hexaphosphate, serving as a
 172 dispersant, to disaggregate the bond between the particles. The particle size
 173 distribution curves of soils were shown in Fig. 2. The results show that the clay
 174 fraction in Djg landslide soil (24%) is more than two times than that from Ydg (9%)
 175 and Dbz (9.1%). Furthermore, the particle size analysis illustrated that the percentage
 176 of silt-sized soil in three landslides ranged from 75.66% to 87.4%. In addition, Ydg
 177 landslide soil consists of the greatest percentage of the sand fraction which reaches up
 178 to 10.55% (Table 2 and Fig. 2).

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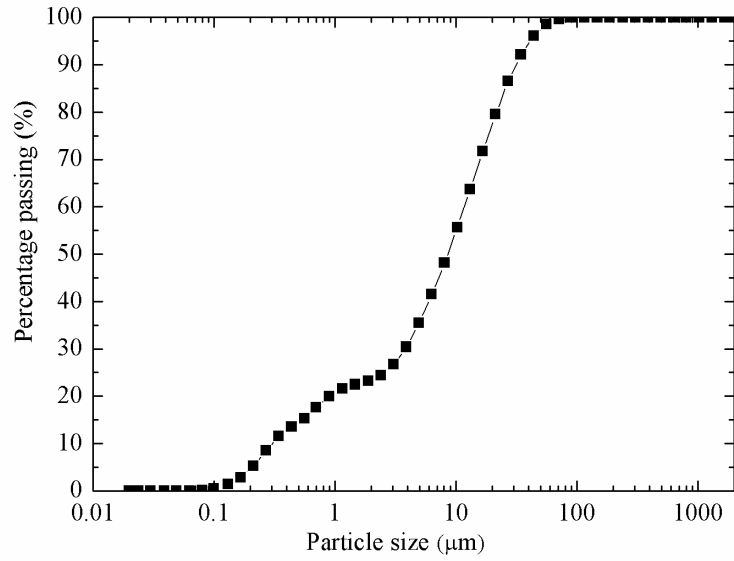
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183 **Table 1.** Physical parameters of slip-zone loess.

| sites | ρ_d | w | ρ | G_s | W_L | W_p | Grain size fractions (%) | | | |
|-------|----------|------|--------|-------|-------|-------|--------------------------|---------------|---------------|-------------|
| | | | | | | | <0.002mm | 0.002-0.005mm | 0.005-0.075mm | 0.075-0.5mm |
| Djg | 1.74 | 19.5 | 2.08 | 2.65 | 36 | 20 | 24 | 11.48 | 64.18 | 0.34 |
| Ydg | 1.47 | 18 | 1.74 | 2.71 | 33 | 19 | 9 | 5.28 | 75.17 | 10.55 |
| Dbz | 1.48 | 16 | 1.72 | 2.70 | 32 | 21 | 9.1 | 6.4 | 81 | 3.5 |

184 Notes: ρ_d = dry density (g/cm^3); w=moisture content (%); ρ = bulk density (g/cm^3); G_s
 185 = specific gravity; W_L =liquid limit (%); W_p = plastic limit (%).

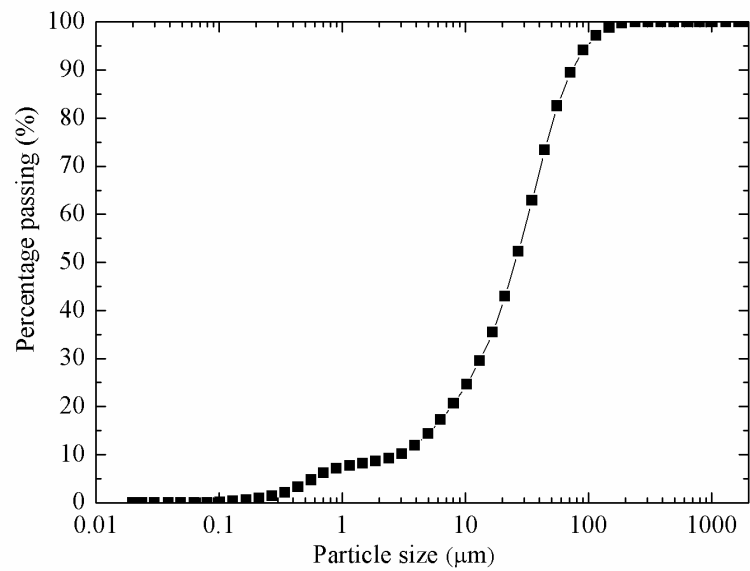


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(a) Particle size distribution curve of soil obtained from DJG

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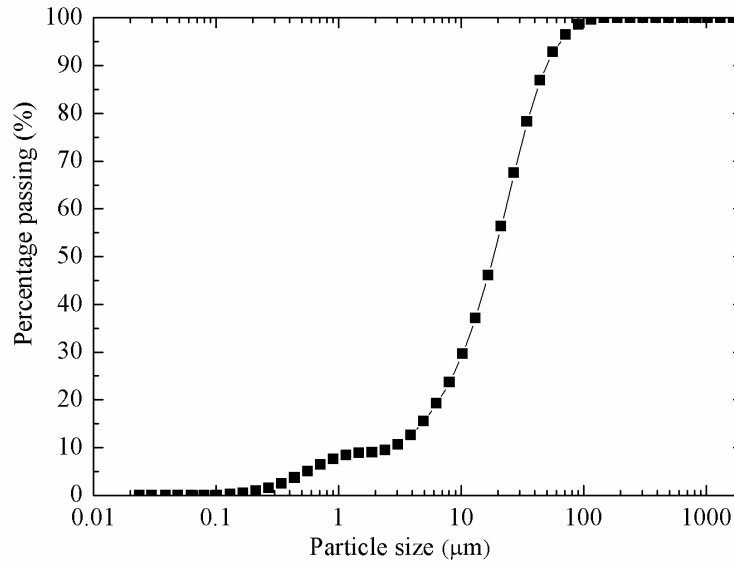


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(b) Particle size distribution curve of soil obtained from YDG

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192

(c) Particle size distribution curve of soil obtained from DBZ

193

194 Fig. 2. Particle size distribution curves.

195

196 3.2. Testing apparatus

197 An advanced ring shearing apparatus (SRS-150), the Bromhead-type ring shear

198 apparatus, manufactured by GCTS (Arizona, USA) was adopted in ring shear tests

