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Technical note

The determination of interface friction by means of vibrating table tests

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ABSTRACT

This paper concerns the laboratory evaluation of dynamic friction in geosynthetic interfaces subjected to sinusoidal base motions. Tests were performed with a sliding block over a vibrating table with both a horizontal plane and an inclinable plane. The horizontal configuration is widely used because it is easier to interpret, whereas the inclined plane set-up is more complicated due to the variation in time of the normal component of the acceleration. An analytical method for interpreting the vibrating table test with the inclined plane configuration is described: for the purpose of comparison two geosynthetic interfaces were chosen, which exhibit very different behaviour from each other; one interface had a constant value of dynamic friction, whereas the second exhibited a relationship between dynamic friction and the relative speed of sliding. The tests, carried out with both the horizontal and the inclined plane configuration, showed how the mobilised friction was influenced by the kinematics of the block: at the same relative speed, the mobilised interface friction during tests with the horizontal plane was greater than that resulting from tests with the inclined plane. This difference may be ascribed to the patterns of relative motion at the interface, occurring in a single direction in the case of the inclined plane, and with a cyclic reversal of direction in the case of the horizontal plane.

1. Introduction

Geosynthetic interface friction under dynamic conditions has been widely studied by means of the “shaking” or “vibrating” table test. The term “vibrating table test” usually refers to testing using a table which moves with a harmonic oscillation, whereas the term “shaking table test” is used when a seismic motion is replicated. In both cases, the table carries one geosynthetic while the second is bound to a rigid block which is, in the most frequently adopted configuration, free to slide over the table. Many authors have studied interfaces on a horizontal plane subjected to a harmonic motion (Yegian and Lahlaf, 1992; Yegian et al., 1995; De and Zimmie, 1998; Yegian and Kadakal, 1998, 2004; Park et al., 2004; Arab and Kavazanjian, 2010; Carbone et al., 2014, 2015).

Newmark (1965) gave the basic approach for interpreting the test: when the table is moving, the block moves in synchronism with the table until “critical acceleration” is reached; when the table acceleration exceeds critical acceleration, the block slides. Critical acceleration is identified during the test and interface dynamic friction is evaluated as a function of the critical acceleration itself. In Newmark's analysis, it is assumed that dynamic friction is independent from loading conditions; in actual fact, variations in mobilised friction can occur in geosynthetic interfaces, for example in passing from small to large displacements (Matasovic et al., 1998). As reported in various experiments (Yegian and Lahlaf, 1992; De and Zimmie, 1998; Lo Grasso et al., 2002; Kotake et al., 2011), dynamic interface friction can depend on the typical parameters which characterise dynamic loading, such as acceleration, amplitude, frequency and duration. In general, literature on the subject indicates a certain dependence of dynamic friction on the level of acceleration, while frequency has a lesser effect. The number of cycles can also be significant in some types of geosynthetics, while normal stress is generally negligible, except in the case of highly deformable materials or low levels of contact stress.

As well as tests where the block is free to slide over the vibrating table, experiments have also been carried out with dynamic devices similar to the direct shear (De and Zimmie, 1998; Yegian and Kadakal, 1998; Kim et al., 2005; Punetha et al., 2018). In this case, one geosynthetic is bound to a horizontal movable plane, while the second is bound to an upper block held firmly by a contrast and the reaction force is measured. Some studies have also analysed a block sliding down over an inclined plane bound to a vibrating table and subjected to a harmonic horizontal motion. Elgamal et al. (1990) measured the interface friction between two pieces of sandpaper and compared the results with numerical simulations; they observed that the critical acceleration

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List of symbols

φ_0	static friction angle
φ_{dyn}	dynamic friction angle
$\varphi_{dyn,0}$	limit value of dynamic friction for sliding speed approaching to zero
β	plane inclination angle
g	gravity acceleration
T	weight component, parallel to the plane
R	reaction force component, parallel to the plane
$\ddot{x}_{tot}$	absolute block acceleration, parallel to the plane
$\ddot{x}_r$	relative block acceleration, parallel to the plane
$\ddot{x}_g$	table acceleration component, parallel to the plane
$\ddot{y}_g$	table acceleration component, normal to the plane
$\dot{x}_r$	relative block velocity
x_r	relative block displacement
M	block mass
t	time
Δt	time step for numerical integration
f	frequency of the horizontal base motion
a	modulus of the horizontal acceleration of the table
a_{max}	maximum acceleration amplitude of the horizontal base motion

during sliding was not constant. Yegian and Harb (1995) applied this type of test to geosynthetics, and encountered difficulty in interpreting the test data due to the variability in block acceleration during the relative motion. For this reason, they opted to present the results in terms of normalised permanent slip displacements as a function of the slope angle. More recently, Wartman et al. (2003) presented a synthesis of data from numerous tests at frequencies ranging from 1.33 Hz to 12.8 Hz with a plane inclination of 11.4°. Here, the authors used a numerical code to back analyse the block displacements measured during the test. The interface friction angle, assumed in the computation, was varied until the calculated acceleration and displacement time-histories of the block closely approximated those measured during the test, thus outlining a relationship between the dynamic friction and the average relative velocity of the block. Kavazanjian et al. (2014) presented a further review of Wartman's data: they used a FLAC numerical model to back analyse the test results, concluding that a simple elasto-plastic interface model can predict interface displacements if interface strength is accurately characterised.

