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Dynamic friction and the seismic performance of geosynthetic interfaces

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ABSTRACT

The stability of geotechnical structures which contain geosynthetic interfaces is closely linked to the shear strength between the geosynthetics themselves, both in static and dynamic conditions. Static friction is the maximum interface shear strength mobilised before displacement, whereas dynamic friction is related to the kinematics of the displacement itself. In polymer materials, dynamic friction may be widely variable, depending on the type, geometry and integrity of the surfaces in contact, as well as on the intensity and time-history of the seismic signal. This means that predicting interface shear strength is not simple. This paper focuses on the evaluation of dynamic interface shear strength between geosynthetics, using the results of both inclined plane tests and shaking table tests; this latter test also provided a means to analyse interface behaviour under the conditions of real seismic records. To this purpose, two common geosynthetic interfaces, which exhibit different behaviour under dynamic loading, were tested. One interface was a smooth HDPE geomembrane in contact with a nonwoven polypropylene geotextile, while the second was a textured HDPE geomembrane in contact with a different type of nonwoven polypropylene geotextile.

The test results shows that dynamic friction mobilised during seismic events depends on the relative speed according to the same law outlined by the free sliding tests and by the shaking table tests carried out with sinusoidal base motions. Moreover, for the two different types of studied interfaces dynamic friction may be greater, lesser or equal to the static friction and the assumption of a constant value of dynamic friction does not lead to an accurate prediction of the seismic displacements under various earthquakes.

1. Introduction

Geosynthetics are widely used to fulfil multiple functions, such as filtration, drainage, waterproofing, separation and reinforcement, however they do involve some particular problems for the design of geotechnical works. Given that the interfaces often constitute preferential sliding surfaces due to the low available friction, one such problem is the proper evaluation of the friction at the interface between geosynthetics. This problem is common in all applications which require the coupling of geosynthetics subjected to tangential stresses in their plane, as occurs, for example, in landfill barrier systems. In addition to the issue of static equilibrium, there is also a problem concerning the dynamic behaviour and, in particular, the limit state of serviceability of such structures, caused by possible excessive displacements during seismic events (Mitchell et al., 1990; Byrne et al., 1992; Anderson and Kavazanjian, 1995; Augello et al., 1995; Matasovic et al., 1998).

Even though studies have been carried out to address this, the dynamic behaviour of geosynthetic interfaces under seismic loading has not yet been sufficiently clarified. From a methodological point of view, seismic damage could be avoided by setting an appropriate safety factor to ensure that maximum static friction is not attained during seismic events i.e., in other words, that relative displacement at the interface does not occur (pseudo-static approach). Besides leading to an excessively conservative design of a structure, this approach does not provide information on any post-seismic displacements related to events exceeding the design hypothesis.

For this reason, literature on the topic is also aimed at predicting seismic displacements of composite structures (Cai and Bathurst, 1996; Ling and Leshchinsky, 1997; Bray et al., 1998; Kavazanjian, 1998; Wartman et al., 2005; Bray, 2007; Zania et al. 2010a, 2010b; Feng et al., 2015). In this regard, modern "performance-based design" acknowledges that some seismic relative displacements may occur between the various elements of the structure and, in particular, between geosynthetics, providing that they are compatible with the serviceability of the structure (Kavazanjian et al. 1998, 2018). However, the accuracy of the method depends on the level of characterisation of the elements involved, and in particular of the interfaces between

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geosynthetics.

Geosynthetic interfaces have also been studied as low-cost base isolation in earthquake hazard mitigation, due to the ability to localise relative displacements (Yegian and Lahlaf, 1992; Yegian and Catan, 2004; Yegian and Kadakal, 2004; Arab and Kavazanjian, 2010; Nanda et al., 2015; Kalpakci et al., 2018).

Since only an appropriate characterization is able to give an accurate level of prediction of the dynamic behaviour of the interfaces, the aim of this research is to outline a methodological approach for evaluating the dynamic friction of geosynthetic interfaces, using inclined plane and shaking table devices.

2. The static and dynamic evaluation of interface strength

There are several types of test available for studying geosynthetic interface strength, under both static and dynamic loading conditions.

For static conditions, there are five main testing methods available: the direct shear test, the annular shear test, the cylindrical shear test, the inclined plane test and the pull-out test. The widely used direct shear test requires large dimension specimens of at least 30 cm × 30 cm wide for the testing of geosynthetic interfaces (ASTM D-5321, 1998). The annular shear device is used to study interface shear strength at large displacements (Stark and Poeppel, 1994; Stark et al., 1996); this equipment is similar to the Bromhead apparatus, but modified in order to allow specimens of large dimensions to be tested. To overcome some of the limitations of the annular shear device, Moss and Anderson (2000) developed the cylindrical shear apparatus. With this device, the two geosynthetic specimens are wrapped around a cylinder, and the test is performed by rotating the inner geosynthetic while the outer geosynthetic remains fixed, held in place at the top and the bottom.