199 and the photos of apparatus were shown in Fig. 3, which consists mainly of a shear

200 box with an outer diameter of 150 mm, an inter diameter of 100 mm and the maximal

201 sample height of 250 mm. The shearing box consists of the upper shear box and the

202 lower shear box. In the shearing process, the upper shear box keeps still while the

203 lower one rotates. The apparatus, which provides an effective specimen area of 98

204 cm², is capable of shearing the specimen for large displacements. The annular

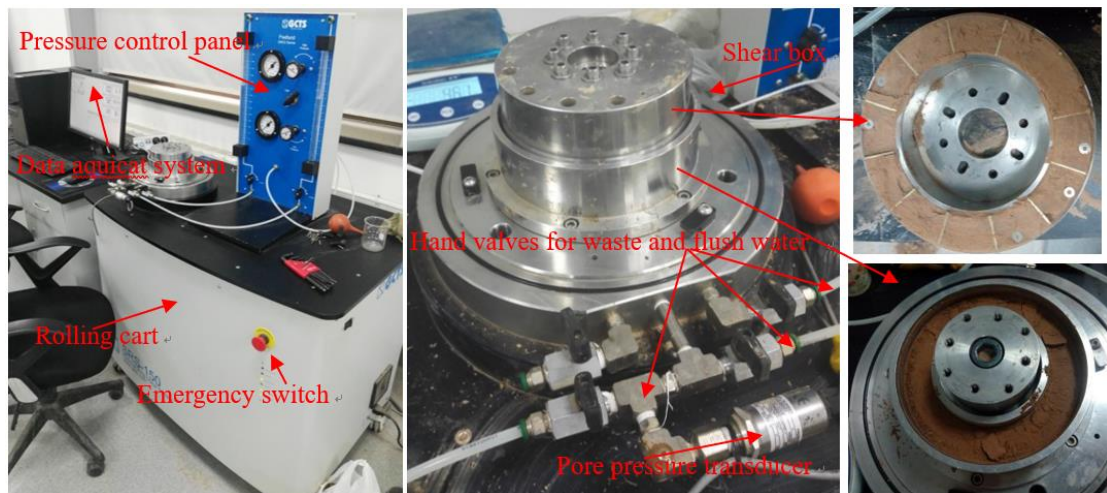
205 specimen is confined by inside and outside metal rings. Moreover, the specimen is

206 confined by bottom annular porous plates and top annular porous plates in which have

207 sharp-edged radial metal fins which protrude vertically into the top and bottom of the

208 specimen at the shearing process. Two annual porous plates were used to provide

209 drainage condition in the test following previous research (Stark and Vettel, 1992).
210 The normal stress, shear strength and shear displacement can be monitored by
211 computer in shearing process. The measurement features of the ring shear apparatus
212 employed in this study are described as follows: shear rate range from 0.001 degrees
213 to 360 degrees per minute, 10 kN axial load capacity, 300 Nm continuous torque
214 capacity, maximum normal stress of 1000 kN/m².
215



216
217 Fig. 3. Ring shear apparatus (SRS-150)

218 3.3. Testing procedure

219 This study was comprised of 3 groups of test results, in which 24 remolded
220 saturated loess samples were sheared with normal stress ranging from 100 to 400
221 kN/m² under two shear rates. In present study, reconstituted samples of the sub 0.5
222 mm soil fractions were prepared for the shear tests as it was reported that the residual
223 strength of the soil was unaffected by its initial structure (Vithana et al., 2012; Bishop
224 et al., 1971). Consolidated drained (CD) tests with single-stage shear was performed.
225 Here, the single-stage shear means shearing the sample under effective pressure or
226 stress conditions after the consolidation of the sample. Specimens were first prepared

227 by adding distilled water to the air-dried soil until the saturated moisture contents
228 were obtained. Then, specimens were kept in a sealed container for at least one week
229 to fully hydrate. Afterwards, specimens are reconstituted in the ring-shaped chamber
230 of the apparatus by compaction. During the compaction process, samples were
231 divided into equal five parts and each part was poured into the shear box and
232 compacted. Samples with a height of 2.5 cm in this study were prepared in five layers
233 of equal height to achieve the required density. The specimen was then consolidated
234 under a specific effective normal stress in a range of 100 kN/m² to 400 kN/m² until
235 consolidation was achieved. In this study, consolidation was completed when the
236 consolidation deformation was smaller than 0.01 mm within 24 hr (Kramer et al.,
237 1999;Shinohara and Golman, 2002). In ring shear tests, the normal stress at the
238 shearing was the same as at consolidation stage. Shear strength of loess specimen was
239 recorded at intervals of 1s before the peak shear strength, after the peak, the sampling
240 rate was increased to 1 min.

241 In this study, ring shear tests were performed in a single stage under naturally
242 drained condition and the samples were subjected to shearing until the residual state
243 was achieved. Following the Bromhead (1992), the residual state was defined when a
244 constant shear stress is obtained for more than half an hour. Drained condition of the
245 shearing process is provided by two porous stones attached on the top and the bottom
246 platen of the specimen container. As for soil specimens with low permeability, the
247 rate of excess pore pressure generation in the shear box may exceeded that of
248 pore-pressure dissipation, this type of condition is identified as naturally drained

249 condition in previous studies (Okada et al., 2004). Furthermore, Tiwari (2000)
250 asserted that it was acceptable to use a shear rate below 1.1 mm/min to simulate the
251 field naturally drained condition. Thus, shear rates of 0.1 mm/min and 1 mm/min
252 were used in this study to simulate the naturally drained condition of the slip zone
253 soils.

254 **4. Results and discussion**

255 **Twenty-four** specimens were tested to investigate the residual shear characteristics
256 of the saturated loess in the ring shear apparatus. Residual shear strength of loess was
257 determined following the research conducted by Bromhead (1992) who pointed out
258 that the residual stage is attained if a constant shear stress is measured for more than
259 half an hour. Tests results are shown in this section.

260 **4.1. Shear behavior**

261 **Figs. 4(a)-6(a)** show the typical shear characteristics of the loess (shear rate of 0.1
262 mm/min and 1 mm/min) obtained from three different locations, where, the shear
263 stress is plotted against the shear displacement. It is a widely accepted fact that
264 normal stress has effect on the shear behavior of the soil (Wang et al., 2019;Eid,
265 2014;Kimura et al., 2015;Stark et al., 2005;Eid et al., 2019), thus, the shear behavior
266 of samples at the peak and residual stages, where, the determined peak friction
267 coefficient as well as residual friction coefficient are plotted in Figs. 4(b)-6(b) against
268 the corresponding effective normal stresses as well. The friction coefficient is defined
269 as the shear stress divided by the effective normal stress.

