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RESEARCH ARTICLE

CONCEPTUAL EXPLANATION TO STUDY THE DEVELOPMENT OF SURFACE ROUGHNESS OF FRP COMPOSITE PILES DURING DRIVING PROCESS

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ABSTRACT

The surface roughness of FRP composite piles may be significantly altered during the driving process. This change could affect the interface pile design parameters. Therefore, an accurate quantification of this change is required to precisely determine the pile shaft resistance. This letter presents the results of an experimental study that investigated the change in surface roughness and interface shear coefficient of two different FRP counterface surfaces that sheared against two different types of sand under increased normal stress levels. The test results indicated that quantifiable surface roughness and interface resistance changes could be induced by the interface shearing process under increased normal stress levels. A conceptual explanation is provided in this study to interpret the observed behaviour. In conclusion, the outcomes of this study demonstrate the importance of considering the shear induced wear of FRP materials during the driving installation process.

INTRODUCTION

During the last two decades fiber reinforced polymer (FRP) tube were used to overcome the negative effects of the aggressive environmental conditions on the conventional pile materials such as steel, concrete, and timber (Iskander and Hassan 2001). As FRP-soil interface shear behaviour controls the pile's shaft resistance, some studies have investigated FRP-granular interface shear resistance (Pando *et al.* 2002, Frost and Han 1999, Sakr *et al.* 2005). These studies have concluded that the interface shear behaviour is controlled by the engineering properties of granular and counterface continuum materials, and the applied normal stress level. The engineering properties of the granular materials include particle shape and grading (D_{50}, mean particle size), and relative density whereas the engineering properties of the counterface continuum materials include surface roughness, and hardness, HV. Uesugi and Kishida (1986) proposed a normalized roughness parameter, $R_n=R_{max}/D_{50}$, that was able to express successfully the influence of surface roughness of counterface continuum material on the interface friction coefficient, $\mu=\tan(\delta)$, where R_{max} is the absolute vertical distance between the highest and lowest valley along the surface profile over a sample length equal to D_{50} (Uesugi and Kishida 1986), and δ is the interface friction angle of the granular material. In fact, FRP composite piles are usually installed by driving method (Sakr *et al.*, 2005). Therefore, during the installation process, FRP pile's shaft will be subjected to interface shear process under different normal stress levels which is function of the driving depth as shown in Fig. 1. The coefficient of the interface friction is dependent on the sliding and ploughing resistances where their contributions are mainly function of the normal stress and the hardness of the counterface surface. Sliding will tend to dominate for a hard counterface material whereas ploughing gets activated beyond a critical normal stress for a softer counterface (Dove and Forst 1999). As the FRP material has a moderate surface hardness compared to steel, it is expected that ploughing mechanism could take place during FRP composite pile driving process. Ploughing includes severe plastic deformation that damages the counterface surface asperities as the granular particles remove and displace material from the surface during translation. Furthermore, ploughing is often accompanied with development of microcracks in the counterface. Therefore, the surface roughness of FRP materials may be significantly altered during installation process. Evaluation of this change in the surface roughness is required to achieving an accurate interface pile design.

Few studies have been directed to quantify the interface shear induced surface roughness change and its effect on the interface shear coefficient. Zettler *et al.* (2000) has observed that the surface roughness of geomembranes is increased when sheared against granular medium. They attributed the observed change in geomembrane surface roughness to particles ploughing effects under shearing process. Fuggle *et al.* (2006) investigated the change in the surface roughness of different types of infrastructure pipe as a result of an interface shearing process against granular materials. In general they concluded that the surface roughness of FRP pipe materials did not change under the shearing process. This result could be attributed to the low normal stress (50 kPa) that has been used by Fuggle *et al.* (2006) which could be less than the critical normal stress value that is required to activate the ploughing

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process (Dove and Forst 1999). Based on the above discussion, there is still need to investigate the behaviour of the interface shear induced FRP surface roughness and interface shear coefficient changes under increased normal stress levels. The main objective of this study is to address this point through an experimental investigation. In the following sections, the testing materials and the conducted experimental program will be presented. Then, the obtained results will be discussed and interpreted, and finally the conclusions of this study will be drawn.

Testing materials and experimental program

Glass Fiber Reinforced Polymer (GFRP), and Carbon Fiber Reinforced Polymer (CFRP) are selected as testing materials in this study. The Vickers Hardness, HV, of GFRP and CFRP is 65 and 49, respectively. The GFRP and CFRP average maximum roughness, R_{max}, were determined using a stylus profilometer (Uesugi and Kishida1986). Two different granular materials were used in this study as listed in Tables 1.

