Shear stress between a soft soil and various pile materials

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ABSTRACT
A relative movement between a pile element and surrounding soil mobilizes shear stress along a pile. The shear stress depends on various factors such as interface type, shearing velocity, and movement magnitude. This paper investigates the shear stress between a soft soil and a steel, uncoated and bitumen-coated concrete block for different shearing velocities, ranging from 0.01 mm/h to 100 mm/h. The tests were performed using a modified direct shear-test box until an ultimate resistance was mobilized, where the lower half of the box was replaced with an appropriate pile material block. The ratio between the interface angle of friction and the internal friction angle of the soil at ultimate resistance was 1.0 and 0.8 for the concrete and the steel block respectively. The shear stress between the soft soil and the bitumen coated concrete block decreased with the decrease of shearing velocity. The bitumen coating significantly reduced the shear stress at low shearing velocities.

RÉSUMÉ
Un mouvement relatif entre un élément de pieu et le sol environnant mobilise la contrainte de cisaillement d'un pieu. La contrainte de cisaillement dépend de divers facteurs, notamment du type d'interface, du taux de cisaillement, et l'amplitude du mouvement. Cet article étudie la contrainte de cisaillement entre un sol meuble et un bloc d'acier et un en béton enduit et non enduit de bitume, et ce pour différentes vitesses de cisaillement, allant de 0.01 mm/h à 100 mm/h. Les essais ont été effectués en utilisant une boîte d'essai de cisaillement direct modifiée jusqu'à ce qu'une résistance ultime soit mobilisée, là où la moitié inférieure de la boîte fut remplacée par un bloc de matériau de pieu approprié. Le rapport entre l'angle de frottement de l’interface et l'angle de frottement interne du sol à la résistance ultime était de 1.0 et 0.8 pour le béton et le bloc d'acier respectivement. La contrainte de cisaillement entre le sol meuble et le bloc de béton enduit de bitume a diminué avec la diminution du taux de cisaillement. Le revêtement de bitume a considérablement réduit la contrainte de cisaillement à de faibles taux de cisaillement.

1 INTRODUCTION

Shear stress and mobilized movement between a pile and a soil is an important component in the design of a piled foundation. Previous studies have shown that the shear strength depends on various factors including interface type and shearing velocity. Potyondy (1961) highlighted the importance of separating shear strength on different types of soils (sand, silt, and clay) and pile materials (steel, wood, and concrete) including surface roughness (smooth and rough). He also proposed using the ratio between interface angle of friction to soil angle of friction. Using a ring shear apparatus, Lehane and Jardine (1992) showed that an organic clayey silt sheared at different rates using a ring shear apparatus experienced a moderate positive rate effect (6 % per log cycle of displacement rate) up to a velocity of about 6,000 mm/h.

In a subsiding soil, the development of shear forces along a pile builds up negative skin friction. If desired, the negative skin friction can be reduced by applying a bitumen coating. The achieved degree of reduction depends on the applied rate of shearing and temperature (Baligh 1978 and Fellenius 1979).

This paper reports the results of an investigation of the shear stress of a soft clayey silt (denoted as gyttja) when sheared at velocities ranging from 0.01 mm/h to 100 mm/h against itself and against a steel plate, uncoated and bitumen-coated concrete blocks. The tests were performed using a direct shear-test box, where, for the second type of tests, the lower half of the box was replaced with a flat surface block of the appropriate pile material.

2 MATERIALS AND METHODS

2.1 Soft soil properties

The soil samples used in the tests were trimmed from undisturbed tube samples obtained from a test field in Randers, Denmark, at depths between 4.1 and 6.3 m. The soil properties are summarized in Table 1. The soil samples were slightly overconsolidated with a preconsolidation margin of about 10 kPa (OCR about 1.2).

