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Variation in interface frictional behaviour during cyclic loading

Variation du comportement frictionnel lors d'un chargement cyclique

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ABSTRACT: Common practice in experimental soil-structure-interaction modelling is to make the model interface either 'rough' or 'smooth' hence removing doubt regarding the interface behaviour and facilitating easier numerical replication of the experimental data. However, this simplification results in unrealistic soil-structure system responses being modelled. Both soil and structural constitutive models have advanced significantly in recent years and it is now imperative that research attention turns to establishing a stronger physical understanding of interface behaviour and developing the corresponding numerical models capable of capturing this behaviour. Element-scale cyclic interface tests have been performed at the University of Nottingham to develop an improved physical understanding of interface behaviour. Through this experimental research programme nuances in the interface behaviour have been observed, such as the impact of fine particle migration on the friction ratio. This paper will present the experimental work undertaken and the corresponding results. Given the quantity of soil-structure-interaction research programmes currently being undertaken, the discussions in this paper should prove interesting to a wide range of researchers and practitioners.

RÉSUMÉ: La pratique courante en modélisation expérimentale d'interaction sol-structure consiste à rendre l'interface du modèle soit «rugueuse» ou «lisse», éliminant ainsi le doute sur le comportement de l'interface et facilitant la réplication numérique des données expérimentales. Cependant, cette simplification conduit à modéliser les réponses irréalistes du système sol-structure. Les modèles constitutifs du sol et de la structure ont considérablement progressé ces dernières années et il est maintenant impératif que la recherche s'attache à établir une meilleure compréhension physique du comportement des interfaces et à développer les modèles numériques correspondants capables de capturer ce comportement. Des tests élémentaires d'interface cyclique ont été réalisés à l'Université de Nottingham afin de développer une compréhension physique améliorée du comportement de l'interface. Ce programme de recherche expérimental a permis d'observer des nuances dans le comportement des interfaces, telles que l'impact de la migration de particules fines sur le coefficient de frottement. Cet article présentera les travaux expérimentaux entrepris et les résultats correspondants. Compte tenu de la quantité de programmes de recherche sur les interactions sol-structure actuellement en cours, les discussions dans le présent document devraient intéresser un large éventail de chercheurs et de praticiens.

Keywords: Soil-structure interaction, pipeline, particle crushing, particle migration

1 INTRODUCTION

Despite advances in the modelling of soil and structural constitutive behaviour, there has been a lack of equivalent development in the study of the soil-structure interface. This is particularly true for situations with cyclic loading of the interface involving large displacements. Such loading histories are common for oil and gas pipelines which can experience cyclic displacements of varying amplitudes due to fluctuations in the fluid and soil temperatures. These axial displacements induce a shear friction between the surrounding soil and the pipelines outer surface. Any changes in the interface behaviour can subsequently result in buckling and failure of the pipeline.

Previous studies have investigated the soil-structure interface through cyclic testing by the use of direct shear (Desai et al., 1985; Fioravante et al., 1999; Ganesan et al., 2014; Scarpelli et al., 2003), simple shear (Oumarou & Evgin, 2005; Uesugi et al., 1989; Uesugi et al., 1990), 3D monotonic loadings (Fakharian & Evgin, 1996) and pull-out tests (Alam et al., 2013; Martinez et al., 2015). However, these studies have imposed relatively few cycles (i.e. 100-1000) and therefore the long-term behaviour is not yet understood. This paper describes the development of a large displacement shearing device and shows the first results from shearing tests between a coarse sand and a steel plate.

2 EXPERIMENTAL PROGRAM

2.1 Experimental device

The experimental device, which was developed at the University of Nottingham, works in a similar manner to a traditional direct shear box with one half of the box being replaced with an interface.**Error! Reference source not found.** In this case the soil sample is confined in a container which is stationary whereas the interface is attached to a shearing table that can move with a rail-carriage system, as shown in Figure 1. The horizontal and vertical actuations are made using a ball screw connected to a stepper motor with interchangeable gearboxes, load cells and displacements transducers facilitating a range of actuation speeds and levels of control precision.

The horizontal ball screw axis is located at the centre longitudinal axis of the device and goes through a clearance made in the shearing table. The horizontal load is measured by using two exchangeable load cells having a maximum load of 1 kN each. These two load cells are attached to the shearing table and are located on either side of the horizontal ball screw. Horizontal displacement is measured by a large displacement sensor at the back of the device with a range of 300 mm.

The vertical load cell is in-line with the vertical ball screw, with the vertical actuation capable of applying loads of up to 2.5 kN. Vertical movement of the soil surface is measured by a 10 mm displacement sensor. The soil sample, which has a maximum diameter of 70 mm and depth of 40 mm, is confined in a stainless steel circular container which sits over the structural interface. The standard steel container can be replaced with a Perspex square shaped container to facilitate visualisation of the grain scale deformations.