Table 1. Geotechnical properties of the testing granular materials

	LBA sand	M sand
Max. dry density (kN/m^3)	17.36	17.36
Min. dry density (kN/m^3)	15.21	15.20
D_{50}(mm)	1.6	0.26
Coefficient of uniformity, C_u	1.3	2.07
Coefficient of curvature, C_c	0.88	1.19
Peak internal friction angle*(degree)	49	35
Residual internal friction angle*(degree)	37	30

* Relative density ≈ 88%

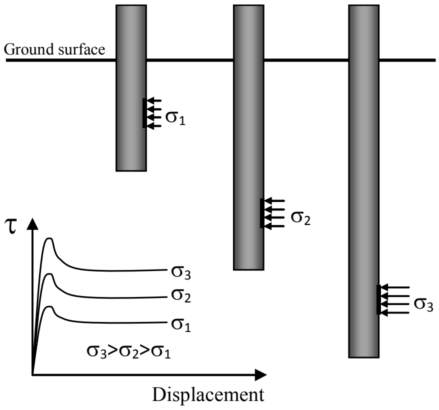

Fig. 1. Evolution of normal and shear stress at a specific area element on the pile shaft during the driving process

To simulate the pile driving conditions in terms of the normal stress change as the driving depth increases, as shown in Fig. 1, the proposed testing approach in this study involves subjecting the FRP counterface testing specimen to consecutive interface shearing tests under increased normal stress levels (27.7, 55.5, 97.3, and 183.5 kPa). The surface roughness of FRP counterface testing specimen, in terms of R_{max}, was measured after shearing under each normal stress level. Modified direct shear apparatus was used for this purpose. The top part of shear box comprises a square box (60 mm x 60 mm) and height of 24 mm. The bottom part of the shear box comprises a sheet of the counterface continuum material glued to a rigid plywood base which is longer than the top part of shear box so the shear area remains constant during a test. The testing granular materials were prepared at 88% relative density using air pluviation technique. The tests were performed at horizontal displacement rate of 0.52 mm/min. Finally, it should be mentioned that the setup of the testing in this study investigate the small shear displacement behaviour. However, field cases could involve tens of meters of displacement.

RESULTS AND DISCUSSION

Shear induced surface roughness changes

A cumulative relative roughness change, ΔR_{max}, is used to quantify the surface roughness change. It is defined as follows:

$$\Delta R_{max} = \left[\frac{(R_{max})^f - (R_{max})^i}{(R_{max})^i}\right] \times 100 \qquad (1)$$

where $(R_{max})^i$ and $(R_{max})^f$ are the initial R_{max} as received from the manufacture, and R_{max} after the completion of the interface shear test under each normal stress level, respectively (Abuel-Naga and Shaia, 2014). The test results in Fig. 2 suggest that $\partial\Delta R_{max}/\partial\sigma_n$ can be considered as normal stress level independent. Furthermore, $\partial\Delta R_{max}/\partial\sigma_n$ is function of surface hardness, HV, and the normalized roughness parameter $R_n=R_{max}/D_{50}$ (Uesugi and Kishida1986). It increases as HV increases and decreases as R_n increases.

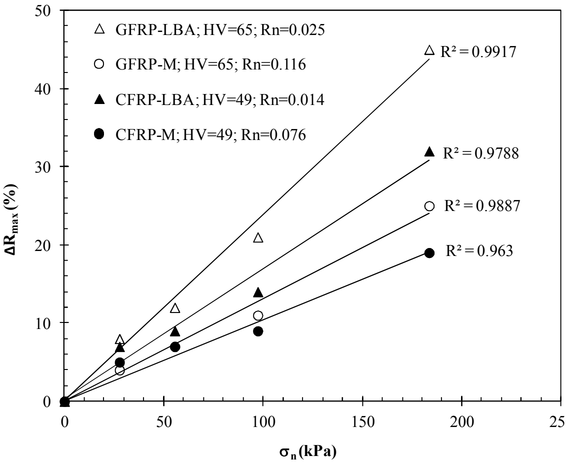

Fig. 2. Evolution of surface roughness as the normal stress increases

The test results in Fig. 2 shows that GFRP (HV=65) shows a low abrasion resistance higher ($\partial\Delta R_{max}/\partial\sigma_n$) compared to CFRP (HV=49). According to Caceres (2002), the wear behaviour of the materials is related to competitive processes of delamination, micro-ploughing and micro-cracking. The former is present in highly ductile material and it is accompanied by fatigue striations. Micro-cracking and micro-ploughing, which could increase the surface roughness, are present in harder material. As GFRP is harder than CFRP in terms of HV value, GFRP is expected to have a higher $\partial\Delta R_{max}/\partial\sigma_n$.