2.2 Interface shear tests

The interface shear tests were performed using a modified direct shear testing device (Figure 1), where the lower half of the box was replaced with an appropriate pile material block. The steel and concrete blocks were made from run-of-the-mill material and saturated and submerged during

Table 1. The soft soil properties (grain size distribution and organic content data from Savery 2019)

Characteristics	Soft soil
Water content, %	105
Liquid limit, %	106
Plastic limit, %	46
Grain size distribution, %	
clay particles	14
silt particles	78
sand particles	8
Undrained shear strength[1], kPa	21
Sensitivity	4
Organic content, %	8
Compression ratio, CR,	0.27
Recompression ratio, RR,	0.04

[1] determined by field vane tests

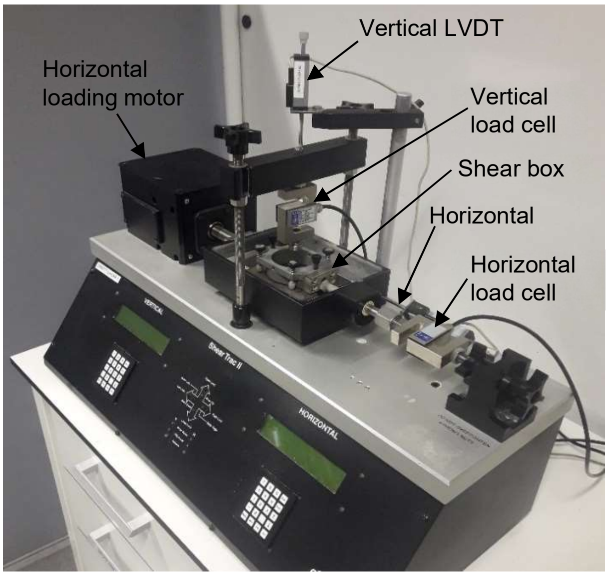

Figure 1. Interface shear test device

the tests. One of the concrete blocks was coated with a 1 mm thick 80/100 penetration bitumen coating. Before starting the tests on the bitumen-coated concrete block, the coating was heated and brushed to ensure a smooth and even 1 mm (±0.1 mm) thick layer for all tests, which thickness was confirmed by micrometer measurements. The tests were then carried out when the coating had cooled to room-temperature, which was 23 to 24 °C.

The first series of tests were conducted to investigate the shear stress between gyttja and different pile material blocks (concrete, steel and bitumen-coated concrete block). A standard direct shear test on a cylindrical gyttja specimen (diameter = 63.5 mm, height = 19.5 mm) was also conducted for comparison. The tests were performed at 20, 40, and 60 kPa normal stresses. As the test specimen was not restrained vertically, the vertical movement (compression) was measured. No shearing started until vertical measurements indicated that the gyttja was fully consolidated for the applied stress. The same soil sample was used for each normal stress, starting with 20 kPa and proceeding with 40 and, then, 60 kPa. However, a new soil sample was used for each interface type. The shearing velocity was determined as the time to full consolidation (based on the consolidation phase) multiplied by a factor of 12.7 and divided by the horizontal displacement required to reach constant volume of the soil specimen. (Head and Epps 2011) assumed to occur at a horizontal displacement equal to 10 % of the soil specimen diameter, i.e., 6.35 mm.

The second series of tests were performed to investigate the effect of the shearing velocity on gyttja/gyttja and on gyttja/bitumen-coated concrete block under three normal stresses. The direct shear tests on the gyttja/gyttja specimen were performed applying five different shearing velocities ranging from 0.01 to 5 mm/h as presented in Table 2. The interface shear test on gyttja/bitumen coated concrete block was performed in two shearing velocity cycles: slow (drained conditions) and fast (undrained conditions). The shearing velocities are presented in Table 3. Unfortunately, due to some unplanned events, the testing program did not go as planned and some of the shearing cycles did not reach the target maximum horizontal displacement of 6.35 mm.

Table 2. Testing program to investigate the effect of shearing velocity on gyttja

Normal stress kPa	Shearing velocity mm/h	Horizontal displacement mm		
20	0.05	1.3-2.3	3.3-4.3	5.3-6.3
	0.25	0.0-0.8	2.3-2.8	4.3-4.8
	5	0.8-1.3	2.8-3.3	4.8-5.3
40	0.05	1.1-2.1	3.1-4.1	5.1-6.1
	0.25	0.0-0.6	2.1-2.6	4.1-4.6
	5	0.6-1.1	2.6-3.1	4.6-5.1
60	0.01	1.0-1.5	3.0-3.5	5.0-5.5
	0.05	1.5-2.0	3.5-4.0	5.5-6.0
	0.1	0.0-1.0	2.0-3.0	4.0-5.0