270 **Figs. 4(a)-6(a)** demonstrate that shear stress increases dramatically within small

271 shear displacement and then reduces with shear displacement, until residual
272 conditions were achieved at large displacements. Furthermore, it is obvious that the
273 peak strength and the residual strength of samples with high shear rate (shear rate
274 equal to 1 mm/min) are almost smaller than that of the samples with low shear rate
275 (shear rate equal to 0.1 mm/min). It can be found that shear displacement to achieve
276 the residual stage for specimens with high shear rate is greater than that of the low
277 rate. For example, the minimum shear displacements for attaining residual condition
278 for Djg specimens with low and high shear rate were about 360 mm and 650 mm,
279 respectively. Under the shear rate of 0.1 mm/min and 1 mm/min, Ydg specimens need
280 approximately 80 mm and 1,400 mm displacement to achieve residual stage. However,
281 Dbz specimens require about 40 mm and 60 mm displacement to reach residual
282 condition for low and high shear rate, respectively.

283 **In Figs. 4(a)-6(a)**, a clear drop can be seen, at any normal stress, for specimens
284 obtained from all sites. During shearing, as reported by Terzaghi et al. (1996), strain
285 softening exhibits a dilative behavior for soils. It is seen that the shear behavior is
286 non-linear against the shear displacement. The loess in Djg, Ydg and Dbz exhibited
287 the typical shear stress and shear strain relationship, i.e., the strain softening behavior
288 for a given shear rate (Figs. 4(a)-6(a)). As seen in Figs. 4(a)-6(a), the lower shear rate
289 results in a more obvious dilation effect during the shearing process with a specific
290 normal stress. It is obvious that Djg specimens showed greater peak-post drop than
291 that of Ydg and Dbz specimens. For example, at the normal stress of 100 kN/m², Djg
292 samples show approximately 47.3% and 36.8% decrease from the peak friction

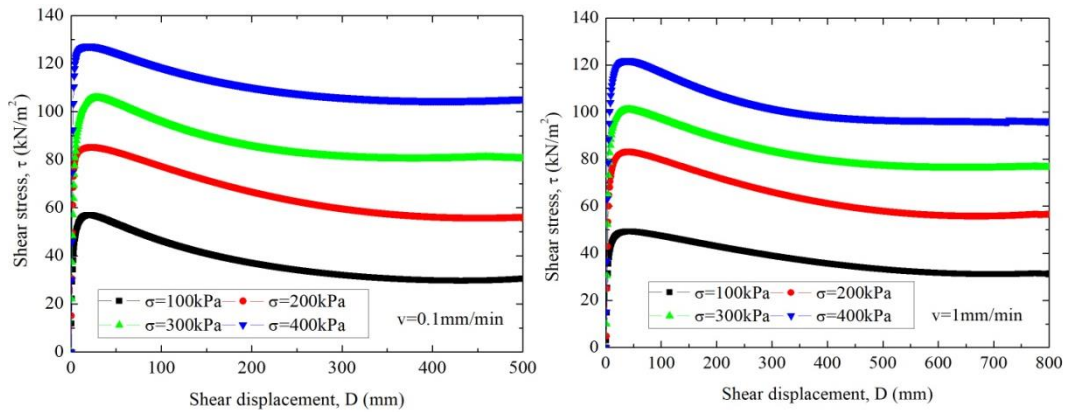
293 coefficient to the residual friction coefficient at low and high shear rates (Fig. 4(b)),
294 respectively, which is greater than in the Ydg samples (about 9.8% and 10.3% in Fig.
295 5(b)) and Dbz samples (about 2.4% and 3.2% in Fig. 6(b)). In Djg samples, an
296 obvious slickenside was observed on the shear surface (Fig. 7). This phenomenon
297 indicates a high degree of reorientation of platy clay minerals parallel to the direction
298 of shearing. In Figs. 4(b)-6(b), on average, it was found that the decrease in the
299 friction coefficient from the peak strength in the Djg sample is almost 18.1% and
300 21.3% for the sample consolidated at normal stress of 400 kN/m² under the low and
301 high shear rate (Fig. 4(b)), while such reduction in friction coefficient in Ydg sample
302 are only about 4.1% and 4.8% (Fig. 5(b)). Furthermore, under the low and high shear
303 rate, the friction coefficient reduction in Dbz samples are only approximately 5.6%
304 and 6.0% (Fig. 6(b)). Skempton (1985) reported that the strength of soils falls to the
305 residual value in ring shear tests, owing to reorientation of platy clay minerals parallel
306 to the direction of shearing. Based on the conclusion that the post-peak drop in
307 strength of normally consolidated soil is only due to particle reorientation after the
308 peak strength (Skempton, 1964; Mesri and Shahien, 2003; Habibbeygi and Nikraz,
309 2018), the results demonstrated that the Djg landslide soil existed the greater particle
310 reorientation compared with that of other two landslide soils.

311

312 **4.2. Effect of normal stress on the friction coefficients**

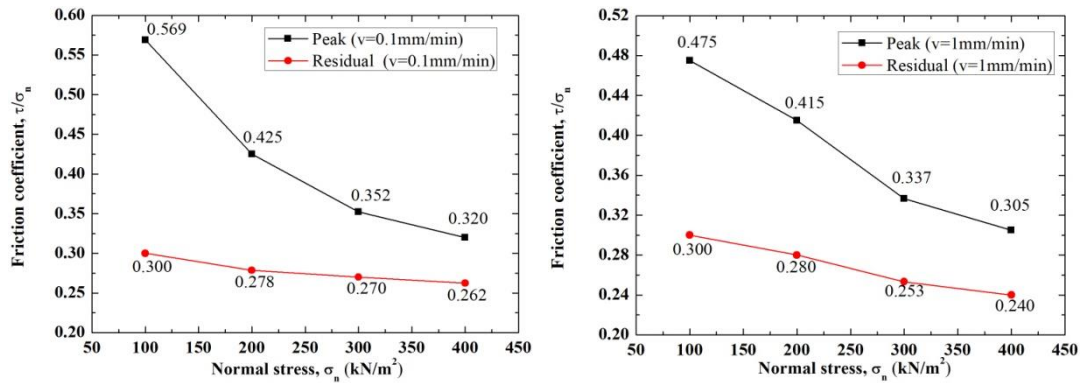
313 It can be seen from the Figs. 4(b)-6(b) that the friction coefficients (peak and
314 residual) are higher at low effective normal stress levels (effective normal stress equal

