Soil Dynamics and Earthquake Engineering 114 (2018) 1–11

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Experimental assessment of the cyclic response of friction-based isolators under bidirectional motions

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ARTICLE INFO

Keywords:
Base isolation
Concave Surface Slider
Cyclic effect
Friction coefficient
Bidirectional motion

ABSTRACT

Experimental research on the lateral response of Concave Surface Sliders (CSS) under bi-directional earthquake excitations has shown significant differences in comparison to the uni-directional case. This is mainly due to the stepwise variation of the direction of the frictional force, which is assumed to be parallel to the device trajectory; on the other hand recentering force can still be considered as directed towards the centre of the device. The present endeavor shows results of a wide experimental campaign on a full-scale CSS device, according to a special testing protocol with both uni-directional and bi-directional dynamic tests. Results have shown non-negligible discrepancies in the hysteretic loops of the device between the bi-axial interaction of the directions of motion, in comparison to radial motions: such a behaviour is expected to significantly influence the overall response of a base-isolated structural system, if it is not properly modeled.

1. Introduction

Most of the experimental and analytic studies on single and double concave surface sliders (SCSS and DCSS, respectively), are focused on uniaxial response [8,16]. Concerning bi-directional motion, a number of issues have been noticed through numerical and experimental investigations [4], even though accessible data about bi-axial tests on full-scale devices are still limited, due to the high level of complexity of the testing setup. Recently, Lomiento et al. [14] investigated the bi-directional response of a full scale CSS device, subjected to bi-directional orbits with different levels of vertical load. Results of such and previous efforts highlighted four main characteristics of the sliding material employed within CSS devices: i. the breakaway effect, responsible for the sudden force increase at the beginning and at each motion reversal (stick-slip); ii. the reduction of the friction coefficient at high values of applied vertical pressures; iii. the variation of the friction coefficient with respect to the sliding velocity; iv. and the cycling effect, that is the decay of the friction coefficient during dynamic tests due to the heating originated at the sliding interfaces [21,7].

When a bi-directional seismic event is considered, concerning the frictional response, the overall behaviour is significantly different in comparison to the uni-directional case and a number of analytical models have been proposed during last years. The main difference is related to the bi-axial interaction of the directions of motion: precisely, the gross value of frictional force, is generally assumed to be parallel to the trajectory of the device, even though some additional direction variation can be experimentally detected [14]. In order to account for the stepwise projection of the frictional force, direction cosines have to be defined, according to components and the modulus of the vectorial velocity. Also Bouc-Wen plasticity model has been widely used to model non-linear hysteretic systems and previous studies have shown that it can also be used for the representation of the lateral bi-directional response of a CSS device [18,9]. The phases-based model seems to be the most correct from the theoretical point of view [11]. Its formulation is both displacement and force based and two different phases are considered: the non-sliding and the sliding phase. During the non-sliding phase, the resultant of the frictional forces mobilized at the sliding interfaces is less than the limiting frictional force: thus, the displacement is kept constantly equal to the last assumed value, whereas both velocity and acceleration values are null. On the other hand, the system starts sliding as soon as the resultant force of the mobilized frictional responses at the sliding interfaces exceeds the limiting frictional force. From that time instant, the frictional response is ruled by a circular domain, which corresponds to the aforementioned force-projection model.

Recent numerical research works on structural systems, base-isolated with CSS devices [19] have been carried out, by using a bi-directional analytical model of DCSS devices where mounting laying defects have been considered in the global response. In that endeavor, the implementation of an improved mechanical model of the device is

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https://doi.org/10.1016/j.soildyn.2018.06.031
Received 7 February 2018; Received in revised form 6 June 2018; Accepted 26 June 2018

presented, calibrated on the outcomes of several experimental dynamic tests performed at Bearing Tester System at EUCENTRE Foundation (Pavia, Italy). Such a research work has shown analytically that the bi-directional lateral response of a CSS device is significantly different in comparison to the uni-directional one, by implying thus that this aspect may lead to unexpected results in the design/modeling phases of a seismically isolated structure.

In the present document the bi-directional response of a full-scale DCSS device is investigated, by presenting results of an experimental campaign carried out by means of the new testing setup for tri-axial tests implemented at the EUCENTRE Laboratory. Ad hoc testing protocols have been defined, by considering both uni-directional and bi-directional tests, in order to fully characterize the lateral response of the device. 1D tests have been used to calibrate frictional characteristics of the device, according to the common practice. Then, a number of bi-directional orbits have been performed. Since frictional properties can be affected by sliding velocity variations during motion, both radial and bidirectional tests have been defined, by applying a special re-sampling procedure: actually, custom displacement input signals have been computed, which lead to a constant value of tangent velocity for all time instants. Such a testing strategy allows to obtain frictional properties directly related to the assumed velocity value, and consequently no additional fluctuation can affect experimental results.

Common standard orbits have been performed as well, in order to evaluate differences of considering a constant rather than a fluctuating modulus of the velocity during motion. At the end of the testing protocol, an earthquake simulation has been run: input signals have been obtained from the time-integration of the dynamic system of a single oscillator, isolated with a bi-directional DCSS device. Due to the large number of performed tests, the device wear has been monitored during the whole test campaign by means of repeated benchmark tests.