The effect of R_n on $\partial\Delta R_{max}/\partial\sigma_n$ can be explained in terms of D_{50} of the granular material. As D_{50} increases (R_n decreases), the number and area of particles contacting the counterface surface decreases causing the actual contact stress per particle

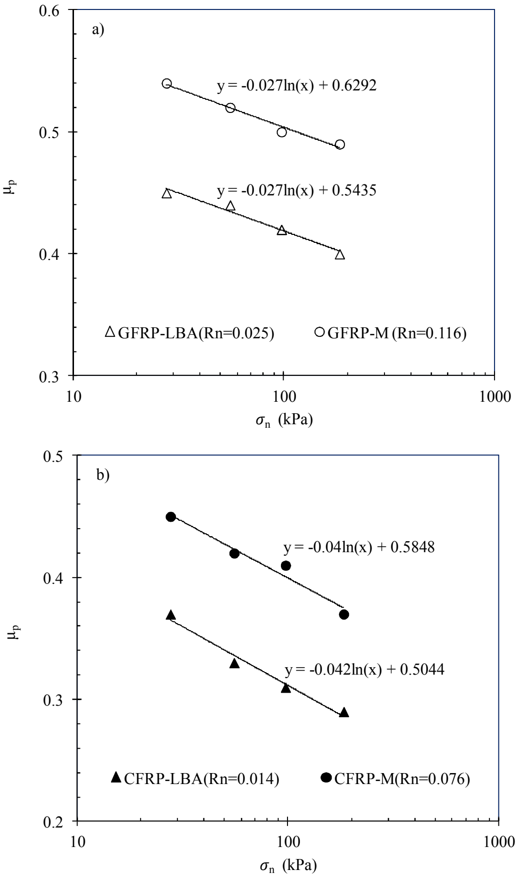

Fig. 3. Evolution of the peak interface shear coefficient as the normal stress increases

to increase. In fact, the possibility of damaging the counterface surface by micro-cracking and ploughing processes increases as contact stress per particle increases (Dove and Forst 1999). Therefore, LBA sand (D_{50}=1.60 mm) is expected to induce more surface roughness changes than M sand (D_{50}=0.26 mm).

Development of the interface shear coefficient

The results in Fig. 3 illustrate that the peak interface shear coefficient, μ_p, decreases as the normal stress increases, and $\partial\mu_p/\partial\sigma_n$ can be considered as R_n independent. This behaviour could be explained in terms of the following three mechanisms: (1) interface shear induced surface roughness increase as shown in Fig. 2; (2) change of the contact area per particle as the normal stress increases (Dove and Frost 1999); (3) interface shear induced striations in the counterface continuum surface (Renard *et al.*, 2012).

According to Uesugi and Kishida (1986), μ_p increases as the surface roughness increases. As the surface roughness increases under the interface shearing process, as shown in Fig. 2, μ_p is expected to increase as the normal stress increases. However, as the results in Fig. 3 show an opposite behaviour, it can be concluded that the interface shear induced surface roughness increase cannot be invoked on its own to explain the observed $\partial\mu_p/\partial\sigma_n$ in Fig. 3.

For elastic polymer surfaces, Dove and Frost (1999) explained the observed decrease of $\mu_p$as the normal stress increases in terms of the contact area per particle that increases as normal force increases but at a rate lower than the applied normal stress causing reduction of both of the contact stress per particle and μ_p. According to the experimental results in Fig. 3, it can be expected that the second mechanism should have a predominant role over the first mechanism.

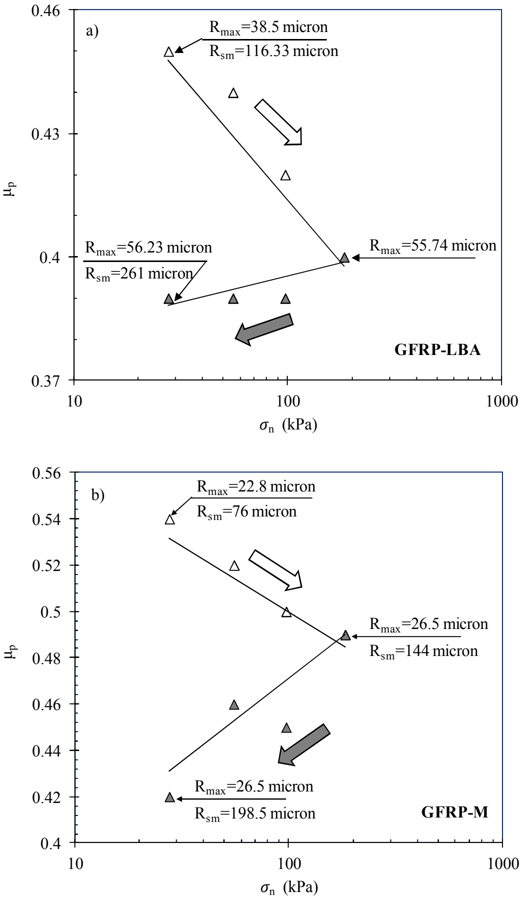

Fig. 4. Evolution of the peak interface shear coefficient under loading/unloading normal stress path