315 or less than 100 kN/m^2) compared with that at high normal stress (effective normal
 316 stress between 200 and 400 kN/m^2). For example, with normal stress increasing from
 317 100 kN/m^2 to 400 kN/m^2 , the peak and residual friction coefficient of Djg landslide
 318 soils at the shear rate of 0.1 mm/min reduce from 0.569 to 0.32 and from 0.3 to 0.262
 319 (Fig. 4(b)), respectively. Similarly, results obtained from other two landslides loess
 320 also show that the friction coefficients decrease nonlinearly with normal stresses (Figs.
 321 5(b) and 6(b)). Furthermore, specimens with shear rate of 0.1 mm/min attained greater
 322 friction coefficients than that with shear rate of 1 mm/min (Figs. 4(b)-6(b)).



323

324 (a) Relationship between shear stress and shear displacement

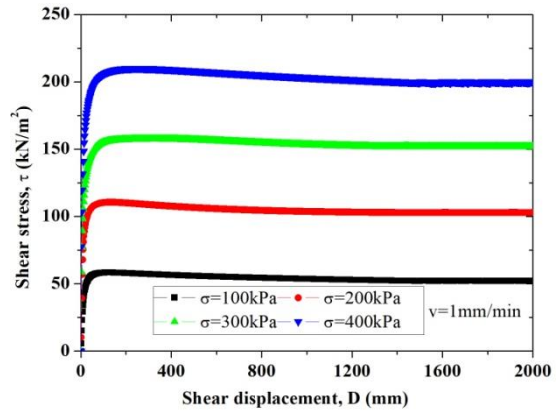
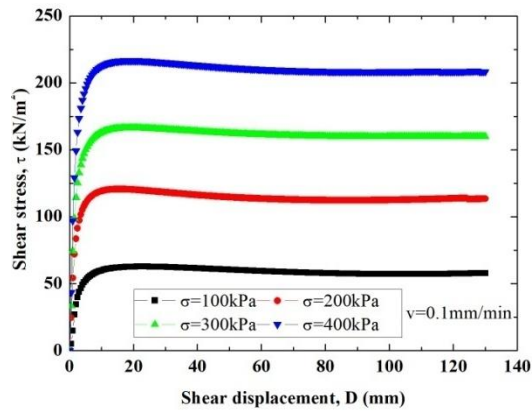


325

326 (b) Relationship between friction coefficient and normal stress

327 Fig. 4. Shear behavior characteristics of Djg soil samples

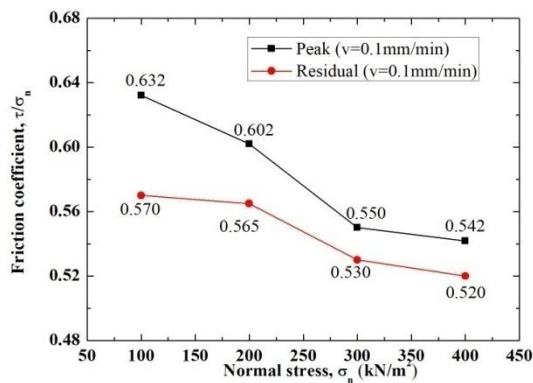
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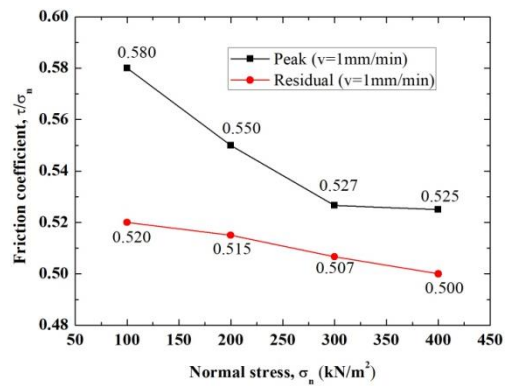
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(a) Relationship between shear stress and shear displacement



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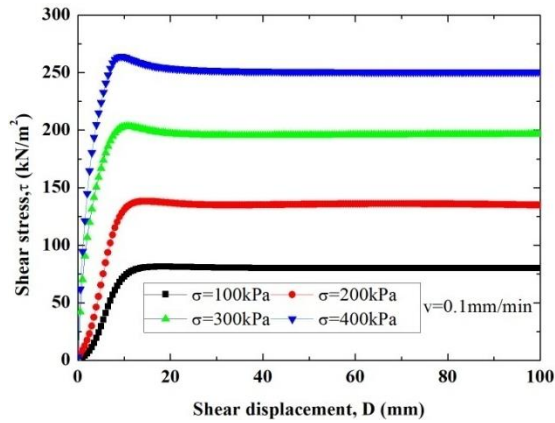


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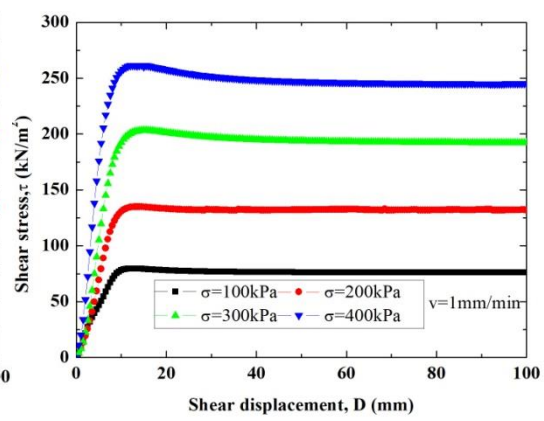
(b) Relationship between friction coefficient and normal stress

