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A new friction law for sliding rigid blocks under cyclic loading

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ABSTRACT

A rigid block sliding down an inclined plane under the action of gravity was monitored with accelerometers and an LVDT to investigate how the transition from static to kinetic friction develops. Once the transition patterns were identified, experiments were carried out to study the response of a dynamically excited rigid block sliding down the inclined plane of a shaking table. Harmonic time series were used as input motions. The laboratory results allowed the definition of a continuous friction law to model the continuous variation of the friction from its static to kinetic condition. This law was implemented into the commercial 3D distinct element code 3DEC to numerically reproduce the experiments carried out, thus validating the friction law. Afterwards, the friction law was used to evaluate the sliding due to the kinetics of the block. Three cases were analyzed: constant friction coefficient, Coulomb friction law and the proposed friction law. These computations were compared to laboratory measurements. It is found that permanent displacements computed by considering the new law are in better agreement with laboratory measurements.

1. Introduction

The sliding characteristics of a rigid block when it is subjected to dynamic loading depend heavily on the physics in the contact between the block-bottom-face and the plate on which it is set down. Recognizing the limitations of the sliding block procedure, there has been a number of investigations to make it more versatile so that it can be used in earthquake geotechnical problems [1]. Most of them have focused on aspects related with the flexibility of the sliding body [2,3]; the coupling–uncoupling of the block sliding plate interface [4,5] (stick-slip movement); the nonlinear behavior of the sliding body [4], etc. Others have recognized the drop of the static friction, μ_s, to the kinetic friction, μ_k, when the block starts sliding and make use of Coulomb's friction law [6].

None the less of the many plausible efforts that have been made to enhance the sliding block procedure, there is still room for its improvement by looking into the phenomena developed in the block-sliding-pad interface. There are several questions that deserve proper explanation. For example, why the block's acceleration keeps on increasing above the yield acceleration (quantity that sets off block sliding, $\ddot{U}_y$) right when sliding starts? Or when the block slides what percentage of the input energy is transmitted through the interface to the block? How the block behaves when sliding? Is the passage from μ_s to μ_k smooth or abrupt? How the block's inertia affects the kinetic friction?

This paper addresses these questions and reaches some conclusions from an experimental investigation on wood–wood and geotextile-wood interfaces. From the results a simple yet reliable law that allows computation of static and kinetic friction is proposed. This new law was introduced into the commercial distinct element code 3DEC [30] to compute permanent displacements of rigid blocks due to harmonic shaking. Throughout comparisons, it is shown that the proposed friction law satisfactorily reproduces the measured block's responses. The results shown in this paper can be extended to other interface materials by carrying out experiments similar to those shown herein. The accurate comparisons between the experimental results and those obtained using the new friction law, indicate that this law is reliable enough to be used in rigid block sliding analyses.

2. Literature review

Several researchers have examined frictional characteristics of different material-composed-interfaces in an attempt to characterize them under dynamic sliding conditions. For example, Constantinou et al. [7] performed shaking table experiments with a rigid block sliding on a Teflon-steel interface. Their experimental conditions closely matched those prevailing during sliding episodes in a frictional interface. However, their friction coefficient estimations did not consider inertial effects [6,8,9] nor the change in sliding velocity rate during dynamic excitation. Instead,

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the problem was simplified by assuming a peak friction coefficient equal to the block peak response acceleration measured in terms of gravitational acceleration, and only the peak interface relative velocity was considered to study the friction coefficient variation.

Yegian and Lahlaf [10] also performed shaking table experiments with a rigid block sliding on a geomembrane-geotextile interface under different input acceleration magnitudes. This is the adequate type of experiments to investigate interface frictional characteristics under conditions prevailing in rigid block sliding, because it closely reproduces dynamic conditions under seismic sliding. Despite the accurate experimental program, the friction coefficient estimations neither considered inertial effects nor the transition from static to kinetic conditions [9,11–14]. However, an increase in block response acceleration above its yield value was noticed and attributed to a possible increase in interface frictional resistance. In a subsequent study, Yegian and Kadakal [15] noticed again the same phenomenon, but this time it was ascribed to stick-slip oscillations.

Recent investigations [8,13,14] point out that the increase in block response acceleration right after reaching its yield value is not due to an increase in friction angle, but rather to a steady decrease from the static friction coefficient to kinetic friction conditions. During this steady decrease some percentage of the input acceleration is being transferred through the interface, thus the kinetic energy the block had when the yield acceleration was reached keeps on increasing, and hence so does the block acceleration.