As the second mechanism has an elastic nature and the first mechanism should increase μ_p, it was expected that μ_p values obtained from unloading normal stress path should be greater than the obtained μ_p values under the loading normal stress path. The interface shear friction coefficient measurements under loading/unloading cycle in terms of the applied normal stress are shown in Fig. 4 for GFRP-LBA and GFRP-M. The results in Fig. 4 show that μ_p values under the unloading path are lower than the irreversible trend. This result indicates that the above two mechanisms are not enough to explain the observed behaviour in Fig. 4. The concept of interface shear induced striations is similar to the mechanism of scratching a surface with an indenter (Bowden and Tabor, 1966; Gee, 2001; Flores *et al.* 2008). As the interface shear process between continuum surface and granular material involves movement of particles along the counterface surface, irreversible micro-cracks and ploughing in form of striations (long thin groove) parallel to the shearing direction can be created in the counterface surface as shown in Fig. 5 (Renard *et al.*, 2012). Therefore, the counterface surface is expected to have irreversible longitudinal passes after completing the interface

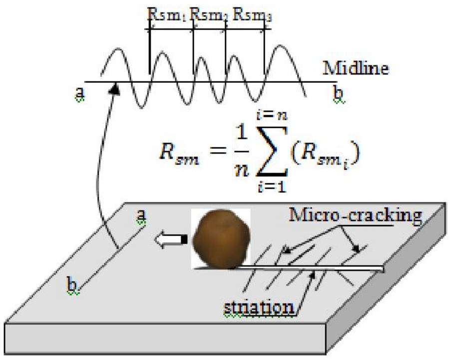

Fig. 5 Interface shear induced striation

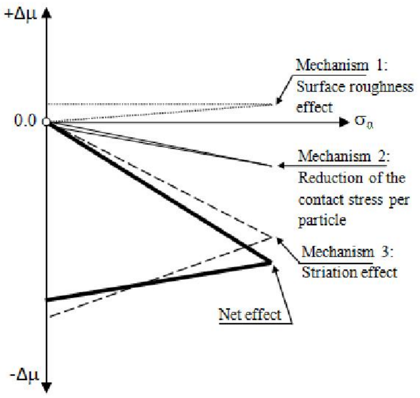

Fig. 6. Schematic conceptual explanation for the effect of the different proposed mechanisms on the change of the interface shear coefficient as the normal stress increases.

shear test under a lower normal stress. So, when the same counterface surface is sheared under the next higher normal stress, these passes will be used by the granular particles as preferential translating passes along the counterface surface. Consequently less particle translating resistance is expected. Therefore, the interface shear coefficient will decrease.

The spacing surface profile parameter, R_{sm}, measured in a direction perpendicular to the shearing direction can be used to quantify the interface shear induced striations as shown in Fig. 5. The parameter R_{sm} expresses the average spacing between two crossing points on the midline that includes high and low peaks as shown in Fig. 5 (Gadelmawla *et al*., 2002). The development of striations can be noticed by monitoring the change in R_{sm} value. The results in Fig. 4 show the R_{sm} value increases significantly (more than double) after subjecting the GFRP to loading/unloading interface shear path. Furthermore, the results in Fig. 4 also show that R_{max} does not change under the unloading path.

Based on the above discussion, the change of interface shear coefficient, $\Delta\mu_p$, under increased normal stress levels can be schematically conceptualized as shown in Fig. 6 where the first and the third mechanism are irreversible whereas the second mechanism is reversible. However, the third mechanism should have a predominant role over the first and the second mechanisms in order to get a net $\Delta\mu$ change similar to the observed behaviour in Fig.4.

Conclusion

Experimental tests were carried out in this study quantify the interface shear induced surface roughness changes under increased normal stress levels for FRP materials. The test results show that the rate of surface roughness change is function of the counterface surface hardness, HV, and the normalized roughness parameter R_n. The test results also indicate that the peak interface shear coefficient decreases as the normal stress increases. This behaviour could be explained in terms of the interface shear induced surface roughness increase, the change of the contact area per particle as the normal stress increases, and the interface shear induced striations in the counterface continuum surface. However, it is concluded that the later is the most predominant factor. In conclusion, the outcomes of this study demonstrate the importance of considering the shear induced wear of FRP materials during the driving process.

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