333

Fig. 5. Shear behavior characteristics of Ydg soil samples

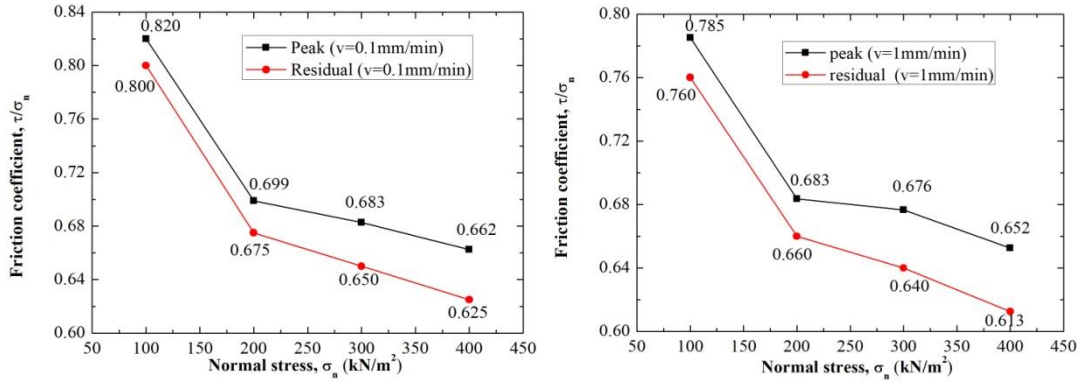


334



335

(a) Relationship between shear stress and shear displacement



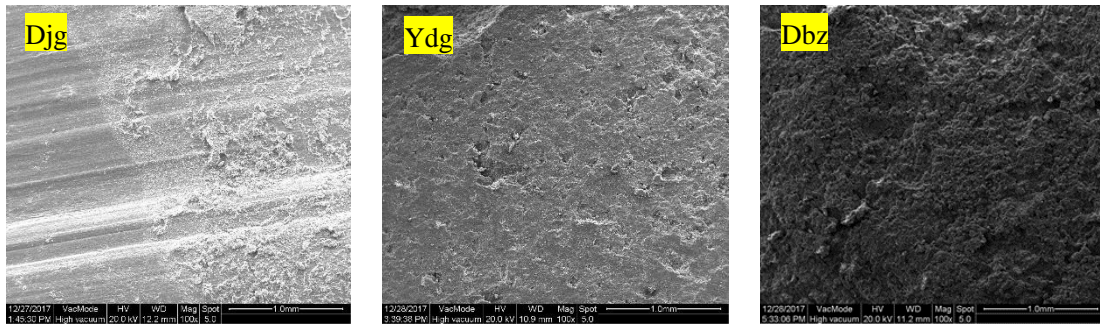
336

337

(b) Relationship between friction coefficient and normal stress

338

Fig. 6. Shear behavior characteristics of the Dbz soil samples



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Fig. 7. SEM photographs of the shear surface of loess samples (100 magnification)

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4.3. Effects of shear rate on residual strength parameter

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Following the previous study reported by (Eid et al., 2019; Terzaghi et al., 1996),

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the maximum value during shear process can be the peak shear stress, whereas the

344

minimum value can be the minimum shear stress. Correspondingly, the maximum

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value can be referred to as the peak shear strength, whereas the minimum value can be

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referred to as the residual shear strength that resulted from particle rearrangements

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after a large shear displacement. Furthermore, the peak and residual strength

348

parameters are determined by using Mohr–Coulomb failure criterion (Terzaghi et al.,

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1996). In this study, the residual strength parameters were analyzed and discussed.

350

For the samples described above, Figs. 8-10 show the relationships between the

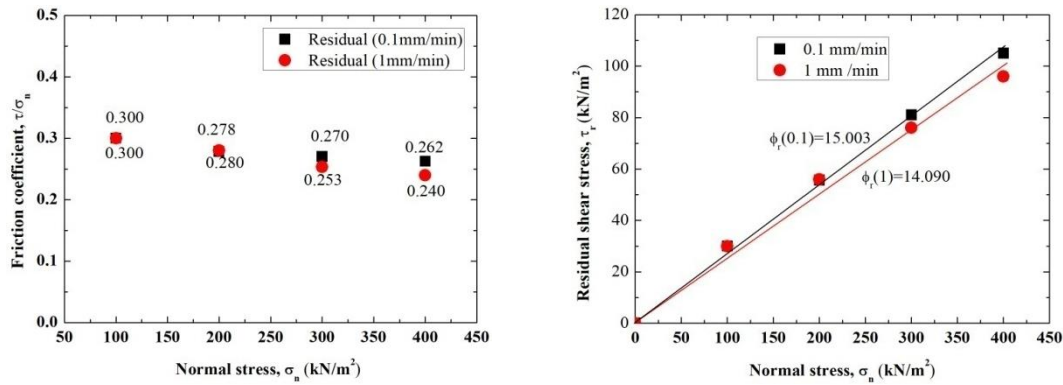
351

residual friction coefficient and the normal stress, and the residual strength parameters.

352 The residual friction coefficient is plotted against the normal stress. The residual
353 friction coefficient is defined as the residual shear strength divided by normal stress. It
354 has been recognized that the shear strength parameters including cohesion and friction
355 angle (Terzaghi, 1951; Stark Timothy et al., 2005; Pakbaz et al., 2018). However,
356 according to the previous studies, the residual angle of soils varies depended on the
357 soil properties as well as the magnitude of normal stress provided the residual
358 cohesion of soil is zero (Kimura et al., 2014; Skempton, 1964). Thus, in this study, the
359 residual frictions are calculated by Coulomb's law assumed the residual cohesion is
360 zero following the previous studies (Skempton, 1985). The residual strength
361 parameters were defined as $\phi_r(0.1)$ and $\phi_r(1)$ at the low shear rate and high shear rate,
362 respectively. And the difference between the residual friction angles at two shear rates
363 was defined as $\phi_r(1) - \phi_r(0.1)$. Comparatively, the residual friction coefficient was
364 defined as $\tau_r/\sigma_n(0.1)$ at the low shear rate and $\tau_r/\sigma_n(1)$ at the high shear rate,
365 respectively. Furthermore, the difference between the residual friction coefficients
366 was defined as $\tau_r/\sigma_n(1) - \tau_r/\sigma_n(0.1)$. Table 2 summarized the residual shear
367 parameters of the landslide soils.