The fourth method of measurement is the inclined plane test (Lalarakotoson et al., 1999; Briançon et al. 2002, 2011; Gourc and Reyes-Ramirez, 2004; Pitanga et al. 2009, 2011; Pavanello and Carrubba, 2016). This device is composed of an inclinable table with a block placed on top; one geosynthetic is fixed to the table tilting at a constant rate of rotation, while the second is bound to the block, which is free to slide along the table. The test procedure (EN ISO 12957-2, 2005) recommends a sliding block of at least 30 cm × 30 cm wide and a tilting rate of 3 ± 0.5°/min for the table. This test is common in Europe, and may be more suitable in determining the behaviour of geosynthetic interfaces at low normal stress (Wasti and Özdüzgün, 2001). Lastly, the large-scale pull-out test is more suitable for the purposes of designing the geosynthetic anchorage (Moraci and Recalcati, 2006; Moraci and Cardile, 2009, 2012; Ezzein and Bathurst, 2014; Cardile et al., 2016, 2017; Moraci et al., 2017).

Dynamic conditions can be studied by means of the shaking table device, the dynamic direct shear test and the inclined plane test. The most common tests are carried out by means of the shaking table device; the table carries one of the geosynthetics of the interface, while the other is bound to a free-sliding block resting over the table. The case of an interface placed on a horizontal plane and subjected to regular cyclical loadings, i.e. triangular or sinusoidal, has been studied by many authors (Yegian and Lahlaf, 1992, Yegian et al., 1995, De and Zimmie, 1998, Park et al., 2004, Carbone et al., 2014, 2015). Tests using replicas of real seismic events have also been carried out with this device configuration (Yegian et al., 1995; Yegian and Kadakal 1998, 2004), while other studies have analysed a sliding block resting over an inclined plane, connected to the shaking table and subjected to a horizontal dynamic loading (Yegian and Harb, 1995; Wartman et al., 2003).

The basic approach for interpreting this test is based on Newmark's sliding block (Newmark, 1965): during table motion the block moves in tandem with the table until it exceeds critical acceleration. When the table acceleration is greater than the critical acceleration, the block slides: as soon as the critical value is detected, interface dynamic friction may be evaluated as a function of the critical acceleration itself.

Experiments with dynamic direct shear devices have also been carried out (De and Zimmie, 1998; Yegian and Kadakal, 1998; Kim et al., 2005); another type of dynamic direct shear device was proposed by Fox et al. (2006) for the dynamic study of GCL interfaces (Ross and Fox, 2015). Lastly, dynamic friction was also measured by means of the inclined plane test, by monitoring the kinematics of the block while it slides (Gourc and Reyes-Ramirez, 2004; Carbone et al., 2015), as discussed in the following.

In detail, Yegian and Lahlaf (1992) and Yegian et al. (1995) studied an interface between a smooth HDPE geomembrane and a nonwoven geotextile with a shaking table; they found that normal stress and frequency of excitation did not affect significantly the dynamic friction angle and they reported that the dynamic friction resistance slightly increased with increased table acceleration and it was not appreciably different from the one observed from static tests. De and Zimmie (1998) conducted dynamic shear tests with eight different geosynthetic interfaces using cyclic direct shear tests, standard shaking table tests and shaking table tests in a geotechnical centrifuge. The research showed that the shaking table results compared well with those from the cyclic direct shear tests; moreover, the tests revealed various characteristics of the dynamic properties of the interfaces, including a dependence of some of the interfaces on the level of normal stress and the excitation frequency. Yegian and Kadakal (1998) tested a smooth HDPE geomembrane and nonwoven geotextile interface using both fixed and free block test setups; they reported some evidence that friction coefficient increased with the sliding velocity. Yegian and Kadakal (2004) analysed a variety of interfaces, performing shaking table tests with sinusoidal base motions and even with earthquake replicas in order to identify a suitable liner to use as foundation isolation; they reported some relationships between dynamic friction and sliding speed for the interfaces considered. Park et al. (2004) performed shaking table tests on four geosynthetic interfaces, founding that the normal stress and the frequency of excitation did not influence the dynamic interface friction angle. They proposed a normalization of the slip displacements, in function of the acceleration and the frequency of the base excitation, in order to predict the in-field peak displacement along bottom liners. Yegian and Harb (1995) used shaking tests with inclined plane configuration and sinusoidal base motions; due to the difficulty in interpreting the tests, they opted to present the results in terms of normalized slip displacements as function of the slope angle. The same test configuration was employed by Wartman et al. (2003) and the interpretation of the data, based on a back-analysis of the block motion using a numerical code, showed a relationship between interface friction and sliding speed. Kim et al. (2005) investigated the dynamic friction of various interfaces by means of a dynamic direct shear device; the tests showed that geotextile-involved interfaces degraded as displacements increased until they reached an apparent steady-state (or "residual strength"). Under dry condition, the shear strengths of these interfaces increased with the displacement rate; however, this relationship disappeared when interfaces were submerged with water. Lastly, they reported that shear strength was generally not sensitive to the applied normal stress.

In general, the dynamic shear properties of interfaces can vary significantly from one to another, depending on the combination of geosynthetics in contact; moreover, various parameters can influence the available shear strength, like the presence of fluid at the interface, which can induce a reduction in friction compared with dry conditions (Yegian and Lahlaf, 1992; Park et al., 2004; Kim et al., 2005), or the state of wear of the surfaces when subjected to an elevated number of sliding cycles (De and Zimmie, 1998; Kim et al., 2005).

3. The experimental device and interfaces tested

The experimental investigation was carried out by means of an inclined plane device in the geotechnical laboratory at the ICEA Department of the University of Padua. The apparatus (Fig. 1) is designed to perform tests under both static and dynamic conditions: for