The purpose of this paper is to perform a comparison between vibrating table test results on horizontal and on inclined plane, conducted in the free sliding block scheme. To this end, the results of tests on two different geosynthetic interfaces will be presented and discussed.

2. Experimental device and materials tested

The experimental investigation was carried out at the Geotechnical Laboratory at the University of Padua using an inclined plane device which is able to perform tests under both static and dynamic conditions (Pavanello and Carrubba, 2016). A reclining plane is positioned over a horizontal mono-directional shaking table; in dynamic tests, the plane inclination is fixed at a given value, and the shaking table oscillates back and forth horizontally. The equipment is completed by a rigid block, placed over the plane: one geosynthetic specimen is fixed to the bottom of the block while the other is laterally clamped to the plane, along its length. The inclined plane is 1.10 m long and 0.25 m wide, while the block is 0.35 m long and 0.20 m wide. The block motion is monitored using both an accelerometer and a video recording of the test. An algorithm, implemented by the authors in Matlab, allows the video clip to be processed by recognising the position of both the table and the block in each frame of the video. This makes it possible to obtain a complete time-history of both absolute and relative block displacements, with a precision in the order of ± 0.2% of the maximum displacement. This technique, besides being very economical, has the advantage of leaving the block motion unaltered, since no instrumentation is in contact with the block. For the experimental programme, a sinusoidal displacement history was applied to the table by gradually increasing acceleration until it reached the maximum amplitude, a_{max}, after about 30 cycles. Further details on the device and on the experimental procedure are given by Carbone et al. (2015).

Two different interfaces were examined in this work; the first was between two specimens of the same sample of a smooth HDPE geomembrane (GMB_s-GMB_s), 2 mm thick with a unit mass of 2000 g/m^2; even though this interface is not common in geotechnical work, it was selected for its regular behaviour. The second interface (GMB_s-GTX) was between the smooth geomembrane and a thermally bonded nonwoven geotextile, made of polypropylene with a unit mass of 130 g/m^2. Both interfaces were tested under dry conditions, with a vertical stress of 5 kPa and at a temperature of about 20 °C.

3. Analytical approach

Although the approach has already been analysed in technical literature, a comprehensive analysis of the sliding block is detailed below in order to clarify some peculiar aspects. The dynamic balance of the forces acting on a block resting on an inclined plane (Fig. 1), parallel to the plane direction, can be written in the following form:

$$T \pm R = m\ddot{x}_{tot} \quad (1)$$

in which $\ddot{x}_{tot}$ is the absolute block acceleration with respect to a fixed reference system, m is the mass of the block, and R is the component of the reaction force parallel to the plane. The symbol for this component is negative in the case of a downwards motion and positive for an upwards motion.

Lastly, T is the weight component parallel to the plane, equal to:

$$T = mg \sin\beta \quad (2)$$

where g is the gravity acceleration and β is the slope angle of the plane. In turn, the absolute acceleration of the block may be expressed as the sum of the “ground” acceleration ($\ddot{x}_g$), i.e. the acceleration of the plane, and of the relative acceleration of the block with respect to the plane ($\ddot{x}_r$):

$$\ddot{x}_{tot} = \ddot{x}_r + \ddot{x}_g \quad (3)$$

Assuming a purely frictional interface behaviour, the maximum value that can be reached by the reaction force (R) component, before relative motion is started, is:

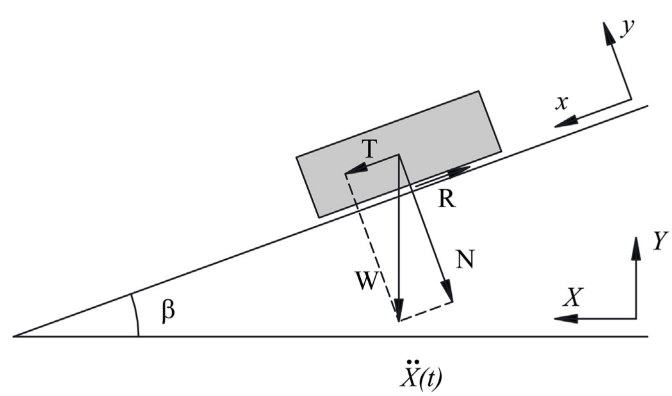

Fig. 1. Diagram of a rigid block resting on an inclined plane.