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Rate-dependent shear behaviour of silt-steel and sand-steel interfaces

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ABSTRACT: This paper presents the viscous effects during rate interface tests on medium-dense Fontainebleau sand and normally consolidated silt in contact with steel plates of different roughness. Six types of surfaces are used - four made of steel (smooth and polished surface; newly manufactured slightly rough surface; rusted medium rough surface, and sand-blasted medium rough surface) and two made of sandpaper to mimic the rusted steel. The tests were carried out in Bromhead type ring shear apparatus under constant normal load (CNL) and constant volume (CV) conditions. There is characteristic roughness ($R_{neutral}$) for silt-steel interface that returns neutral viscous effects in undrained conditions. Below $R_{neutral}$ the undrained shear strength of silt-steel interface decreases with increasing shearing rate. When the surface roughness is higher than $R_{neutral}$, the interface undrained shear strength increases with increasing shearing rate. The shear strength behaviour on medium-dense sand-steel interface is more complex. The rate-dependency of sand is influenced by normal stress, displacement level, and surface roughness. The steady state interface shear stresses can be consider as rate-independent during shearing under high normal stresses. However, when low normal stress level is applied, rate-dependency phenomenon can be observed for smooth interfaces and it weakens with increasing interface roughness. For medium-dense sand viscous effects were found when R_a (arithmetic average roughness) is lower than 1 μm. Furthermore, this research shows influence of surface texture origin and topography on mobilized interface shear strength. It also presents how classical roughness parameters (i.e., R_a, R_n) might be misleading is interface shear strength interpretation.

Keywords: interface; rate-dependency; sand; shear behaviour; silt

1 INTRODUCTION

1.1 Rate-dependent interface shear behaviour – short historical background

Interface shear behaviour is crucial aspect of geotechnical design and was under extensive research since early days of modern soil mechanics era. Historically, the shearing behaviour of sand-steel interfaces were started by Poytondy (1961). The significant contributions were done in next decades by, among others, Uesugi and Kishida (1986), Fakharian (1996), Porcino et al., (2003), Ho et al. (2011), Tovar-Valencia et al. (2018), and Han et al. (2018). Each of those authors introduce specific measure of interface roughness and try to link the particle size, roughness and interface shear strength to describe interface shear behaviour. They also tested the interface shear behaviour in different displacement regimes – form small displacements (e.g., Uesugi and Kishida, 1986) to extremely large ones (e.g., Ho et al., 2011), and under different boundary conditions, i.e., under constant normal load (CNL) (e.g., Ho et al., 2011), constant volume (CV) (e.g., Tsubakihra and Kishida; 1993) or constant normal stiffness (CNS) (e.g., Porcino et al., 2003). Most of these research was related to monotonic shearing with omission of viscous effects, as these were much more significant for cohesive soils (e.g., Martinez and Stutz, 2019). This was the reason that rate-dependency (also called viscous effects) of soil-steel interfaces was firstly investigated by Littleton (1976) for cohesive soils. This topic was later expanded by, among others, Tsubakihara and Kishida (1993), Lemos and Vaughan (2000), and Martinez and Stutz (2019). In terms of sands, the rate-dependency is far less investigated, although the rate dependency during sand shearing is well recognized (e.g., Di Benedetto et al., 2002). Some of notable contributions are as follows. Fakharian (1996) have not found any significant viscous effects on dry sand-steel interface. On the other hand, Quiterios (2017) found small-magnitude of positive rate effects on sand-steel interfaces, but only for peak values. Liu et al. (2019) found no rate effects on ultimate (steady state) interface friction angle. Such a limited studies prove a significant lack of more comprehensive investigation on that issue.