Table 3. Testing program to investigate the effect of shearing velocity on gyttja/bitumen coated concrete block

Normal stress kPa	Cycle	Shearing velocity mm/h	Horizontal displacement mm		
40	Slow	0.01	1.8-2.3	3.8-4.3	5.8-6.3
		0.1	0.0-1.8	2.3-3.8	4.3-5.8
	Fast	1	1.0-1.5	3.0-3.5	
		10	1.5-2.0	3.5-4.0	
		100	0.0-1.0	2.0-3.0	4.0-5.0
60	Slow	0.01	1.8-2.3	3.8-4.3	5.8-6.3
		0.1	0.0-1.8	2.3-3.8	4.3-5.8
	Fast	1	1.8-2.3	3.8-4.3	
		10	0.0-0.8	2.3-2.8	4.3-4.8
		100	0.8-1.8	2.8-3.8	4.8-5.8
80	Slow	0.01	1.8-2.3	3.8-4.3	
		0.1	0.0-1.8	2.3-3.8	4.3-5.8
	Fast	1	0.0-0.2	1.7-2.2	3.7-4.2
		10	0.2-0.7	2.2-2.7	4.2-4.7
		100	0.7-1.7	2.7-3.7	4.7-5.7

3 RESULTS AND DISCUSSION

3.1 Effect of interface type

The results of the tests for gyttja and different pile materials are presented in Figure 2 (placed after Figure 4). The shear stress on gyttja sample was increasing with the associated compression of the sample. Within the range of the horizontal displacement, none of the tests performed on gyttja samples mobilized a peak shear stress (the shear stress and the compression was still increasing). In contrast, all tests on gyttja/pile material except one (gyttja/concrete at 20 kPa normal stress, Figure 2 a), mobilized a peak shear stress followed by a plastic, strain softening or hardening response. It is interesting to note that the compression of the gyttja/steel and gyttja/bitumen specimen ceased after reaching the peak strength, while the gyttja/concrete specimen was still compressing at peak strength. These results support the findings described by Lupini at al. (1981) that the presence of hard interface promotes a sliding shearing mode (gyttja/steel and gyttja/bitumen specimen). However, according to Tsubakihara and Kishida (1993), if the interface roughness exceeds a critical value, then the failure occurs within the soil specimen and the peak shear stress agrees with the shear strength of soil (gyttja/concrete specimen).

Figure 3 presents the failure envelops for different interface types. The lowest interface friction angle was obtained for the gyttja/bitumen interface and the gyttja/concrete interface angle of friction, δ_c, was similar to the soil angle of friction, ø' ($\delta_c \approx 1.0$ø'). The ratio of interface angle of friction to soil angle of friction for gyttja/steel shear test was 0.82. These results are in general agreement with results reported by Potyondy (1961) for silt-structure tests conducted using a shear box under normal stress ranging from 48 to 383 kPa.

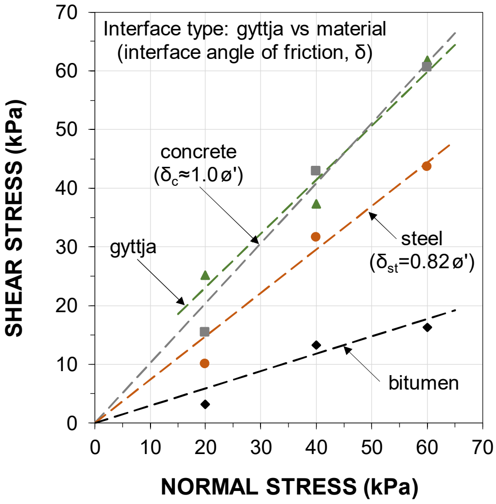

Figure 3. The maximum mobilised shear stress versus normal stress obtained from interface shear tests

3.2 Effect of shearing velocity

Figure 4 shows the results from the direct shear tests on gyttja specimens applying different shearing rates under three values of normal stress. The shear stress increased with increasing shearing velocity. The soil compressed (Figure 4 b) at low velocities (0.01 to 0.25 mm/h). However, no compression occurred at the largest velocity applied in this study (5 mm/h). This may indicate a shift from drained to undrained conditions. Tika et al. (1996) and Fearon et al. (2004) observed an increase or little volume change during fast shearing of cohesive soils using a ring shear apparatus. This finding was confirmed by Martinez and Stutz (2019) who studied the effects of shearing rates on kaolin clay samples sheared against steel plates with different roughness using a shear box device enhanced with an imaging system to analyse the soil deformation.

