



unidirectional shaking table. Tests have been performed on cylindrical specimen of concrete on sanding paper supporting surface.

2.1 Experimental setup

The footprint specimen has a radius of 11 cm and a height of 8,5 cm, with a mass of 8 kg. The specimen of concrete is supported on a layer of sanding paper fixed on the horizontal plan of the shaking table. A load cell is connected to the specimen through a horizontal hollow steel profile which is welded on a vertical rigid steel element (Fig. 1). The horizontal profile is directly connected on the top of the specimen, while the load cell is screwed on the horizontal steel element. The ABS specimen-load cell connection elements have been obtained through 3D printing.

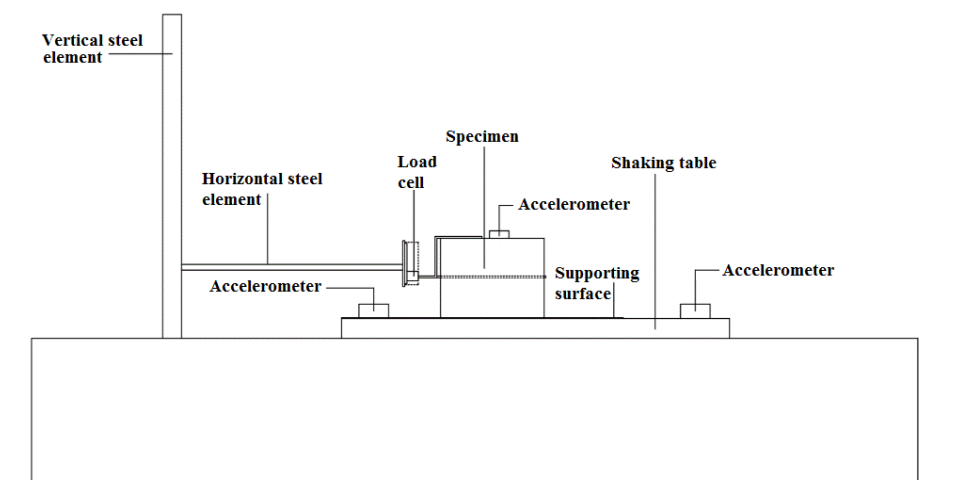


Fig. 1 – Scheme of test setup

The relative movement between the supporting surface and the specimen is ensured by the horizontal load provided by the fixed steel element system as result of reaction to the relative displacement due to the shaking table. A pair of accelerometers is employed to record the shaking table acceleration and the specimen top's surface. Fig. 2a shows an image of the test apparatus adopted to assess the dynamic friction coefficient.



Fig. 2 – Shaking table test setup



The shaking table consists of steel profiles, whereas the upper platform, where specimens can be fixed, is made of aluminium [15]. Two parallel tracks are located side by side and connected through transversal rectangular sections (Fig. 3). Tracks' profiles are 3 meters long and the section's size is 40x100x4 mm. Upon the steel profiles there are aluminium guides allowing the motion, along the longitudinal direction, of sliders that support two 600x500x10 mm aluminium platforms. Each track has its own platform, which is moved by a linear electric actuator anchored under it. Type and section of the steel profiles are the same of the bottom ones, while the length is shorter (600 mm). The linear electric actuators adopted are manufactured by the company LinMot and each is made of a stator, a slider and a motor. The longitudinal ones have a slider's length of 800 mm and a maximal stroke of 510 mm, whereas the transversal ones have a slider's length of 500 mm and a maximal stroke of 330 mm. The power supply, the two transformers and the four drivers to control the motors are provided by LinMot. The drivers are fundamental for the tuning of the motors (i.e. the initial configuration of all the control parameters) to have a response coherent with the input data. This operation is done through the software LinMot-Talk that is also used to switch on the actuators and to bring them in the home position. The software used for the activation and control of the shaking table is LabView. The seismic input is sent to the shaking table through a myRIO device manufactured by National Instruments. This device is physically connected to the motors' drivers and also to an accelerometer, which is located on the platform and allows catching the actual response of the system.



