Experimental study of Leda clay-steel interface shear behaviour

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ABSTRACT
Understanding the interface shear behaviour between Leda clay and structure is significantly important for the design and stability analysis of many geotechnical structures (e.g., friction piles, retaining walls, and earth reinforcement). In this study, direct shear tests have been conducted to investigate the shear behaviour of the interface between Leda clay and steel material. All tests are carried out with a standard direct shear test apparatus at normal stresses which range from 250 to 450 kPa. Furthermore, the effects of several parameters (e.g., steel surface roughness, overconsolidation ratio (OCR) of the Leda clay, and saturation degree) on the interface shear behaviour are also studied. Valuable results have been obtained with regard to the interface behaviour of Leda clay. The results presented in this paper can be useful for geotechnical design on Leda clay.
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RESUMÉ
La compréhension du comportement au cisaillement de l'interface entre une argile Leda et une structure est essentielle pour la conception et l'analyse de plusieurs ouvrages de géotechnique (pieux à frottement, murs de soutènement, terre-armée, etc.). Dans cette recherche, des essais de cisaillement rectiligne ont été conduits pour étudier le comportement mécanique de l'interface argile Leda/matériel d'acier. Tous les tests ont été effectués avec un appareil de cisaillement rectiligne standard. Les pressions normales appliquées varient entre 250 à 450 kPa. En plus, les effets de plusieurs paramètres (rugosité de la surface de l'acier, degré de surconsolidation de l'argile Leda, degré de saturation, etc.) sur le comportement de l'interface ont été aussi étudiés. D'importants résultats ont été obtenus. Les résultats présentés dans cet article peuvent être utiles pour la conception d'ouvrages de géotechnique sur l'argile Leda.

1 INTRODUCTION

Thick deposits of Leda clay cover large areas of the provinces of Quebec and Ontario. The existence of Leda clays in these areas has made infrastructure expansion challenging for geotechnical engineers. As the aforementioned areas are fairly heavily populated and industrialized, the importance and behaviour of Leda clays as a foundation soil has led to several investigations of their geotechnical properties (e.g., Crawford 1963, Leroueil 1999). At the locations where Leda clays exist, many foundation engineers have adopted the use of pile foundations as subsurface supporting (heavy) structures to ensure the safe transmission of loading deep into a harder stratum (e.g., moraine, rock). Long end bearing piles, driven through the Leda clay to the deep underlying harder stratum, are often used when heavy loads must be supported (Roy et al. 1981). In many cases, short friction piles in the clay would provide much less expensive foundation solutions. However, their use has been relatively limited despite their lower cost (Roy et al. 1981). This is mainly due to the many unknown aspects of their geotechnical behaviour in the Leda clays. In particular, the interface shear behaviour between pile materials (steel, concrete, and wood) and Leda clay is not sufficiently known. To design reliable and cost-effective pile foundation structures (especially friction piles), it is crucial to understand the mechanical behaviour at the interface pile-Leda clay. This is especially true with regard to interface strength properties used in stability analyses.

Several studies have been conducted to understand the interface shear behaviour between pile construction material and cohesionless soils (e.g., Yoshimi and Kishida 1981; Evgin and Fakharian 1996) and the factors that affect the interface shear behaviour. Compared to the large number of research carried out to study the interface behaviour of granular soils, only a few researchers (e.g., Tsubakihara et al. 1993, Tsubakihara and Kishada 1993, Zimnik et al. 2000; Hammoud and Boumekik 2006, Tan et al. 2008, Tariq and Gerald 2009) have conducted studies on the shear behaviour of the interface between cohesive soils and structure. Previous research findings have significantly contributed to a better understanding of the interface shear behaviour of soil-structure. They reveal that the surface roughness, water content, soil composition and structure, and the intensity of the normal load have significant influence on the interface shear behaviour.

However, since Leda clay is a special type of soil and different from "normal" cohesive soils, the results of the aforementioned studies cannot be directly applied to a Leda clay-structure interface. Thus, there is the need to gain knowledge about the interface shear behaviour of Leda clay-structures for a safe and cost-effective design of pile foundations on these soils. Moreover, this understanding is not only important for pile design, but also crucial for the cost-effective design and accurate performance predictions of other relevant civil engineering structures (e.g., retaining walls, reinforced earth, and shallow foundation buried structures (e.g. lined tunnels)). However, no studies have addressed the interface shear behaviour between Leda clay and structure.

