Soil Dynamics and Earthquake Engineering 106 (2018) 14–30

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Historical development of friction-based seismic isolation systems

Paolo M. Calvi[a,*], Gian Michele Calvi[b]

[a] Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA
[b] Scuola Universitaria Superiore, IUSS, Pavia, Italy

ARTICLE INFO

Keywords:
Base isolation
Friction pendulum
Multi-surface base isolation
Friction-based isolation systems, seismic protection, seismic performance

ABSTRACT

Base isolation has emerged as one of the most effective high-tech strategies for protecting infrastructure under seismic loading. This review paper discusses the historical development of friction-based seismic isolation systems, focusing on systems that have successfully been deployed and used as seismic safety measures for structures located in Europe. The conception and implementation of the Friction Pendulum system, the development of low friction materials and the effects of heating, contact pressure and velocity are discussed in light of past and recent numerical and experimental evidence. The merits of multiple surface devices, namely the Double Curvature Friction Pendulum and the Triple Friction Pendulum are also discussed, along with current knowledge and research gaps. Two European case studies, the Bolu Viaduct and the C.A.S.E. Project, are presented to illustrate that sliding base isolators can be used to meet otherwise unachievable design objectives. Finally, existing problems such as the response to high vertical accelerations, the potential for bearing uplift and the relevance of residual displacement are analyzed.

1. Introduction

In today's "performance-based" context, one effective way of protecting structures, and achieving a desired performance, is to mitigate the seismic demand on the system itself. To this end, one of the most promising solutions identified over the past few decades consists of installing low lateral stiffness devices, referred to as base isolators, beneath key supporting points of the structure. Base isolation has emerged as one of the most effective high-tech strategies for protecting infrastructures under seismic loading, both in the context of new construction, and in the retrofit of existing systems.

The goal of base isolation is normally to prevent the structure from damage, by shifting the fundamental period of a structure to the long period range and by absorbing the full displacement demand induced by seismic ground motions at the isolation layer. Isolating a structure results in a controlled structural response with reduced accelerations and lateral forces transmitted to the structure. The reduced seismic demand allows the superstructure to remain elastic, or nearly elastic, following a design level event. Furthermore, isolating a structure contributes to reducing the likelihood of damage to displacement sensitive and acceleration sensitive equipment, nonstructural components, and content.

Extensive research has been conducted on the topic of base isolation over the past few decades and the volume of information available in the literature has grown significantly, particularly in the last 15–20 years. To this end, a number of excellent reviews of aspects of the development, theory, and application of this technology can be found in the literature (e.g. [1–7] amongst many others).

However, given the amount of research available on base isolation, no single paper can provide an exhaustive literature review. Thus, authors are forced to either provide a general discussion of the topic, at the cost of providing limited details, or to provide detailed discussions, focusing only on selected issues. Furthermore, there is a steadily increasing production of new numerical and experimental literature, as a result of growing interest in the subject.

In this context, this review paper is dedicated to the historical development of friction-based seismic isolation systems, and particularly to systems that have successfully been deployed and used as seismic safety measures for structures located in Europe.

Though the concept of seismic isolation dates back more than one hundred years (e.g. [8,9]), modern friction sliding base isolators came about in the late 1980s and to date there are relatively few base-isolated structures in Europe.

While the concept of a friction-based isolating system was simple and attractive, the lack of a suitable restoring force delayed the implementation of sliding systems. Some attempts have been made at using a combination of flat sliders and "spring systems" that could serve as re-centering elements. One example can be found in the work of [10], who tested an isolation system utilizing a combination of elastomeric bearings and flat sliders. However, it was only after the

---

* Corresponding author.
E-mail address: pmc85@uw.edu (P.M. Calvi).

https://doi.org/10.1016/j.soildyn.2017.12.003
Received 16 August 2017; Received in revised form 20 October 2017; Accepted 3 December 2017
0267-7261/ Published by Elsevier Ltd.

conception of the modern Friction Pendulum ([11]) that sliding base isolators became a competitive alternative (and eventually a replacement) to more traditional solutions.

This paper begins by analyzing one rudimentary pendulum system proposed in 1909 (see [8]) to outline that the idea of isolating structures was conceived over 100 years ago but was unachievable because of technological limitations.

The modern Friction Pendulum is then introduced, focusing on a number of challenges that were gradually overcome. An extended discussion will be presented on problems associated with the performance of low friction materials and the effects of heating, contact pressure and velocity, in light of the most recent experimental evidence. Double Concave Friction Pendulum and Triple Friction Pendulum bearings are subsequently introduced. Their properties and benefits are discussed, and potential performance limitations and current knowledge gaps are outlined.

Two notable European case studies, the Bolu Viaduct (Turkey) and the C.A.S.E. Project (Italy), are used to illustrate the utilization of sliding base isolators as seismic solutions in two very different, but extremely challenging contexts.

Finally existing problems, such as the response to high vertical accelerations, the potential for bearing uplift and the relevance of residual displacement, are analyzed.