Fig. 3 – Shaking table

The accelerometers and the load cell are connected each other to synchronize the output value. The sampling frequency of load cells and accelerometer is 10 Hz, while a dynamic sinusoidal input with frequency of 83 Hz is adopted.

2.2 Experimental methodology and calculation method

The LabView code is used to set the input and output sampling rates to generate a sinusoidal seismic signal or to load a real one. The shaking table test consists in the assessment of the shear force acting on the surface between concrete sample and sanding paper through the load cell. Comparing accelerations recorded on the shaking table surface (a_g), and that one derived from the load cell (a_s), the friction acceleration (a_f) can be computed (Eq. (1)).

$$a_f = a_g - a_s \quad (1)$$

Therefore, the dynamic friction coefficient (μ_d) is obtained as given in Eq. (2):



Dynamic friction coefficient is assessed at each time step in order to identify the dependence on the motion velocity. Fig. 7 depicts the dynamic friction variation with the motion velocity.

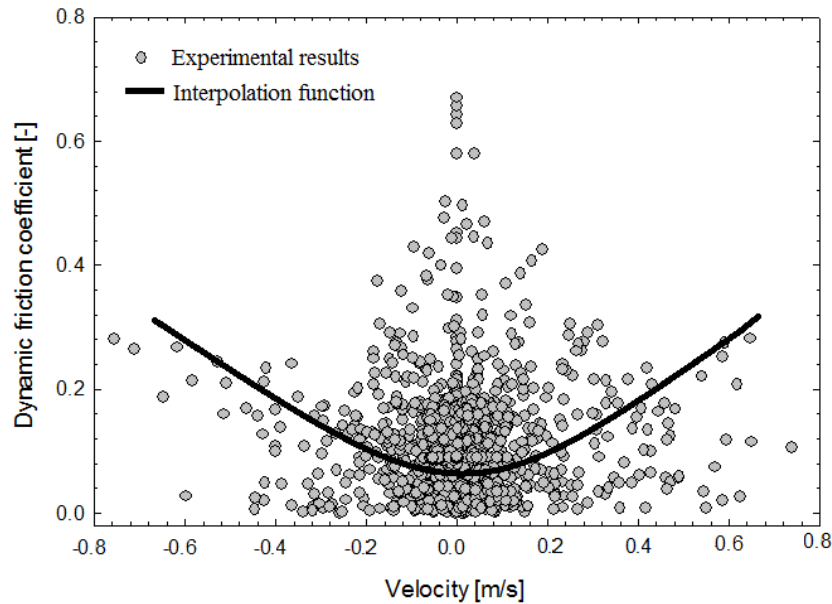


Fig. 7 – Relation between dynamic friction coefficient and motion velocity

The result of test confirms that the dynamic friction coefficient depends on the velocity of the excitation. In particular, the action of an earthquake induces positive and negative velocity, which means that the rigid sample passes continuously through static and dynamic conditions. For dynamic conditions ($-0,1 < v < 0,1$ m/s), the dynamic friction coefficient monotonically increases. In case of quasi static conditions, the friction coefficient tends to correspond to the static friction coefficient. The mathematical relationship between motion velocity and friction coefficient is approximated by a polynomial equation given in Eq. (5).

$$\mu = 0.29 \cdot v^2 - 0.04 \cdot v + 0.11 \quad (5)$$

where v represents the motion velocity. Eq. (5) demonstrates that for quasi static conditions the friction coefficient tends to be equal to the static one ($\mu=0.11$).

4. Numerical method

The reliability of the numerical analysis depends on different assumptions such as material behavior and geometric nonlinearity of the contact surfaces. To verify the experimental tests, a 3D Finite Element (FE) model has been created using SAP2000 by introducing the friction coefficient at different velocities. This software is capable to model the geometric nonlinearity of the contact surfaces. The specimen has been modelled with 8 nodes solid elements and the material strength class has been defined as $f'_c=25$ MPa (class C20/25 according to NTC2018). Fixed restraints have been assigned at the top surface and side face perpendicular to the direction of motion in order to model the specimen's boundary condition (Fig. 8).