368 Fig. 8 shows that the residual friction coefficients are relatively low in Djg
369 samples. The coefficients $\tau_r/\sigma_n(0.1)$ and $\tau_r/\sigma_n(1)$ at the normal stress of 100 kN/m²
370 to 400 kN/m² ranged from 0.3 to 0.262 and from 0.3 to 0.24, respectively. The
371 difference between the friction coefficients, $\tau_r/\sigma_n(1) - \tau_r/\sigma_n(0.1)$, at each normal
372 stress level are varied in a range of -0.022 to +0.002. For the difference between the
373 residual friction angles, $\phi_r(1) - \phi_r(0.1)$, ranged from -1.212° to +0.079° (Table 2). For

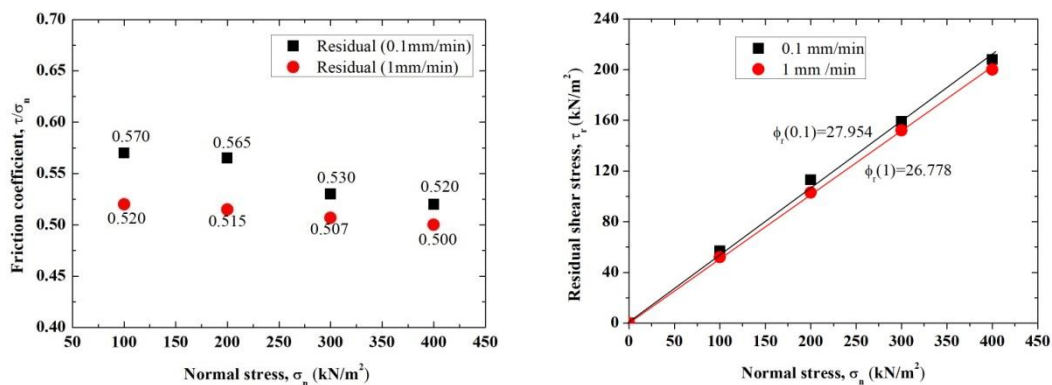
374 normal stress above 200 kN/m², the residual friction coefficient $\tau_r/\sigma_n(0.1)$ was found
 375 to be greater than the residual friction coefficient $\tau_r/\sigma_n(1)$. For this sample, residual
 376 friction coefficients show a slight decrease with the shear rate for normal stress above
 377 200 kN/m².



378

379 Fig. 8. Relationships between residual shear stress and normal stress, and residual
 380 strength parameter for Djg soil sample

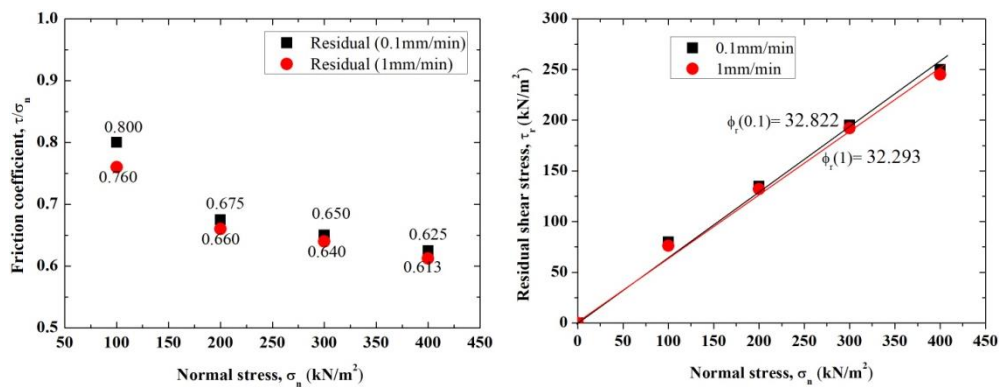
381 Fig. 9 gives the results of the Ydg samples. The coefficients $\tau_r/\sigma_n(0.1)$ and τ_r/σ_n
 382 (1) under the normal stress of 100 kN/m² to 400 kN/m² ranged from 0.57 to 0.52 and
 383 from 0.52 to 0.50, respectively. Furthermore, the difference $\tau_r/\sigma_n(1) - \tau_r/\sigma_n(0.1)$ at
 384 each normal stress was from -0.05 to -0.02. As for the difference between the residual
 385 friction angles, $\phi_r(1) - \phi_r(0.1)$, was in a range of -2.218° to -0.909°. In case of Ydg
 386 soil sample, the residual friction coefficients decreased with increase of shear rate for
 387 all normal stress levels.



388

389 Fig. 9. Relationships between residual shear stress and normal stress, and residual
 390 strength parameter for Ydg soil samples

391 Fig. 10 presents the results of the Dbz samples. The coefficients $\tau_r/\sigma_n(0.1)$ and $\tau_r/\sigma_n(1)$
 392 $\tau_r/\sigma_n(1)$ at the normal stress of 100 kN/m² to 400 kN/m² ranged from 0.8 to 0.625 and
 393 from 0.76 to 0.613, respectively. The difference $\tau_r/\sigma_n(1) - \tau_r/\sigma_n(0.1)$ at each normal
 394 stress was from -0.04 to -0.01. The difference $\phi_r(1) - \phi_r(0.1)$ was from -1.425° to
 395 -0.405°. For Dbz samples, there was somewhat decrease tendency of the residual
 396 friction coefficients with the increasing of the shear rate for all normal stress levels. It
 397 is noted that the maximum difference was found at the lowest normal stress of 100
 398 kN/m².



399
 400 Fig. 10. Relationships between residual shear stress and normal stress, and residual
 401 strength parameter for Dbz soil sample

402 From the experimental results on the three selected landslides, it was found that
 403 there is a negative relationship between residual friction coefficients and shear rates
 404 for all samples (Figs. 8-10). Such a negative effect of shear rate (higher residual
 405 friction coefficients at lower rates) has been reported in the literature for fine-grained
 406 soils (Gratchev Ivan and Sassa, 2015;Tika et al., 1996). This effect may be closely
 407 associated with ability of clay particles in specimen to restore broken bonds at

408 different shear rates. Previous scholars concluded that with higher shear rates, the
409 breakdown of the bonds between clay particles or flocs exceeds the restoration bond,
410 leading to reduction in residual friction coefficients (Osipov et al., 1984; Perret et al.,
411 1996). In contrast, the bonds between particles are rebuilt quickly and the recovery
412 rate can catch up the breakdown rate at lower shear rates. Therefore, the weaker
413 bonding between particles could explain the strength drop with the increasing of the
414 shear rate in this study.