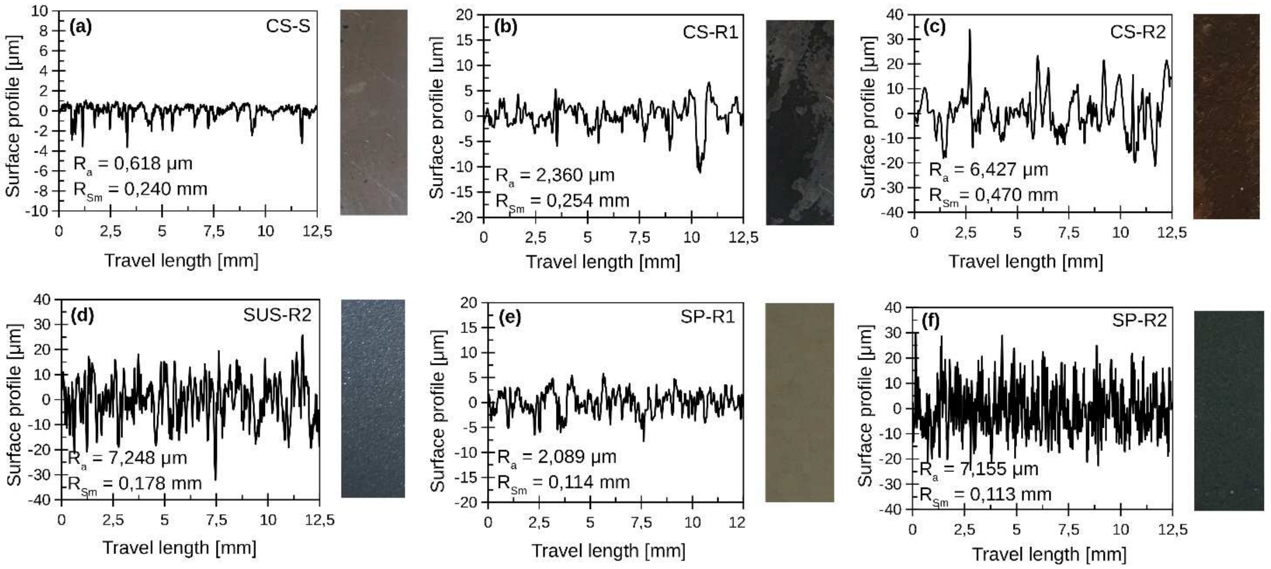

Figure 1. Roughness profiles for (a) CS-S, (b) CS-R1, (c) CS-R2, (d) SUS-R2, (e) SP-R1, and (f) SP-R2. (R_a =arithmetic roughness, R_{sm} = mean peak width).

1.2 Research Aims

The research presented in this paper shows the key results of laboratory interface testing campaign at Gdansk University of Technology (GUT) in 2023-2024, in particular: (1) the viscous effects during rate interface testing on medium dense Fontainebleau sands and normally consolidated silt in contact with steel plates of different roughness, and (2) the influence of surface texture origin and topography on mobilized interface shear strength. The aim is to point out critical aspects of silt-steel and sand-steel interface shear behaviour and how viscous effects can potentially affect them.

2 TESTING SETUP

2.1 Soils

Two types of soil were tested. The first one is normally consolidated, soft, organic silt (orSi) form the Vistula Marshlands. The second soil is medium dense Fontainebleau sand NE34 (FS). The essential soil properties are summarized in Table 1, as more detailed data is provided elsewhere. For orSi – refer to Konkol (2023), and for FS – see Andria-Ntoanina et al. (2010).

2.2 Interfaces

Six different interfaces were used. Four of them are made of steel (CS = construction steel or SUS = stainless steel): (1) smooth and polished surface (CS-S), (2) newly manufactured slightly rough surface (CS-R1), (3) rusted (weathered) medium rough surface (CS-R2), and (4) sand-blasted medium rough surface (SUS-R2). Next two interfaces utilize the sand paper (SP). They are of the same roughness as corresponding slightly rough and medium rough steel plates. However, they have different topography, i.e., three times higher mean peak width (R_{Sm}) and the number of peaks per unit length (R_{pc}). The roughness profiles are presented in Figure 1. The usage of SP interfaces is due to common usage of such a material in physical modelling to represent the rusted surface (e.g. Martinez and Frost, 2017).

Table 1. Basic soil properties in interfaces tests

Parameter	orSi	FS
γ [kN/m3]	16,4	16,2
ϕ_c' [°]	34,8	31,5
$c_{u,DSS,1\%/h}$ [kPa]	31,1	N/A
D_r [-]	N/A	0.66
D_{50} [µm]	18	210

Note: γ = soil total unit weight; ϕ_c' = critical angle of internal friction; $c_{u,DSS,1\%/h}$ = undrained shear strength in direct simple shear test under shear strain rate of 1%/h; D_r = relative density; D_{50} = average particle size of a soil.