In consideration of the facts mentioned above, a research program has been conducted at the University of Ottawa to study the shear behaviour of the interface between Leda clay and steel. The objective of this paper is to present and discuss some results of the shear tests which were performed on the interface of Leda clay-steel.

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2 EXPERIMENTAL PROGRAMS

2.1 Testing apparatus

The interface shear behaviour of soil-steel can be tested by using one of a number of tests (e.g., simple shear test, the torsion or ring shear test). The advantages and disadvantages of each method have been summarized by Kishida and Uesugi (1987) and Paikowsky et al. (1995). Despite some inherent problems (e.g., principal stress rotation, stress non-uniformity, and failure plane definition), the direct stress shear apparatus is a commonly used device for interface testing because it is simple and well suited for this purpose (Miller and Hamid 2004). Hence, a standard direct shear test machine was used to conduct the shear tests on a Leda clay-steel interface. This direct shear apparatus uses a microprocessor controlled drive system and keyboard entry that provides the machine with a wide range of features which includes pause and speed changes from 0.00001 to 9.99999 mm/minute. Normal loads can be applied to the specimen by adding weights to the weight hanger. The changing shearing stresses are recorded through a mounted loading cell which is horizontally fixed to the shear box. The vertical deformation is recorded through a linear variable differential transformer (LVDT) which is mounted vertically on top of the loading yoke. The horizontal displacement is recorded through an LVDT which is horizontally fixed onto the shear box. All recorded data were gathered by using a computerized data logging system. The results were automatically monitored and saved by the software Labview.

2.2 Materials used in the experimental programs

2.2.1 Leda clay

The undisturbed Leda clay material used in the present study was collected from the Ottawa area. The samples were recovered from a depth which ranged from 8 to 12 meters. The mineralogy of the Leda clay was dominated by quartz, feldspars, illite, chlorite and amphibole (Kondo and Torrance 2005), which is typical of Leda clays. However, it should be mentioned that the mineralogical composition of Leda clays is dependent on the geographical location (Law and Bozozuk 1988). Standard laboratory geotechnical tests were carried out on the clay samples to obtain their basic geotechnical characteristics. Table 1 summarizes the main properties of the Leda clay used and Figure 1 shows its grain size distribution curve.

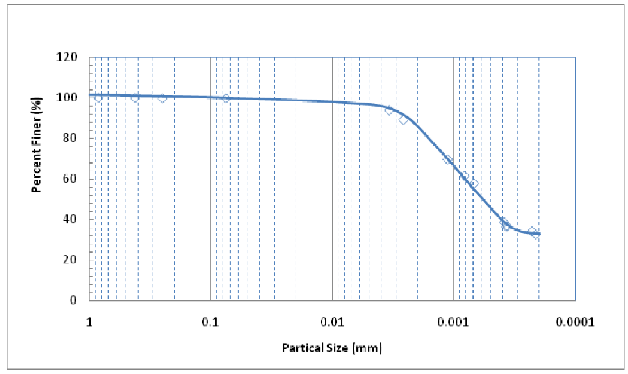

Figure 1. Grain size distribution of the Ottawa Leda clay used in the study.

Table 1. Summary of the main characteristics of the Leda clay used in the study.

Property	Value/Classification
Classification	CH
Water content (%)	82
Liquid limit (%)	66
Plastic limit (%)	25
Plasticity index (%)	40
Liquidity index	1.4
Clay fraction (%)	84
Activity	0.48
Laboratory vane shear strength (kPa)	9.7
Sensitivity	6
Pre-consolidation Pressure (kPa)	150
Natural void ratio	2
OCR (overconsolidation ratio)	1.1
Sodium chloride concentration	3-4 g/l
Optimum water content, Dry unit weight at optimum	22%, 14.95 kN/m^3

2.2.2 Steel material

The steel plates were fabricated from milled steel rods which made up the shear box with inner dimensions of 60 X 60 mm and a thickness of 5 mm. Table 2 summarizes the main mechanical properties of the steel. The surface of each steel plate was finished to a specific surface roughness. The roughness was measured using high precision LVDT. The LVDT together with the data logging system recorded the interface profile. The surface roughness was evaluated based on the method proposed by Yoshimi and Kishada (1981) and Uesugi and Kishada (1986). The average maximum surface roughness (R_{max}) of the three categories of steel was 20 μm, 5 μm and 1 μm, respectively.