415 As for Ydg and Dbz specimen, it is found that the shear rate effect on the friction
416 coefficient can be seen to decrease with normal stress (Figs. 9-10). By contrast, there
417 is an increasing tendency in the influence of shear rate on the friction coefficient with
418 normal stress in Djg specimen (Fig. 8). Gibo et al. (1987) reported that the residual
419 friction angle of soils was controlled by the effective normal stress as well as by the
420 CF. Interestingly, Ydg (with CF 9%) and Dbz (with CF 9.1%) specimens with almost
421 the same fraction of clay showed similar shear rate effect on the residual friction
422 coefficient with normal stress increasing, however, Djg (with 24% CF) showed the
423 contrast tendency of shear rate effect on residual friction coefficient with normal
424 stress, indicating that such effect is closely associated with CF.

425 Table 2 summarizes residual strength parameters including $\phi_r(0.1)$ and $\phi_r(1)$ of
426 all specimens obtained from the ring shear tests in this study. As for the Djg samples,
427 the residual strength parameter $\phi_r(0.1)$ and $\phi_r(1)$ for all normal stress were found to
428 be 15.003° and 14.09° (Fig. 8), respectively. However, the residual friction angles ϕ_r
429 (0.1) and $\phi_r(1)$ of the Ydg samples were obtained to be 27.954° and 26.778° (Fig. 9),

430 respectively. In the case of Dbz sample, the friction angles $\phi_r(0.1)$ and $\phi_r(1)$ were
431 high, 32.822° and 32.293° (Fig. 10), respectively. The residual friction angles $\phi_r(0.1)$
432 and $\phi_r(1)$ under all normal stresses were from 15.003° to 32.822° and from 14.09° to
433 32.293° , respectively.

434 Due to the influence of the shear rate, the difference $\phi_r(1) - \phi_r(0.1)$, at each
435 normal stress level varies in different locations, while the value of $\phi_r(1) - \phi_r(0.1)$
436 under all normal stress for the Djg, Ydg and Dbz samples were -0.913° , -1.176° and
437 -0.529° , respectively (Table 2). Wang (2014) and Fan et al. (2017) asserted that the
438 residual shear strength of remolded loess hardly affected by shear rate below 5
439 mm/min. However, the results in this study shown that $\phi_r(1) - \phi_r(0.1)$ under all
440 normal stress levels were negative for loess. Moreover, the absolute value of $\phi_r(1) -$
441 $\phi_r(0.1)$ in Ydg samples even reached up to 1.176° . Therefore, the ring shear test
442 results provides a basis for some general comments on the use of tests results with
443 different shear rates, partially deepening some aspects deriving from previous studies.

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455 Table 2. Residual shear strength parameter of landslide soils.

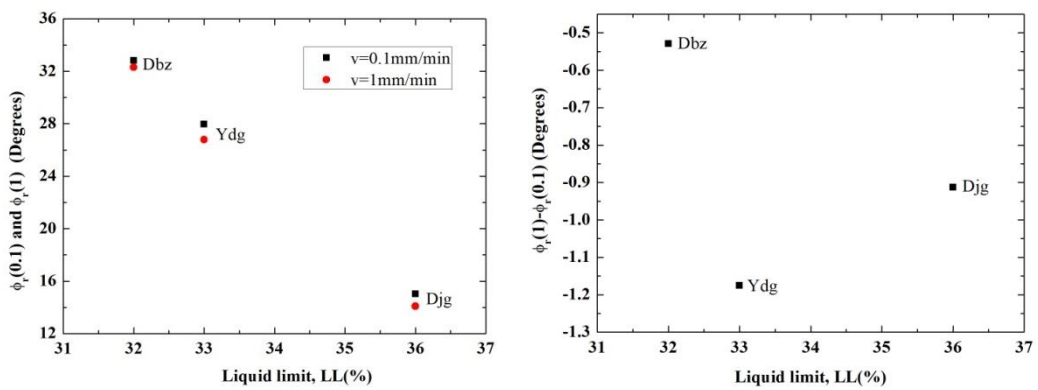
| No | Sample | Normal stress (kN/m ²) | Residual strength parameter | | | | Difference in parameter | |
|----|--------|---------------------------------------|-----------------------------|----------------------|------------------------|----------------------|--|----------------------|
| | | | $\phi_{r(0.1)} (^\circ)$ | | $\phi_{r(1)} (^\circ)$ | | $\phi_{r(1)} - \phi_{r(0.1)} (^\circ)$ | |
| | | | Under each σ_n | Under all σ_n | Under each σ_n | Under all σ_n | Under each σ_n | Under all σ_n |
| 1 | Djg | 100 | 16.699 | 15.003 | 16.699 | 14.090 | 0 | -0.913 |
| | | 200 | 15.563 | | 15.642 | | 0.079 | |
| | | 300 | 15.110 | | 14.216 | | -0.894 | |
| | | 400 | 14.708 | | 13.496 | | -1.212 | |
| 2 | Ydg | 100 | 29.683 | 27.954 | 27.474 | 26.778 | -2.209 | -1.176 |
| | | 200 | 29.466 | | 27.248 | | -2.218 | |
| | | 300 | 27.923 | | 26.870 | | -1.053 | |
| | | 400 | 27.474 | | 26.565 | | -0.909 | |
| 3 | Dbz | 100 | 38.660 | 32.822 | 37.235 | 32.293 | -1.425 | -0.529 |
| | | 200 | 34.019 | | 33.425 | | -0.594 | |
| | | 300 | 33.024 | | 32.619 | | -0.405 | |
| | | 400 | 32.005 | | 31.487 | | -0.518 | |

456

457 **4.4. Influence of the shear rate on the residual friction angles according to soil**
 458 **properties**