3. Testing equipment and experimental program

Experiments were performed with an instrumented $15 \times 25 \times 3.5$cm aluminum rigid block sliding down on a wooden inclined plane (see Fig. 1). The block had a geotextile sliding surface, which could be exchanged by a wooden one. Accordingly, tests were carried out for two different interfaces: geotextile on wood and wood on wood. For the geotextile on wood interface (GWI), the static friction angle (ϕ_s) was about 23.21° ($\mu_s = 0.429$), and for the wood on wood interface (WWI) it was about 24.40° ($\mu_s = 0.454$). These values were determined from the results of a number of tilt tests performed by increasing the sliding pad inclination at the same rate to ensure equal shear stress increase at the block-pad interface each time block sliding was set forth.

Two types of tests were carried out: (1) static tests that consisted in letting the rigid block slide along an inclined plane,

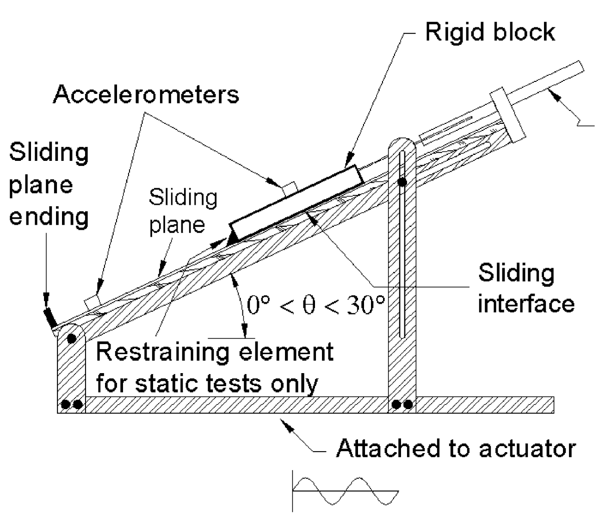

Fig. 1. Shaking table and instrumentation used in this study.

and (2) dynamic tests, in which the same rigid block was shaken while resting on an inclined plane. For static tests, the block mass was 1.37 and 1.90 kg for the GWI and WWI, respectively, and for dynamic tests the mass was 6.5 kg for GWI and 1.93 kg for WWI. The shake table has a pad that can be set at inclinations between 0° and 30°. Fig. 1 depicts the general equipment-instruments-rigid block arrangement to carry out the experimental investigation.

Static tests made it possible to monitor block's movements and thus determine its passage from static to kinetic conditions and consequently to estimate the displacement required for the friction to switch from its static value to its dynamic one. The testing procedure was as follows: the inclination of the sliding pad was steadily increased to a value that ensured block's sliding. (In order to prevent its sliding, while inclining the pad, a wedge was placed at the down hill side of the block, as shown in Fig. 1) When the block was allowed to slide freely (by removing instantly the wedge) along the inclined plane, under the action of gravity, its accelerations and displacements were measured by an accelerometer and a linear variable displacement transducer (LVDT), respectively. The behavior of the block was continuously monitored along a distance of 160 mm.

Dynamic tests were performed using a shaking table designed for this purpose [16]. During the tests, three accelerometers recorded the block's accelerations. A comparison between motions imposed by the actuator and those recorded on the sliding plane showed that no strenuous noise contaminated the recorded time histories. Displacements were computed by integrating accelerograms and then compared to measured relative displacements using an LVDT, which provided redundant information that confirmed the reliability of the monitoring systems. The input motion was recorded directly on the sliding plane, to have a precise knowledge of the actual excitation. The excitation used was a harmonic signal with a frequency and amplitude of 3.5 Hz and 6 cm, respectively. All dynamic tests were performed on rigid blocks settled on the shaking pad inclined at different angles. Two inclinations (θ) were considered: 6° for the GWI, and 5° for the WWI.

4. Laboratory determinations of sliding friction

4.1. Static tests

The experimental results are presented herein in terms of the accelerations, velocities and displacements of the rigid block. The horizontal accelerations of the block during sliding are presented in Fig. 2a. The initial acceleration is zero, i.e., static friction conditions prevail. Then, acceleration increases almost linearly until it reaches a relatively constant value, as depicted in Fig. 2b by a relatively constant slope of the time–velocity curve. Fig. 2d shows the effect of the friction characteristics more clearly on the block velocity rate at the beginning of sliding (circled area in Fig. 2b). Afterwards, it becomes nearly constant. This velocity rate variation at the early stages of the test can be attributed to the transition from the static to the kinetic condition, as shown later. The corresponding block displacements are shown in Fig. 2c, which describes a smooth curve, as should be expected given the almost time-linear variation of velocity.

From the response of the block, it is possible to estimate the kinetic friction coefficient and the corresponding $\mu_s \rightarrow \mu_k$ transition, by making the linear hypothesis pictured in Fig. 3a. Here, μ_e is the initial boundary condition imposed by the wedge-restraining element (see Fig. 1). Herein, it will be considered as an external friction coefficient and $g\sin(\theta)\cos(\theta)$ stands for the block horizontal acceleration, $\ddot{U}_H$, when the friction coefficient is zero (neglecting wind friction).