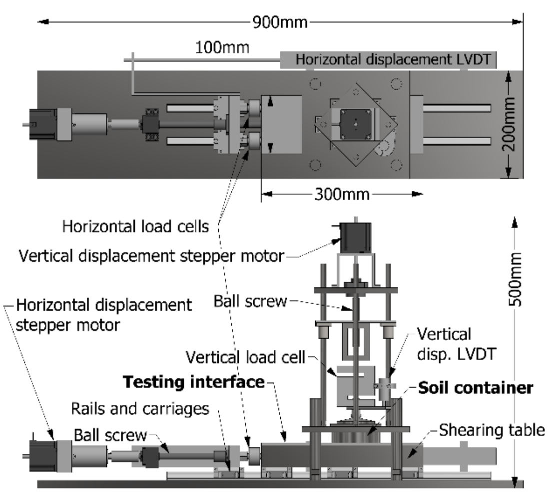

Figure 1. Detailed view of the soil-interface shearing device

2.2 Soil and interface properties

The soil used in the experimental programme was a coarse sand, with a D_{50} = 1.66 mm and a uniformity coefficient, C_u = 1.1, sieved from Leighton Buzzard sand ('Fraction A'). Fraction A grains range from sub-angular to sub-rounded with a specific density of 2.65.

For the interface, a stainless steel plate with a roughness height (R_t) of less than 1µm was used. However, more informative than the absolute roughness height is the roughness height relative to the grain size as given by the normalized roughness (R_n) proposed by (Uesugi et al., 1989) and given in Eq. 1. With Fraction A sand, the steel plate used gave an R_n value less than 10^{-3}. To ensure consistency between all steel interface plates used in this testing programme, all interfaces were tested for Vickers hardness with an average value of 188 and a standard deviation of 7.4 being obtained.

$$R_n = R_t / D_{50} \tag{1}$$

3 EXPERIMENTAL PROCEDURE

In interface testing, it is critically important to minimise the gap between the interface and the soil container to prevent particles from becoming trapped. Therefore, a 1/1000" thick, steel, Starrett 667 Series Feeler Stock was slid between the container and interface, and the height of the container adjusted until the gap was equal and minimised across the entire footprint of the container.

To ensure the soil used was consistent across all tests, the sand was washed and sieved with a 0.8 mm sieve to remove any dust particles. The sand was then dry pluviated from a constant drop height and constant rate in order to achieve homogenous samples. Once pouring was completed, the top of the sand sample was levelled, the top cap positioned and an initial vertical confining load applied. All samples had a consistent height of 32mm ± 1mm with other properties shown in Table 1.

Table 1. Initial properties of the sand samples

Property	**Value**
Bulk density	1.624 g/cm^3
Void ratio	0.632
Relative density	90%

All tests were carried out at the same normal stress (100 kPa) and displacement rate (1 mm/s). The tests were separated into two series: one with a cyclic displacement of 6 mm and another with 10 mm.

4 DATA PROCESSING

From the obtained data it is straightforward to produce plots of interface friction ratio (horizontal force divided by the vertical force) against horizontal displacement such as the example shown in Figure 2. Although it is clear from Figure 2 that there is a pattern with cycle number, in order to investigate this further it is necessary to obtain a representative friction ratio for each cycle. Therefore the friction ratios obtained during part of the displacement cycle (from +/- 80% of the maximum displacement, as shown in Figure 2) were averaged. This resulted in two friction ratios; one for the forward (positive) and one for the reverse (negative) direction. The absolute value of these averaged friction ratios were further averaged to provide a single friction ratio for that cycle.

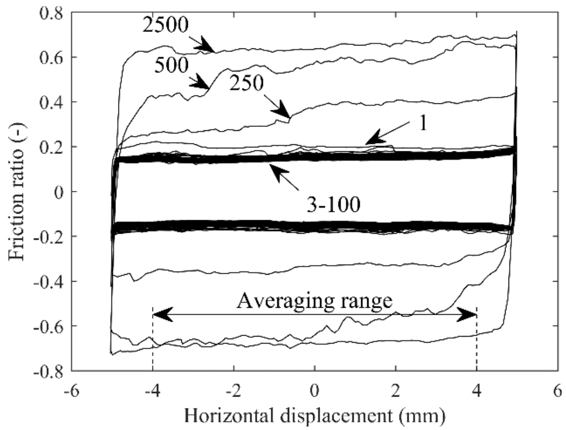

Figure 2. Typical cyclic response of friction ratio vs. horizontal displacement with cycle numbers labelled

5 GENERAL OBSERVATIONS

Two series of five identical tests were carried out to assess the repeatability of the experiment and to validate the experimental device.