2. The “pendolo Viscardini” (1909)

In 1909, following the Messina earthquake, a friction-based isolation device was patented and proposed by Mario Viscardini (see Fig. 1 and [8] for a more detailed description). Viscardini states that perfect safety of a structure can be obtained allowing it to move as freely as possible with respect to the ground and affirms that such a performance can be obtained by introducing, at any contact point between soil and structure, a device consisting of a spherical body free to spin in any direction within two curved boxes, whose curvature assures a unique equilibrium position. He suggests to construct the building directly on such devices, using provisional shear keys, to be later removed.

This proposal induced discussions, followed by a firm decision condemning it, for reliability reasons. The burial stone came from Arturo Danusso [12], who wrote: we immediately understand that if we could practically put a house on springs, like an elegant horse-drawn carriage, an earthquake would come and go like a peaceful undulation for the happy inhabitants of that house, but concluded: I think that a certain practical sense of construction is sufficient by itself to dissuade from choosing mechanical devices to support stable houses.

From the patent drawings in Fig. 1, it is here assumed that the column side is 300 mm, and the spherical roller has a similar diameter. It is further assumed that the upper and lower spherical plates have a size of about 600 mm and their radius of curvature (r_s) is about 1000 mm. Considering reasonable values for contact pressure and sinkage depth, an estimate of the vertical load carrying capacity is about N = 1000 kN.

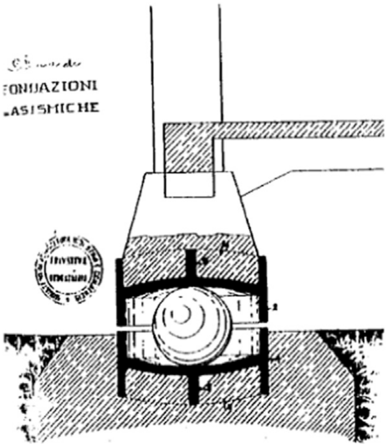

Fig. 1. The “Viscardini pendulum” (from [8]).

From these assumed values, it is straightforward to estimate the following properties:

$$\text{pendulum period of vibration: } T_p = 4\,\pi\sqrt{\frac{r_s}{g}} = 4s \tag{1}$$

$$\text{corresponding horizontal“stiffness” : } k_p = \frac{4\ \ \pi^2 m}{T^2} = 250 kN/m \tag{2}$$

The total displacement capacity can be assumed to be approximately equal to the difference in diameter between plates and spherical roller, i.e. $\Delta_u = 300$ mm.

The calculation of the horizontal friction force V (at the onset of motion, at both points of contacts, upper and lower) can be determined from standard equations, such as:

$$\mathrm{V} = \frac{\mathrm{Nb}}{r} = \frac{1000\ \ b}{150} = 0.67 - 3.3\ kN \tag{3}$$

Where b is a material-dependent constant and r is the radius of curvature of the spherical roller (previously assumed to be 150 mm).

The uncertainties associated with the properties of the materials available at the beginning of the twentieth century, allow only to brake the value of the constant b between 0.1 (e.g. for hardened steel used in spherical rollers) and 0.5 (e.g. for steel used in railway applications). However, this knowledge gap is not considered critical, since the resulting equivalent friction coefficient μ is always lower than 1%:

$$\mu = \frac{2\mathrm{V}}{N} = 0.13 - 0.67\ \% \tag{4}$$

Considering an average value of $\mu = 0.4\%$, the force-displacement relationship that may characterize the Viscardini's bearing is reproduced in Fig. 2. It is shown that the applied horizontal force, normalized with respect to the weight of the structure, corresponds to an acceleration of 0.4% g and 7.9% g, at the onset of motion and at the maximum displacement, respectively.

A cycle of this sort implies a very low equivalent damping (ξ_e), slightly higher than 3%:

$$\xi_e = \frac{2\mu\mathrm{N}}{\pi\mathrm{V}_{max}} = 3.2\% \tag{5}$$

The discussion presented above suggests that the Viscardini device might have had a vertical load carrying capacity and a horizontal displacement capacity acceptable for a reasonably wide scope of applications, while the shear force inducing movement was certainly too low, resulting in buildings oscillating under moderate winds and accidental actions. Perhaps, if not removed, the temporary shear keys that Viscardini recommended for construction purpose, could have worked as useful sacrificial links in case of an earthquake, but this option was

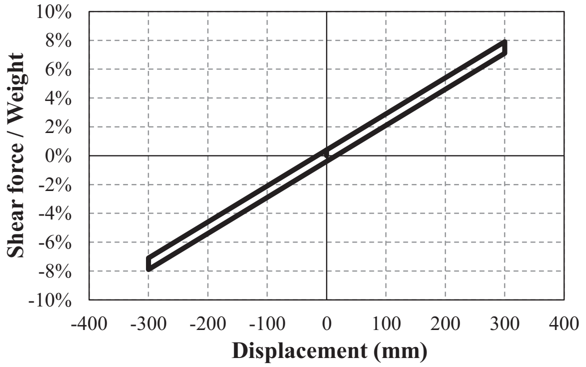

Fig. 2. Force-displacement hysteresis of Viscardini's device based on assumed values.