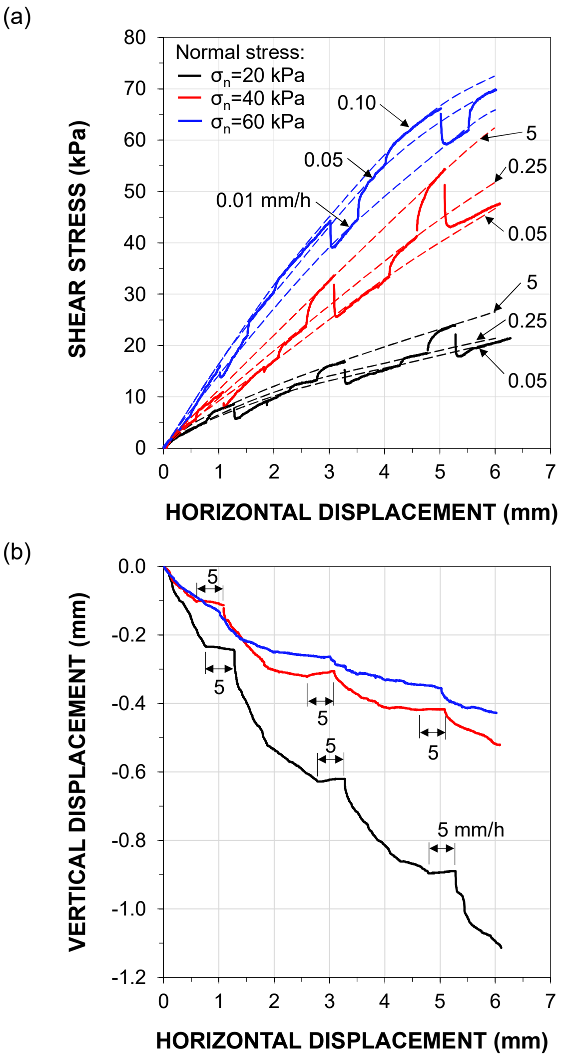

Figure 4. (a) Shear stress and (b) vertical displacement versus horizontal displacement at different normal stresses and shearing velocities performed on gyttja/gyttja