There are several surface roughness quantities proposed by various authors. Two most common will be utilized here. The first one uses the concept of Uesugi and Kishida (1986) and was latter refined by Tovar Valencia et al. (2018):

$$R_n = \frac{R_{max,avg}\ (L=D_{50})}{D_{50}} \qquad (1)$$

where: $R_{max,avg}$ = the average largest single roughness depth within the evaluation length L which starts at every measurement point (see Figure 2), D_{50} = average particle size of a soil. The second normalization uses the R_a and D_{50} and was used, among others, by Ho et al. (2010):

$$R_n = \frac{R_a}{D_{50}} \quad (2)$$

where: R_a = Arithmetic average roughness, also called centre line average roughness (R_{CLA}). The summary of normalized roughness is presented in Table 2.

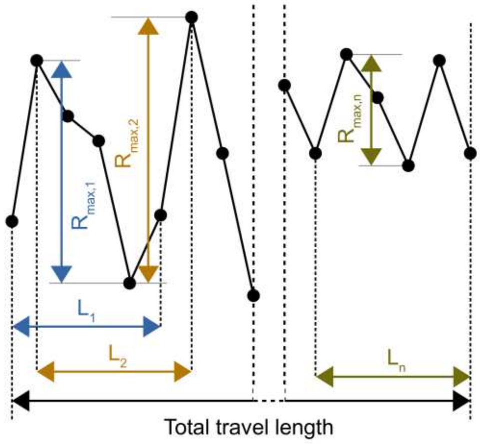

Figure 2. Definition of the parameters used for normalized roughness R_n (modified after Tovar-Valencia et al., 2018); $L_1 = L_2 = ... = L_n = D_{50}$; $R_{max,avg} = (R_{max,1} + R_{max,2} + ... + R_{max,n})/n$

Table 2. Surface roughness quantities

Soil	Interface	R_n (Eq.1)	R_n (Eq.2)
orSi	CS-S	0,007	0,003
orSi	CS-R1	0,019	0,011
orSi	CS-R2	0,064	0,031
orSi	SUS-R2	0,102	0,035
orSi	SP-R1	0,022	0,010
orSi	SP-R2	0,137	0,034
FS	CS-S	0,0013	0,034
FS	CS-R1	0,0023	0,131
FS	CS-R2	0,0078	0,357
FS	SUS-R2	0,017	0,403
FS	SP-R1	0,0035	0,116
FS	SP-R2	0,035	0,398

2.3 Ring shear apparatus

Investigation was conducted in Bromhead ring shear type apparatus modified to performed interface shearing tests. The interfaces were mounted directly to the top cap. Tests were carried out using guidelines given by Stark and Vettel (1992).

2.4 Testing program

Testing program involving different interface types are presented in Table 3. Tests includes Constant Normal Load (CNL) tests, and Constant Volume (CV) tests under monotonic or variable shearing rate conditions. The orSi is tested in submerged conditions and FS is tested in dry state.

Table 3. Interface testing program

Soil	Interface	Testing conditions
orSi	CS-S	M-CNL, M-CV, V-CNL
orSi	CS-R1	M-CNL, M-CV, V-CNL
orSi	CS-R2	M-CNL, M-CV, V-CNL
orSi	SUS-R2	M-CNL, M-CV, V-CNL
orSi	SP-R1	M-CNL, M-CV, V-CNL
orSi	SP-R2	V-CNL
FS	CS-S	M-CNL, V-CNL, V-CV
FS	CS-R1	M-CNL, V-CNL
FS	CS-R2	V-CNL
FS	SUS-R2	V-CNL
FS	SP-R1	V-CNL
FS	SP-R2	V-CNL

Note: orSi = organic silt; FS = Fontainebleau sand, M = monotonic test; V = variable rate test; CNL = constant normal load; CV= constant volume.