For every test carried out, the initial friction was 0.18 which then decreased to 0.15 over the first few (less than 20) cycles. This decrease in interface friction ratio has been observed in previous research such as that of Fakharian and Evgin (1997). However, in these experiments, following this initial decline in interface friction ratio, it subsequently increases slowly with each cycle. Once the friction ratio increases to 0.2, the rate of increase instantly becomes more rapid. At the same time, an audible particle crushing sound is notable. During the tests, it was observed that crushed sand fines accumulate at the edge of the container, outside of the shearing zone (as shown in Figure 3 around the sample). At the end of the experiments, when removing the sand, the top is relatively undisturbed and all the sand grains appear to still be intact. However, at the bottom of the sample, a thick layer (approximately 5mm) of crushed sand mixed with intact grains is present as can be seen in Figure 3.

Figure 3. State of the lower part of soil sample post-test and after container removal

6 REPEATABILITY

While carrying out tests for repeatability, it was found that this rapid increase in interface friction ratio occurred at a different numbers of cycles in each test. For the 6 mm cyclic displacement tests, it occurred at 50, 100, 100, 100 and 200 cycles (see Figure 4) whereas for the 10 mm cyclic displacement tests, it occurred at 50, 50, 100, 200 and 700 cycles (see Figure 5).

Initially it was suspected that this variation in number of cycles to onset of rapid friction ratio increase was a consequence of inconsistencies with the experimental apparatus. Therefore a lengthy process was undertaken to refine the device and procedure, and to examine possible sources of error. However, regardless, there was still a change in the number of cycles at which grain crushing occurred. Despite this inconsistency with regards to cycle number, it was observed that the friction ratio at which this rapid increase began was consistent across all tests.

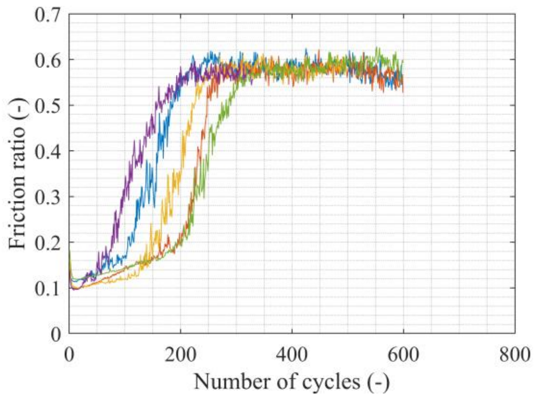

Figure 4. Characteristic friction ratio for 6mm displacement tests vs. number of cycles

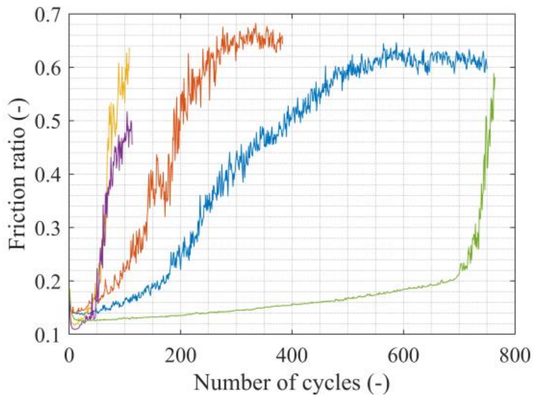

Figure 5. Characteristic friction ratio for 10mm displacement tests vs. number of cycles

7 INTERFACE DAMAGE

Two additional tests were conducted at 6 mm displacements to assess the impact of grain crushing on the interface. These two tests were stopped during the grain crushing phase at friction ratios of 0.3 (A) and 0.4 (B) and were compared to an unstopped previous test carried out until maximum friction ratio (C), as shown in Figure 6.

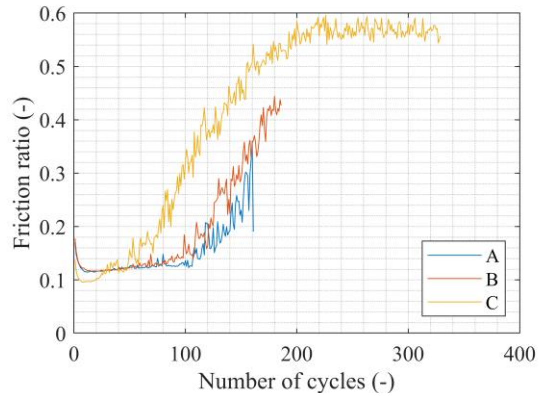

Figure 6. Tests stopped at 0.3 (A) and 0.4 (B) friction ratios and one previous test (C)

The samples were then removed and the surface condition of the steel plate was examined (Figure 7). Images show localized damage on the interface with Test A showing a lower damage area than Test B. The unstopped test shows damage across the entire surface. Small grooves can also be seen in both stopped tests (A & B), the length of which correlated to the cyclic displacement magnitude of 6 mm.