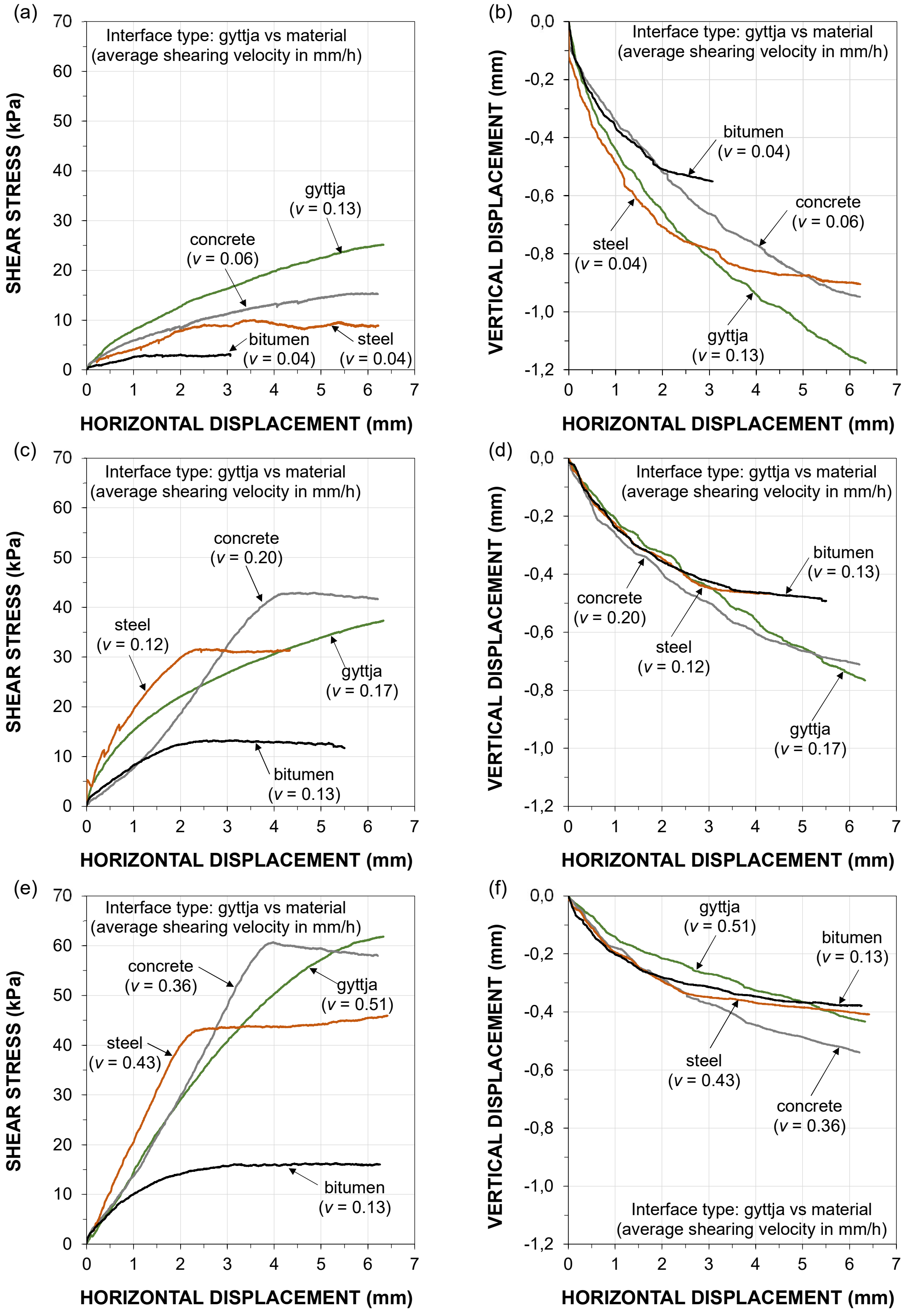

Figure 2. Shear stress and vertical displacement versus horizontal displacement from tests performed at: (a) and (b) 20 kPa, (c) and (d) 40 kPa, and (e) and (f) 60 kPa normal stress, respectively

Figure 5 presents the shear stress on gyttja/gyttja specimen normalized by the normal stress at different shearing velocities. The increase in shear stress was about 16 % per log cycle. This finding is consistent with data reported by McCabe (2002) who found a positive rate effect from undrained triaxial tests performed on soft, organic, clayey silt. The tests were conducted under the confining stress of 100 kPa and subjected to triaxial compression at slow and fast axial strain rates ranging from 0.001 to 1 %/min. The author reported the increase of the undrained shear strength of 15 % per log cycle increase in strain rate.

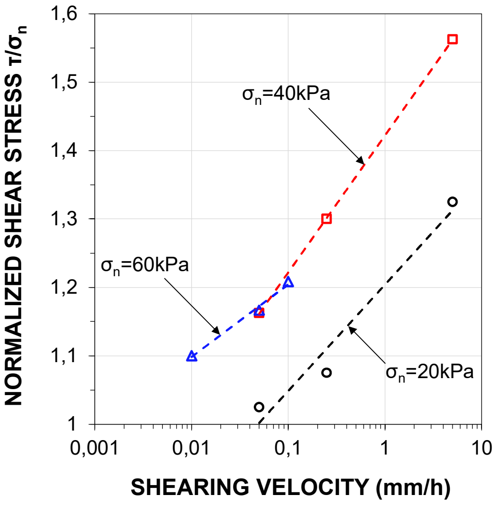

Figure 5. Normalized shear stress versus shearing velocity (a gyttja sample)

Figure 6 (placed after Figure 7) presents the results from the interface shear tests on gyttja/bitumen coated concrete block for the various shearing velocities and normal stresses. The blue curves present the results from slow shearing tests (0.01 and 0.1 mm/h) and the red curves show the results from the fast shearing tests (1, 10, and 100 mm/h). There was a significant difference between the mobilized shear stress at slow and fast shearing rates. Increase in shearing velocity increased the shear stress. The soil compressed only at velocities equal to or slower than 1 mm/h. This finding further supports the suggestion of the shift from drained to undrained conditions.