To consider the effect of friction, Friction-Pendulum Isolator elements have been used to model the contact surface (Fig. 8). This element is able to model combination of different conditions varying from at-rest to slide, or from uplift to slam-down for the cases of friction and rocking, respectively. The pendulum radius of the slipping surface was set to zero to consider the flat surface friction. The element models the



where K_x and K_y are the elastic shear stiffness constants in the absence of sliding, and a_x and a_y are binaries parameters deepening on velocity in x and y direction:

$$a_x = \begin{cases} 1 & \text{if } \dot{d}_x z_x > 0 \\ 0 & \text{otherwise} \end{cases}, a_y = \begin{cases} 1 & \text{if } \dot{d}_y z_y > 0 \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

A high value of the pre-slip stiffness property in the horizontal direction has been used. This value does not affect the dynamics of the model, but only it is used to avoid ill-conditioned problem. This value has been selected as one order magnitude less than the value defined for the effective linear vertical stiffness. In addition, post slip stiffness has been set to values obtained from experimental tests to verify the results for different velocity conditions.

4.1 Numerical results

The results of the experimental tests have been compared with the FE model. Three different dynamic tests have been performed and the response of the model at the top surface (fixed restraint point in Fig. 8) has been assessed in terms of acceleration. The friction coefficients at different velocity condition (slow and fast) have been varied until the response of the FE model corresponds to the force recorded by the load cell in experimental tests. The final value used for slow and fast friction velocities are 0.23 and 0.4, respectively. Fig. 9 shows the results obtained from numerical modelling and experimental tests. Results show that the dynamic friction first decreases and then it increases proportionally to the velocity (Fig. 7). Results show a good agreement which confirms the reliability of the experimental tests to evaluate the dynamic friction coefficient. However, for the third input motions (Fig 5.c, and Fig. 6.c), the result is more compatible with that one obtained from experimental test.

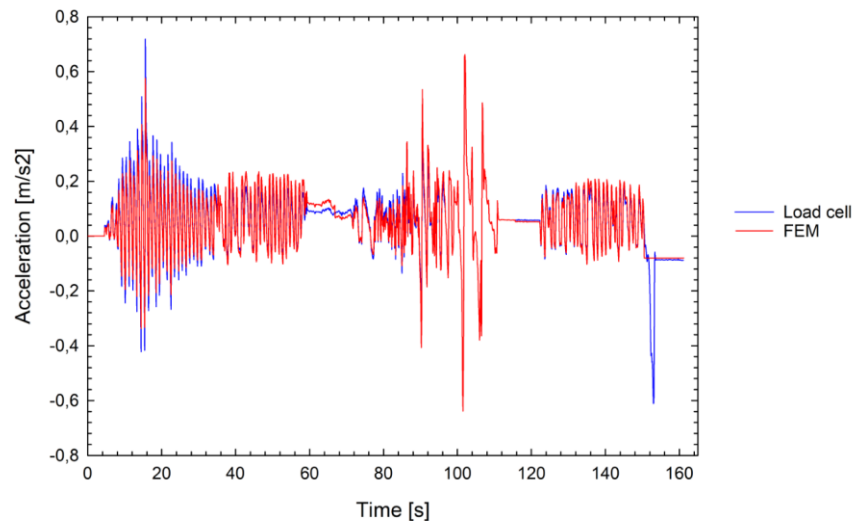


Fig. 9 - Comparison between FEM model and experimental test

5. Conclusions

In this paper the dynamic friction coefficient under different velocity conditions was investigated. Experimental tests were performed using a shaking table developing a new setup capable of measuring the friction coefficients at low and fast velocity conditions. A mathematical formulation between velocity and dynamic friction coefficient was extrapolated by a preliminary test on a benchmark specimen. Further, the



- [14] Aydan Ö (2019): Some considerations on the static and dynamic shear testing on rock discontinuities. *2019 Rock Dynamics Summit: Proceedings of the 2019 Rock Dynamics Summit (RDS 2019), May 7-11, 2019, Okinawa, Japan*, 201.
- [15] Cimellaro GP, Domaneschi M (2018): Development of Dynamic Laboratory Platform for Earthquake Engineering Courses. *Journal of Professional Issues in Engineering Education and Practice*, **144**(4), 05018015.