In Figure 9 there is evidence of crushed particles being ingrained within the plate in localised areas for Test A & B (as encircled with the dashed lines), with this area being larger for Test B. In the case of Test C this extends across the entire footprint of the shearing area. It can be concluded therefore that this damage caused by crushing increases the friction ratio. Hence, friction ratio increase is not due to a homogeneous increase across the entire shearing area but due to localized damage having a much higher friction ratio (e.g. 0.6) than the rest of the surface (e.g. 0.2) resulting in an average value in between these two extremes, until the entire plate is in the same state as in the case of Test C.

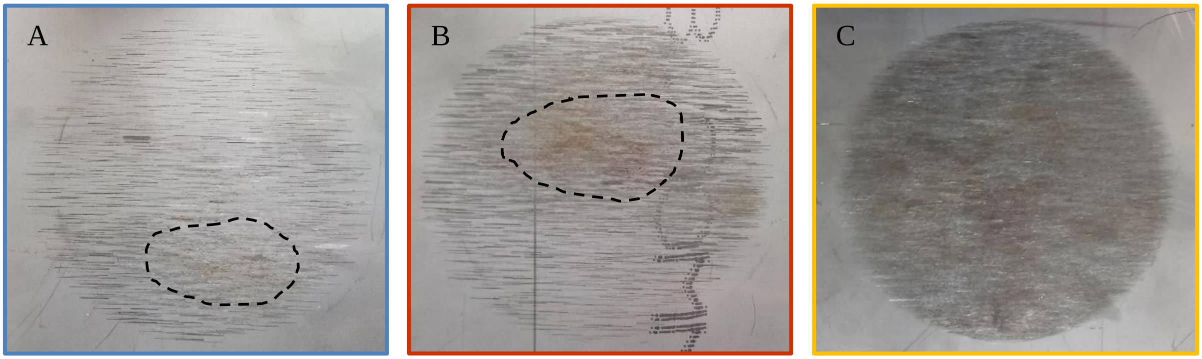

Figure 7. Damage of the steel plate at (A) 0.3 friction ratio, (B) 0.4 friction ratio and (C) full damage

8 DISCUSSION

Previous research undertaken with this interface shearing device (Hashemi & Heron, 2017) using a transparent perspex container allowed the effect of interface shearing on the sand grains to be directly observed. Results showed that, at first, sand grains are sliding at the surface and not rotating. This sliding behaviour results in an increase in the friction ratio due to the formation of grooves on the surface of the interface.

Once the friction ratio increases to a certain value, some sand grains start rotating, disrupting the force chain through the soil matrix, and provoking grain crushing. At this stage, grain crushing is localized covering only a small portion of the surface. Continued breakage results in progressively more damage occurring and the interface friction ratio increasing. This phenomenon then spreads out covering more and more of the shearing area.

By assuming that respectively no damage and full damage is present at the start and end of the grain crushing phase, an estimate of the area affected by crushing at any stage of the test can be made. The number of cycles between the onset of crushing and a fully fully damaged state (constant friction ratio) is approximately 100 cycles for tests at 6 mm displacements and 60 cycles for 10mm displacements. This suggests that the crushed area spreading rate might be proportional to the displacement cycle amplitude and therefore the damaged surface can be expressed by cumulated displacement as shown in Eq. 2.

$$S_{\text{damage}} = 6.4\text{mm} \times d_{\text{accumulated}} \quad (2)$$

9 CONCLUSION

Understanding soil-interface frictional behaviour is important in the study of all soil-structure interaction problems. The large displacement cyclic behaviour is particularly prevalent the modelling of pipeline behaviour which can experience large displacements (>5 mm) over a very large number of cycles (in the thousands). Most research in the past has focused on smaller displacements and lower number of cycles.

For this purpose, the University of Nottingham has designed a large displacement soil-interface shearing device. Tests were undertaken to investigate the interface behaviour at different cyclic displacement amplitudes and after large numbers of cycles.

Results showed that despite an initial drop of interface friction ratio over the first few cycles, the friction ratio then increased slowly until a point at which a rapid increase occurs (increasing from 0.2 to 0.6 within 100 cycles). This rapid increase was found to be caused by a change in the shear mechanism which resulted in grain crushing occurring at the interface. Between every test, the cycle number at which the rapid increase in friction ratio begins is not consistent however, a sharp increase is mainly seen when the friction ratio reaches 0.2 indicating that that the change in mechanism and associated crushing is not a function of the number of cycles but of the friction ratio.

Some tests were ended at points during the rapid increase in interface friction. By examining the condition of the surface of the plate it was possible to determine that the damage associated with the crushing action is initially localized and grows over the number of cycles. As such, it was possible to propose an equation which correlated rate of damage growth per cycle to the displacement per cycle.

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