Figure 7 presents the obtained shear stress on gyttja/bitumen coated concrete block as a function of shearing strain rate. As can be seen from the graph, the shear stress was influenced by the strain rate. Below the strain rate of about 28×10^{-6}/s, the shear stress was equal for all three normal stresses. The lowest shear stress was obtained for the lowest strain rate and was about 1 kPa, which means 95% reduction to the undrained shear strength of the tested gyttja. At higher strain rates the shear stress increased with the increase of normal stress. The shear stress obtained at the highest strain rates was similar to the shear stress on gyttja samples. This finding was unexpected and may be explained by the penetration of soil particles into the coating. Khare and Gandhi (2009) investigated the shear stress of bitumen coated piles in sand using modified direct shear-test box and model piles. The authors showed that by increasing the normal stress from 50 to 75 kPa the shear stress increased by about 20 % for a 2- and 3-mm-thick bitumen coated sample using the shearing rate of 0.25 mm/min.

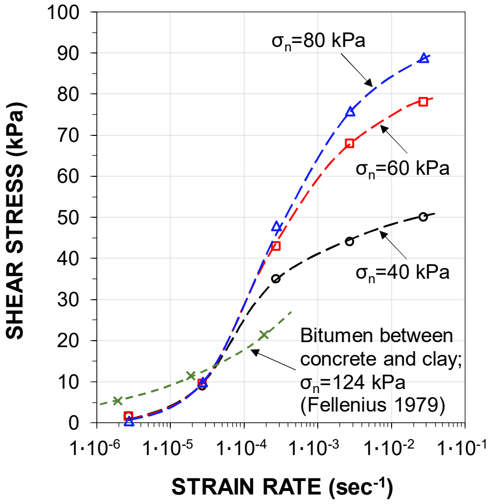

Figure 7. Shear stress versus shearing strain rate

The findings are in general agreement with those of Fellenius (1979) who carried out laboratory shearing tests on soft clay/bitumen/concrete specimens to investigate the strain rate effect. In both studies the shear stress increased with increasing shearing rate. The higher shear stress at low strain rates obtained by Fellenius (1979) could be explained by the lower temperature (4°C) at which his tests were conducted. The lower shear stress at higher strain rates may be explained by the soil type used in the study, which was soft and sensitive highly plastic clay (72 % clay size fraction).

4 CONCLUSIONS

The development of shear stress between gyttja and different pile materials and the effect of the shearing velocity was investigated and the results were:

The ratio of interface angle of friction to gyttja angle of friction for concrete and steel was 1.0 and 0.8, respectively. The movement needed to reach the peak shear stress was 2.3 and 4 mm for the gyttja/steel and gyttja/concrete specimen, respectively, while the gyttja/bitumen coated concrete block specimen needed 1 to 3 mm movement to reach the peak shear stress.

After reaching the peak shear stress, the interface sliding occurred on the gyttja/steel and gyttja/bitumen coated concrete block. Due to greater roughness of the gyttja/concrete interface, the failure occurred within the gyttja specimen. A peak shear stress was not reached at any normal stress on gyttja specimens.