2. Three-dimensional testing setup

A special testing setup has been installed at the EUCENTRE Laboratory in Pavia [20], in order to carry out three-dimensional tests. The Bearing Tester System has been specifically designed to carry out static and dynamic tests on isolation and dissipation devices. The base table (1.7 m x 4.3 m) allows vertical, longitudinal, roll, pitch and yaw degrees of freedom, under a static vertical load up to 40,000 kN and an additional dynamic vertical load up to 10,000 kN, whereas the maximum allowance of longitudinal force is 2828 kN. The maximum longitudinal stroke is + / − 450 mm, with a peak velocity of 2.2 m/s. The BTS Controller is an MTS real-time, digital controller that provides PID closed loop control with a delta-p feedback signal.

For three-dimensional tests a new sliding bench has been implemented within the original system, which allows the transverse translational degree of freedom. With such a configuration, bi-directional orbits and earthquake simulations can be performed. For the transverse degree of freedom, a total stroke of + / − 260 mm and a peak velocity of 0.6 m/s can be achieved, with a horizontal force capacity equal to 1000 kN.

The force feedback response is generally measured by the load cells at the connection between the actuators and the respective bench. Thus, the recorded data contain the force of the device together with the summation of the frictional and inertial forces originated by the testing machine: these two contributions have to be removed in the data reduction phase, in order to consider the device force only. To this aim, an innovative recording system has been designed, in order to capture only the force response of the device, without any interference coming from the testing machine.

On the other hand, displacements recordings are returned by the control software of the testing system, whereas both the velocity and acceleration responses are computed by means of direct time-derivation of the displacement signals.

3. Testing protocol

The present testing campaign has been carried out on a full-scale Double Concave Surface Slider (DCSS) device: both the sliding surfaces have the same radius of curvature and a non-articulated slider is implemented. The sliding material consists of a circular pad, made up of polyethylene (PE), which generally experiences a different behaviour in comparison to PTFE sliding interfaces [3]. The equivalent radius of curvature of the device is approximately equal to 3,0 m and a displacement capacity equal to 250 mm can be achieved.

Ad hoc testing protocol has been defined, with both uni-directional and bi-directional tests for a comprehensive characterization of the lateral response of the device. In both cases entrance and exit loops have been implemented, to guarantee “zero initial condition” (zero displacement and acceleration and given velocity) at the beginning of the first loop and at the end of the last loop.

According to the common practice and to standard code regulations (e.g. [1,5]), the input signal for uni-directional tests is a sinusoidal waveform, with periodically varying velocity. The ideal input signal for frictional characterization would be a triangular waveform, because of its constant velocity: however, at high speed, the instantaneously change in the velocity sign at the cycle inversion may jeopardize the testing system stability. The input signal studied for the test presented in the present work features a combination of triangular and sinusoidal waveform, able to keep the maximum velocity over a wider displacement range (Fig. 1).

In Table 1 the main characteristics of uni-directional tests, i.e. maximum displacement and velocity, vertical load and number of cycles are listed: basically, the characterization has been conducted on 4 levels of vertical load W, for 9 velocity intensities V. Two full cycles per test have been run (plus entrance and exit loops). Given the highly demanding testing protocol, the definition of a WEAR CHECK test was needed. Such a test represents a benchmark check at the beginning, during and at the end of the whole testing protocol: unidirectional motions have been performed by applying the same sliding velocity and vertical load values, in order to notice any decay and/or changes in the force response and to monitor the wear of the sliding material; in this way same initial conditions of the isolator response can be ensured for each test. Results have shown no significant variations in both frictional properties and material wear, and approximately overlapped hysteretic responses have been found among the performed benchmark tests. Uni-directional tests have been used to characterize the frictional behaviour with respect to both sliding velocity and vertical load.

For bi-directional tests, a number of curvilinear and stepwise linear orbits have been studied, with maximum radial displacement $D_{\max}$ of 0.2 m, and with a maximum value of tangent velocity of 0.356 m/s, obtained from the sliding frequency of the device.

$$V_{\max} = 2\pi D_{\max}\left(\frac{1}{2\pi}\sqrt{\frac{g}{R_{eq}}}\right) = D_{\max}\sqrt{\frac{g}{R_{eq}}} = 0.356 m/s \tag{1}$$

Stepwise linear orbits (box and hourglass, Fig. 2 – [18]) show the behaviour of a CSS device subjected to linear trajectories featuring the following characteristics: i. constant offsets in the direction orthogonal to the motion for part of the orbit, which means corresponding constant value of the recentering force, ii. sudden and sharp direction changes, which imply stick slip effect, and iii. radial motion for part of the hourglass orbit. The overall lateral response for both the planar directions is expected to be stepwise linear as well as in the uni-directional case, with lower values of the “apparent” friction coefficient when the motion is radial, since the friction force is decomposed in the two main directions. Over each of the linear branches of such orbits, a wide range with constant velocity has been implemented.

Then, cloverleaf, eight-shape, spiral and circular orbits have been implemented (Fig. 3). For curvilinear orbits, cloverleaf, eight-shape, spiral and circular orbits have been considered. Also for such bi-