3 RATE-DEPENDENT SHEAR BEHAVIOUR OF SILT-STEEL INTERFACES

3.1 Interface rate-dependent shear behaviour

The full picture of rate-dependency of interface shear behaviour with silt is presented in Figure 3, where the normalized peak (yield) values are shown in relation to shearing rate. The magnitude and type of viscous effects depends of interface type and drainage conditions. For instance, the CS-S interface in undrained conditions exhibit negative rate effects, CS-R2 neutral, and SP-R1 positive. The shear behaviour of steel interfaces with similar R_a are much the same and surface topography seems to less important, as SUS-R2 and CS-R2 are very similar. The behaviour of SP interfaces is more complex – similar to steel in drained regime and different in undrained regime, which is likely related to the properties of the material.

3.2 Normalized roughness

Figure 4 shows the rate dependency of the yield interface shear strength in drained and undrained conditions with relations to normalized roughness. In both R_n concepts (Eq. (1) and Eq. (2)), only the SP interfaces under undrained conditions do not account for the trend line. It is likely the influence of surface material, as the preliminary tests on SP with different R_{sm} but the same R_a show the same outcome. The rest of the data fit very good to the drained or undrained trends.

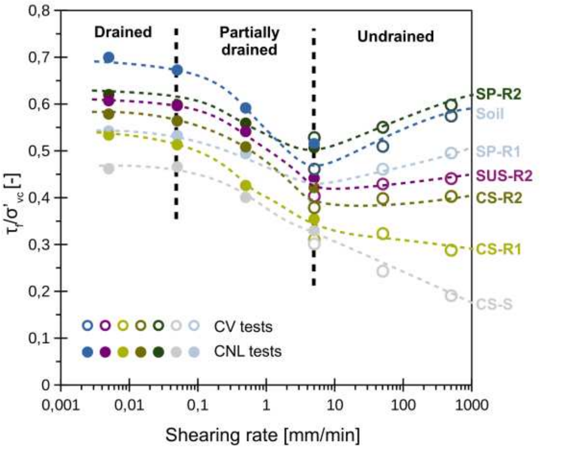

Figure 3. orSi-steel viscous interface shear behaviour (τ_f = yield interface shear stress, σ'_{vc} =effective consolidation stress).

4 RATE-DEPENDENT SHEAR BEHAVIOUR OF SAND-STEEL INTERFACES

4.1 Stress-dependency and displacement-dependency of viscous effects

The key outcomes of rate interface shear tests on dry FS are presented in Figure 5. The viscous behaviour of sand-steel interface combines stress and displacement level, roughness, and surface topography. The coupled peak and isotach behavior according to TESRA concept (e.g., Di Benedetto et al., 2002) can be observed for CS-S interface. When shearing rate increases, the interface shear strength temporary increases (characteristic "peak" is noticed) and then moves to higher interface shear strength level. When shearing rate decreases, the interface shear strength temporary decreases (characteristic "minimum" is seen) and then moves to lower interface shear strength level. This mechanism is also valid for SP-R1 interface. The displacement level seems to switch viscous behavior to pure TESRA type (only temporary "peaks" and "minima" are maintained), see CS-S and SP-R1 results in Figure 5a-b. Under high stress level (400 kPa) the viscous effects almost entirely vanish for CS-S interface, see Figure 5c-d. Increase in surface roughness also significantly weakens the viscous effects. It is more pronounced for steel interfaces (no viscous effects expect the relaxation during short pauses in CS-R1, CS-R2 and SUS-R2 can be seen) than for sand-blasted interfaces (SP-R1 still exhibits coupled peak and isotach behaviour, while SP-R2 is not). As a result, when of moderate (or higher) surface roughness is used, the sand-steel interface behaviour is rate-independent (consequently, stress and displacement level became non influential factors).