Table 2. The properties of the steel plates (at temperature = 25°C).

Properties	Value
Density (×1000 kg/m^3)	7.7-8.03
Poisson's Ratio	0.27-0.30
Elastic Modulus (GPa)	190-210
Tensile Strength (Mpa)	394.7
Yield Strength (Mpa)	294.8
Hardness (HB)	111
Impact Strength (J)	123.4

2.3 Test specimen preparation

Undisturbed Leda clay samples, which were directly obtained from Shelby tubes, were cut from a vertical profile into squares of approximately 60 x 60 x 12 mm in size to fit the top half of the shear box. These samples were used to study the interface shear behaviour of the normally consolidated Leda clay-steel. They were also used to investigate the effect of steel surface roughness and OCR on the interface shear behaviour. Prior to placement in the shear box, the square samples were wrapped in saturated filter papers and placed on top of porous stones. The porous stones were kept submerged in distilled water in a humid room until they reached complete saturation. Trial studies have shown that specimens attain saturated conditions within a period of 24 hours. As well, no volume increase of the soil sample was measured. However, to study the effect of the initial saturation degree, density and salt content of Leda clay on the interface shear behaviour, further preparation of the Leda clay samples was necessary. The details of the preparation and results obtained are published in Taha and Fall (2010).

2.4 Testing procedures

2.4.1Consolidated drained interface shear tests

A series of direct shear consolidated drained (CD) tests were carried out to examine the interface shear behaviour of normally consolidated Leda clay sheared with respect to varying steel interfaces. CD tests were also performed on samples with various OCRs. This interface testing series is carried out in accordance with ASTM D 3080. This procedure is selected to simulate the effect of slow loading after pore water pressure dissipation. Interfaces for shear testing were constructed by first placing the specified steel plate into the base of the shear box. The prepared Leda clay specimen was installed in the top halve of the shear box in such a way that the interface between the clay and steel was located exactly between the two halves of the shear box. The prepared test samples in the shear box were submerged in water. To conduct CD tests on normally consolidated Leda clay, the test samples were first left to completely consolidate (against the interface steel plate) at normal stresses high above their preconsolidation stresses. The normal stresses (applied during the shear test) were maintained at 250, 350 and 450 kPa based on previous experimental work (e.g., Dam 1999). Furthermore, these stresses encompass a realistic range of operational stresses in geotechnical structures (Dejonga and Westgateb, 2005). After the completion of the primary consolidation, the samples were sheared at a slow rate of 0.0185 mm/min in order to minimize pore-pressure development during shearing. This shearing rate is selected based on the time required to reach 50% consolidation, i.e. the t_{50} at a 5 mm displacement to failure, and also previous work (e.g., Kisheda and Nishiyama 1993). In a review of the previous work of Kisheda and Nishiyama (1993), a shearing rate of 0.03 mm/min was used in their interface CD tests on Kawaski marine clay to avoid changes in pore pressure during shearing. This indicates that 0.0185 mm/min is a reasonable shearing speed. To conduct CD tests on Leda clay with various OCRs, the samples were left to completely consolidate at stresses two to three times higher than these three normal stresses: 250, 350 and 450 KPa. After the completion of the primary consolidation, the samples were slowly unloaded to the desired normal stresses to produce three OCR values of 1, 2 and 3. The samples were then sheared according the procedures described above.

2.4.2 Consolidated undrained interface shear tests

A series of consolidated undrained (CU) direct shear tests were carried out to examine the interface shear behaviour of disturbed and undisturbed Leda clays that have different initial saturation degrees. The soil specimens were left to consolidate under normal stresses of 250, 350 and 450 KPa prior to shearing in a conventional direct shear apparatus. ASTM D 3080 is applied in this series of Leda clay-steel interface tests. After the completion of the primary consolidation, the samples were sheared at a fast rate of 1.25 mm/min. The details of the test procedure have been previously described by Lane et al. (2001). The shearing rate was selected to simulate the CU condition or rapid shearing. It can be assumed that the specimens were sheared under undrained conditions due to the relatively rapid strain rate used for shearing and the low coefficient of permeability of the soil specimens (Vanapalli and Lane, 2002). Furthermore, this is a reasonable assumption for fine-grained soils as the shearing of the specimen was completed over a short period of time (i.e., 5 to 10 minutes). Vanapalli and Fredlund (2000) used similar assumptions for analyses of shear strength test results on a silty soil. The test results can be analyzed based on the assumption that there is no significant change in suction of the soil specimen during the shearing stage.