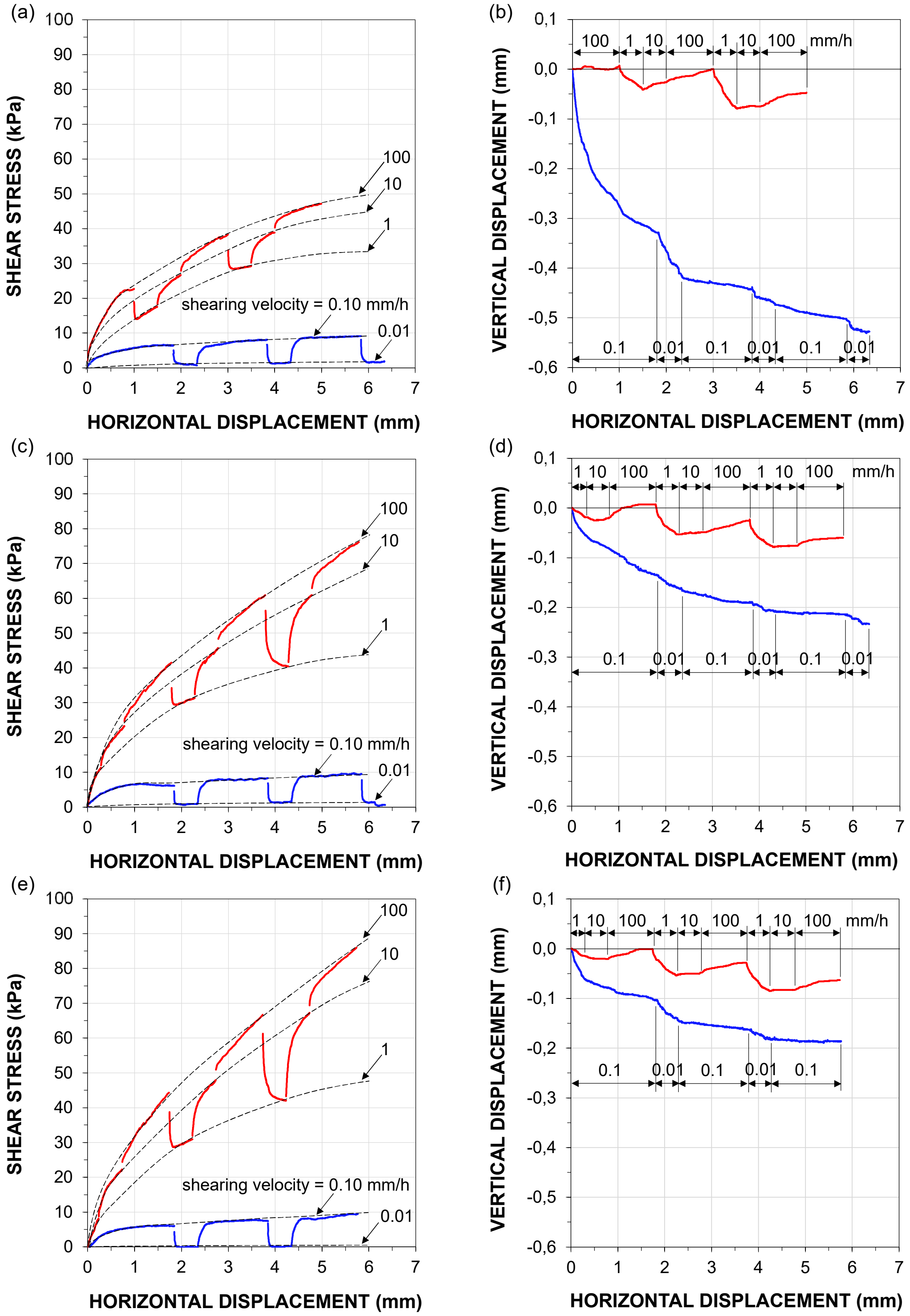

Figure 6. Shear stress and vertical displacement versus horizontal displacement from tests performed at: (a) and (b) 40 kPa, (c) and (d) 60 kPa, and (e) and (f) 80 kPa normal stress, respectively, and different shearing velocities

The shear stress between gyttja and the bitumen concrete block increased with the applied shearing velocity. The bitumen coating significantly reduced the shear stress at low shearing strain rates and was independent of the applied normal stress.

The reduction at the shear strain rate of 2.8×10^{-6} s^{-1} was 95 % compared to the undrained shear strength of gyttja. At fast shear strain rates (above 28×10^{-6} s^{-1}), the shear stress increased with increasing normal stress.

The shear tests with variable shearing rates on gyttja showed a positive rate effect with a 16 % increase in shear stress per log cycle of shearing velocity.

The soil compression at shearing velocities faster than 5 mm/h was constant indicating a shift from undrained to drained conditions.

5 ACKNOWLEDGMENTS

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