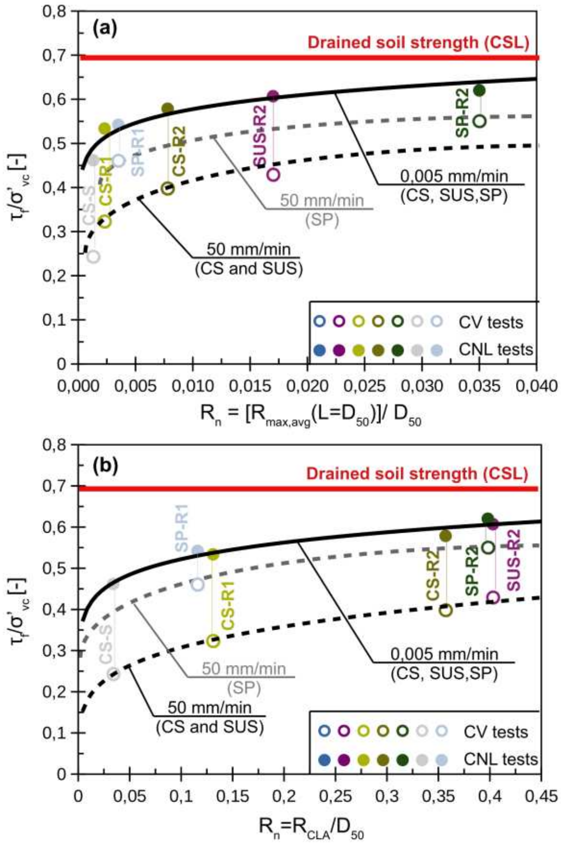

Figure 4. Interface shear stress versus normalized roughness or orSi: (a) Eq.(1), and (b) Eq. (2). (τ_f = yield interface shear stress, σ'_{vc} = effective consolidation stress).

4.2 Normalized roughness

The steady state interface shear strength (at 50 mm of tangential displacement and under shearing rate of 50 mm/min) versus the normalized roughness is presented in Figure 6. Firstly, The trend line can be established for a given material (SP and CS interfaces) and surface topography (the results for SUS-R2 and CS-R2 differs significantly). Furthermore, the interface shear strength is lower under normal stress of 400 kPa. The only exceptions are CS-S and SP-R1. The reason is unknown. Notably, the SUS-R2 shearing results are in agreement with Ho et al. (2011) (who tested the same sand and used steel plate of similar R_a).

5 CONCLUSIUONS

The following general comments can be made:

- The viscous effects depends on surface roughness and material type. This conclusion is valid for all interface tests.
- Sand paper should be used with caution to simulate the rusted, steel interface involving soft soil. Sand paper can successfully mimic rusted surface for roughness close to critical one and when drained conditions are applicable.