3 RESULTS AND DISCUSSIONS

In this section, typical direct shear test results for different Leda clay-steel interfaces are presented and discussed. In general, the shear test results are presented by using three types of graphs: shear stress–relative displacement curves, shear relative displacement–vertical displacement curves and shear strength envelopes, which give the interface shear strength parameters (cohesion or adhesion, *c*, friction angle, *φ*).

3.1 Shear behaviour of the interface between normally consolidated Leda clay and steel

Figure 2 shows typical shear stress versus relative shear displacements for the interface between Leda clay and steel with a surface roughness of 5 µm. Typical shear stress–relative shear displacement curves from direct shear tests performed on the Leda clay alone are also presented in Figure 2 for comparison. Typical shear stress–vertical displacement and shear stress-normal stress curves will be presented in the next section to avoid repetition and keep the paper at a reasonable length. From Figure 2, it is obvious that the curves of the Leda clay and interface are relatively different. It can be observed that at a normal stress of 250 kPa, the shear resistance of the normally consolidated Leda clay is higher than that of the Leda clay-steel interface. However, at normal stresses higher than 250 kPa, the shear resistance of Leda clay becomes less than the interface shear resistance.

It can be seen that the Leda clay-steel interface exhibits distinct peak and postpeak shear stress behaviour, which is not true for the curves of the Leda clay. In other words, the Leda clay-steel interface exhibits postpeak displacement-softening behaviour whereas the normally consolidated Leda clay has approximately postpeak plastic behaviour.

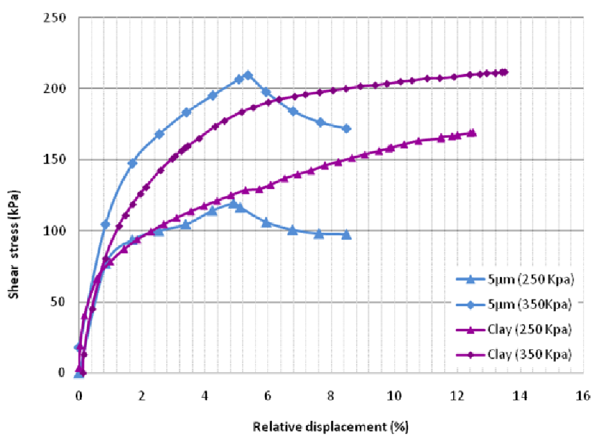

Figure 2. Shear stress vs. relative shear displacement of Leda clay-steel interface and Leda clay alone.

3.2 Effect of steel roughness on the interface shear behaviour

Typical results of the effect of steel surface roughness on shear stress-shear displacement curves, vertical displacement-shear displacement and shear stress-normal stress curves are presented in Figures 3 to 5, respectively. Figure 3 shows a comparison between the shear stress vs. relative displacement curves of the Leda clay interfaces with various values of roughness. It can be noted that an increase in the interface surface roughness results in an increase of the interface shear resistance. This behaviour is due to the increase in the interlocking forces and contact area between the asperities of the Leda clay and steel as the surface roughness increases.

Figure 4 illustrates the impact of steel surface roughness on the vertical deformation behaviour of the Leda clay interface. From this figure, it can be observed that a higher roughness is associated with a higher contraction at the interface. This behaviour can be attributed to the fact that surfaces with higher roughness have higher asperities. This induces more remolding and collapse of the clay structure during the shearing process. Tsubakihara and Kishada (1993) recorded a similar behaviour in their interface tests with Kawasaki marine clay. They observed that the volumetric strain increases as the surface roughness increases.

Figure 5 shows typical interface shear strength envelopes for various values of roughness. It can be seen that the angle of internal friction increases as the surface roughness increases. The diagram shows that the angle of internal friction of the Leda clay is almost equal to that of the rough interface and higher than those of the 5 µm and 1 µm interfaces. It is noteworthy to mention that similar observations were made by Hamid and Miller (2009) from the results of their interface direct shear tests on a low-plasticity fine-grained soil.