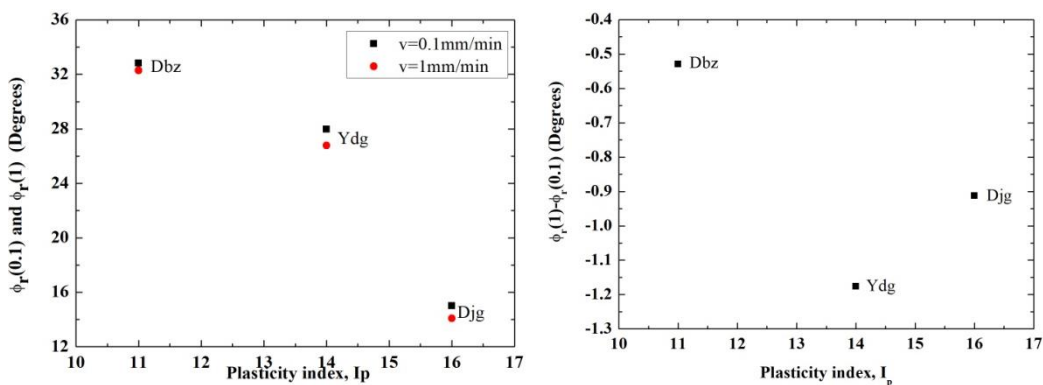
459 It has been recognized that residual shear strength of soils is closely related with
 460 soil properties, such as particle size distribution (PSD), liquid limit (LL), plasticity
 461 index (Ip) and clay fraction (CF) (Terzaghi et al., 1996; Sayyah et al., 2016; Xu et al.,
 462 2018; Eid et al., 2016). Fig. 11 depicts the relationships between residual friction
 463 angles as well as the difference in the residual friction angles and soil properties
 464 including LL, plasticity index (Ip) and clay fraction (CF) at two shear rates. The
 465 residual friction angles at two shear rates decreased nonlinearly with the increasing of

466 the LL. As for the relationship between the ϕ_r and I_p , the ϕ_r under the low and high
 467 shear rates decreases from about 32° to 15° with increasing the I_p from 11 to 16. These
 468 findings agree well with the early studies (Wesley, 2003;Tiwari et al., 2005). With
 469 increasing of CF from 9% to 24%, the residual friction angles under low and high
 470 shear rates were found to decrease (Fig. 11). These observations are consistent with
 471 previous studies (Lupini et al., 1981;Gibo et al., 1987). Interestingly, for Dbz and Ydg
 472 soils of which have similar percentage of clay fraction, the residual friction angles at
 473 both shear rates varied. However, in the relationships between the difference in the
 474 residual friction angles and the soil properties, no clear correlations were found.



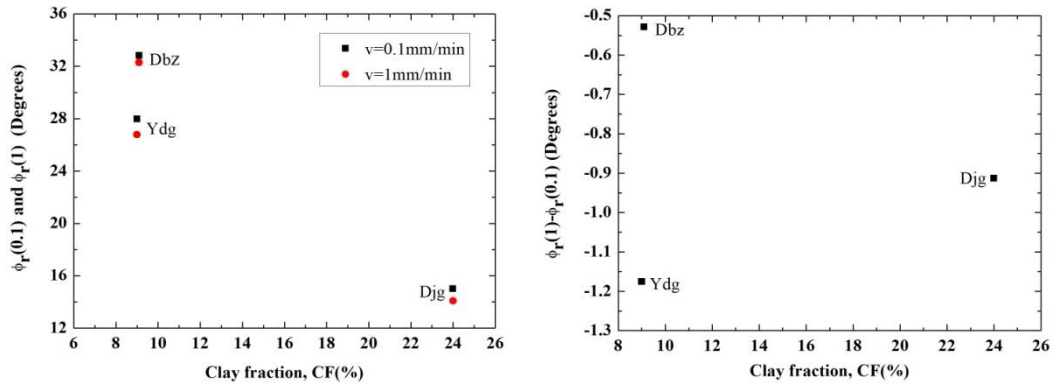
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Fig. 11. Relationships between residual shear parameter, the difference in residual shear parameter and the soil properties at two shear rates

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483 5. Conclusion

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A series of ring shear tests were conducted on loess obtained from three landslides to study the residual shear characteristics of saturated loess. Based on the test results, the effect of the shear rate on the residual shear characteristics of loess in naturally drained condition was examined. The following conclusions can be drawn:

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1. Ring shear test revealed that: (i) shear displacement to achieve the residual stage with high shear rate is greater than that of the low shear rate; (ii) Both the peak and residual friction coefficient became smaller with increase of shear rate for each sample; (iii) The greater difference between the peak and the residual friction coefficient in loess samples could be attributed to relatively well-developed slickenside on the shear surface.

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2. At the two shear rates, there was a nonlinearly decrease trend of the residual friction coefficient with the normal stress in all loess samples. The difference between the friction coefficients, $\tau_r/\sigma_n(1) - \tau_r/\sigma_n(0.1)$ was found to decrease

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with normal stress in Ydg and Dbz specimens while increase with normal stress

498 in Djg specimens, indicating that CF may be closely associated with shear rate
499 effect on residual friction coefficient with normal stress. Therefore, as for Ydg
500 and Dbz with relatively low fraction of CF, there is an increase effect of shear
501 rate on residual friction coefficient with decreasing of normal stress. Thus, for the
502 application of measured residual friction coefficient for stability analysis of
503 shallow landslides with lower overburden pressure, it is significant for us to use a
504 low shear rate in ring shear tests to measure residual shear strength parameters.
505 On other hand, for Djg with high CF, it is more reliable to use a low shear rate in
506 ring shear tests to determine residual friction coefficient for stability analysis of
507 deep landslides with high overburden pressure.

508 3. The difference at the two shear rates, $\phi_r(1) - \phi_r(0.1)$, under each normal stress
509 level were either negative or positive. However, under all normal stress, the
510 difference at the two shear rates $\phi_r(1) - \phi_r(0.1)$ was found to be negative. Such
511 negative shear rate effect on loess could be attributed to greater ability of clay
512 particles in specimen to restore broken bonds at low shear rates.

513 4. The relationships between the ϕ_r under two shear rates and soil properties (LL, Ip),
514 demonstrated that the ϕ_r at both shear rates decreased gradually with the
515 increasing of LL and Ip. However, no clear correlations between the difference in
516 the ϕ_r at low and high shear rates and the soil properties were found.

517 A first attempt was made in this work to describe some shear rate effect on the
518 residual characteristics of the saturated loess. The obtained experimental results do
519 suggest that the residual shear behavior of saturated loess, can be affected, to a certain

520 extent, by the shear rate. However, a more quantitative evaluation of such effects, and
521 a deeper understanding on the underlying processes must be achieved in order to
522 assess their role in the initiation and mobility of loess landslides.

523

524

525 **Code availability:** Code can be made available by the authors upon request.

526 **Data availability:** Data can be made available by the authors upon request.

527 **Author contributions:** BL, JP and QH conceived and designed the method; BL

528 produced the results, and wrote the original manuscript under the supervision of JP.

529 JP and QH writing-review and editing.

530 **Competing interest:** The authors declare that they have no conflicts of interest.

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536 **manuscript.**

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