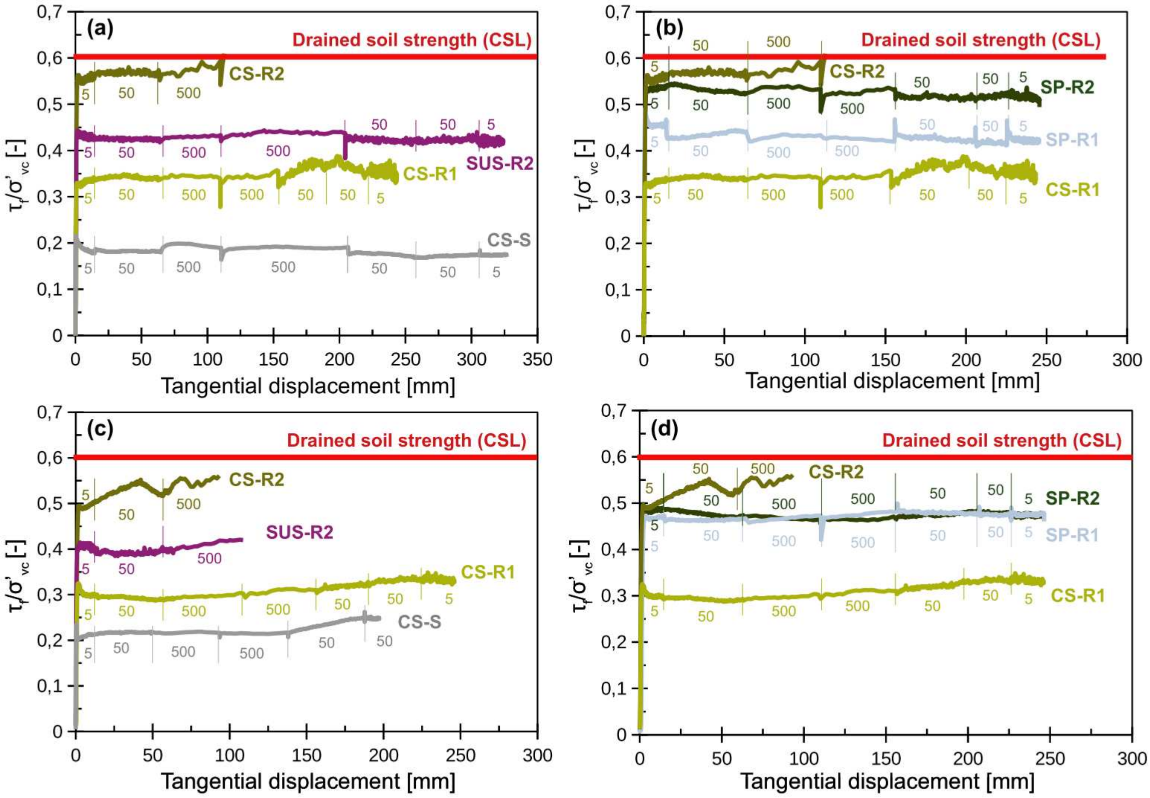

Figure 5. Normalized interface shear strength for CNL shearing under 100kPa: (a) CS and SUS interfaces, (b) SP versus CS interfaces, and under 400 kPa: (c) CS and SUS interfaces, (d) SP versus CS interfaces (τ_f = yield interface shear stress, σ'_{vc} =effective consolidation stress, numbers on plot denote shearing rate in [mm/min]).

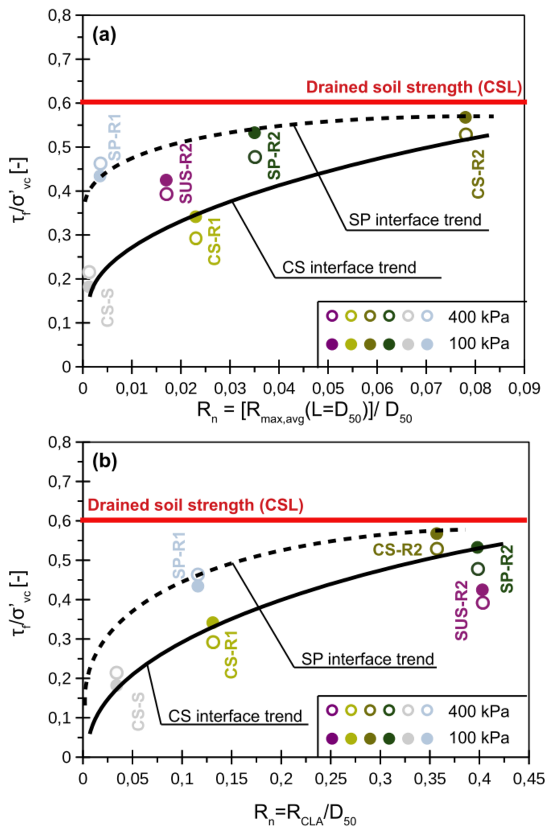

Figure 6. Interface shear stress versus normalized roughness for FS: (a) Eq.(1), and (b) Eq. (2). (τ_f = yield interface shear stress, σ'_{vc} = effective consolidation stress).

For other cases (e.g., undrained shearing, middle range roughness), SP interfaces return different response than steel. The reason is more likely related to the material properties. Sand paper is made of corundum particles, material of much more hardness and more brittle than steel.

- The steel surface topography and origin (rust or sandblasted) seems to be lesser issue for orSi-steel interfaces. For sand-steel interfaces, the surface topography has impact on the interface shear strength. This impact is stronger when steel surface is used instead of SP surface. Preliminary tests on SP surface on different R_{sm} but the same R_a show similar results suggesting surface material as the governing reason.
- The rate-dependency of sand-steel interface is influenced by normal stress, displacement level, and surface roughness making it complex issue. The steady state interface shear stresses can be consider as rate-independent during continuous shearing under high normal stresses or under moderate and high surface roughness. However, when low normal stress level ans smooth surfaces are applied, rate-dependency phenomenon can be observed (in most cases - coupled peak and isotach behaviour according to TESRA concept – see Di Benedetto et al., (2002)).

AUTHOR CONTRIBUTION STATEMENT

JK: Data curation, Conceptualization, Formal Analysis, Methodology, Writing- Original draft, Supervision, Visualization, Investigation, Funding acquisition, Writing- Reviewing and Editing.

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