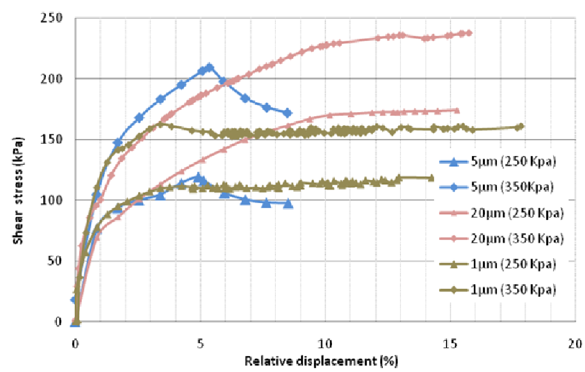

Figure 3. Shear stress vs. horizontal displacement of the Leda clay interface for different surface roughness.

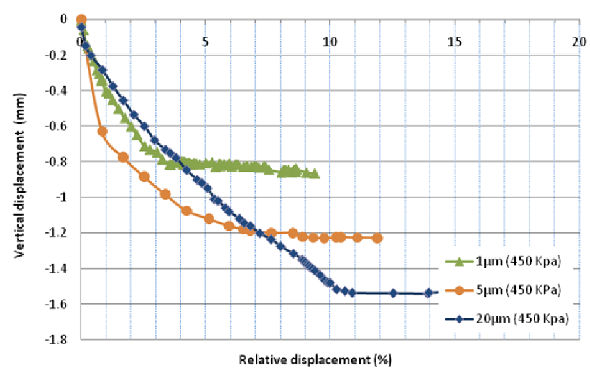

Figure 4. The effect of the surface roughness on vertical deformation at 450 KPa.

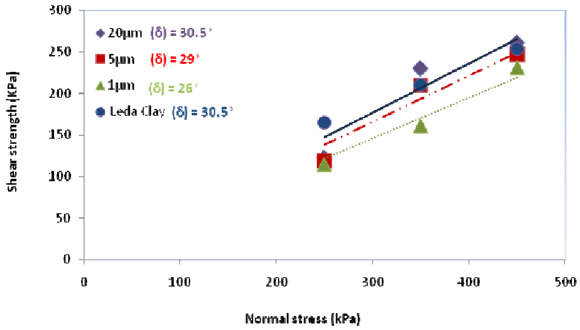

Figure 5. Shear stress vs normal stress for Leda-clay steel interface and Leda clay alone.

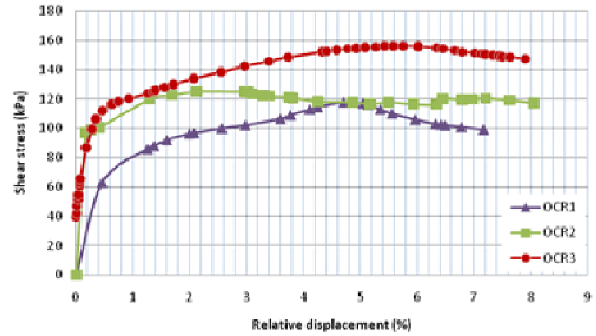

Figure 6. Shear stress vs. horizontal displacement of the Leda clay interface for OCRs 1, 2 and 3 at a normal stress of 250 kPa.

3.3 Effect of Leda clay's OCR on the interface shear behaviour

The results obtained have shown that the OCR has a significant impact on the interface shear behaviour of Leda clay. Some sample results are presented in Figures 6-8. Figure 6 shows the effect of OCR on the shear stress-shear displacement curves of the interface shear behaviour under normal stresses of 250 and 450 kPa. An analysis of Figure 6 reveals that the peak interface shear stress is a function of the OCR. A higher OCR leads to a higher peak shear stress. This is attributed to the fact that an increasing OCR ratio results in more densification of the porous medium of Leda clay and stronger clay aspirates with higher interlocking forces that resist shearing deformation.

Figure 7 displays the shear displacement vs. vertical deformation behaviour of Leda clay interfaces at low normal stress and for the three OCRs. From this figure, it is clear that increasing the OCR of Leda clay leads to a reduction of the interface compressibility. Moreover, the OCR 3 curve shows dilation behaviour in the beginning of shearing. This can be attributed to the rise of dense clay asperities out of their embedment location within the steel asperities. As the shearing propagates, and after passing the peak strength zone, crushing the clay asperities causes an interface contraction with a level less that that observed at OCRs 1 and 2. DeJong and Westgate (2005) observed similar dilation behaviour in their study on sand-geomembrane interface response due to overconsolidation.

In Figure 8, the Mohr-Coulomb diagram indicates that the interface angle of friction increases as the OCR increases. This suggests that the preloading of Leda clay soil would enhance its interface interaction.

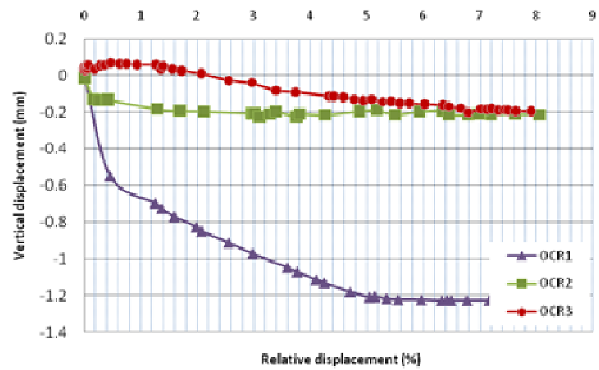

Figure 7. The effect of OCR on the interface vertical deformation at a normal stress of 250 kPa.

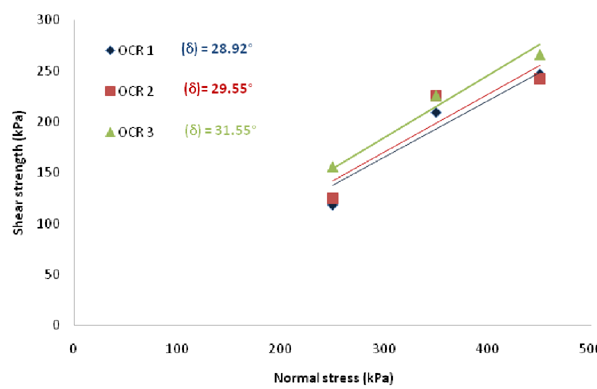

Figure 8. Interface shear envelopes of the Leda clay-steel Interface for different OCRs

3.4 Effect of the initial saturation degree of Leda clay on the interface shear behaviour

Figure 9 illustrates the effect of the initial saturation degree on the shear stress-shear deformation curve of the Leda clay interface. It can be observed that a lower saturation degree is associated with a higher peak shear stress. This can be attributed to the fact that a lower saturation degree results in higher matrix suction. The matrix suction increases the bonds between the clay particles, thereby leading to stronger clay asperities.

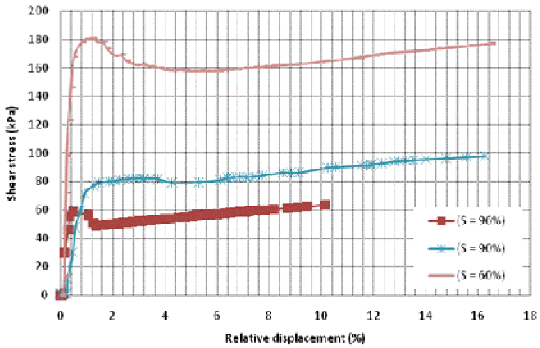

Figure 9. Shear stress vs. relative displacement of the Leda clay interface for various initial saturation degrees and under a normal stress of 250 kPa.

4 CONCLUSIONS

In this paper, the results of an experimental study on the shear behaviour at the interface region between Leda clay and structural material, such as steel, are presented. Experiments with different roughness of steel and degrees of saturation of Leda clay are carried out using an automated direct shear machine connected with an LVDT, loading cell and a data logging system. The effect of various parameters, such as OCR, on the interface shear behaviour is also studied. Valuable results have been obtained with regards to the interface shear behaviour of Leda clay-steel. Furthermore, the obtained results indicate that the interface friction angle increases as the steel surface roughness and OCR of Leda clay increase. However, increasing the surface roughness will result in more interface contraction. On the other hand, the results show that the interface friction angle increases as the saturation degree of Leda clay decreases. The results presented in this paper can be useful for foundation designs in Leda clay.

5 ACKNOWLEDGEMENTS

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