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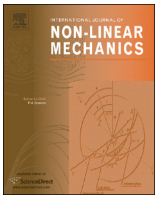

# The impact of the concave distribution of rolling friction coefficient on the seismic isolation performance of a spring-rolling system

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## ABSTRACT

A complex yet realistic nonuniform rolling friction force distribution of a spring-rolling isolation system could lead to great complexity in determining its seismic response. This paper investigates the isolation performance of a spring-rolling isolation system assuming that the rolling friction force gradually and linearly increases with the relative displacement between the isolator and the ground. A series of ground motions with different characteristics were applied to this system. The analysis results show that the considered concavely distributed friction force is capable of dissipating the earthquake energy, and it is also able to modify the structural natural period. These merits combined help to improve the isolating efficacy of the spring-rolling isolation system compared with scenarios with uniform distribution pattern, and more importantly lead to a relatively optimum isolation state, avoiding a sudden amplification of the structural seismic response, regardless of the input motion characteristics.

## 1. Introduction

Earthquakes have been increasingly inducing serve damages to building and bridge structures in recent decades. To mitigate the seismic demand to the structures, a variety of isolation devices have been developed and demonstrated its seismic resistant merits. However, for the traditional isolation devices, e.g. laminated rubber bearing and lead rubber bearing isolator, have tendency to amplify the demand to the isolated structure when subjected to high-intensity ground shaking [1,2].

In order to achieve an optimum isolation mechanism, an old type isolation device called rolling-based isolation, has been refined in the last two years (2014 and 2015). For example, Harvey and Gavin [3] proposed a mathematical model for double rolling isolation systems (RISs) and validated it against experimental data. In addition, the effect of the initial conditions, the mass of the isolated object, and the amplitude and period of the disturbance on the system's performance were studied. Simultaneously, Harvey, Zehil and Gavin [4] presented a simplified model that was applicable to RISs with any potential energy function. The model has demonstrated its effectiveness in predicting peak responses for a wide range of disturbance frequencies and intensities. Later, Harvey and Gavin [5] proposed a novel reduced order modeling approach to examine the performance of structures incorporated with lightly- and heavily-damped RISs. Furthermore, Ismail and Casas [6–7] proposed and studied a roll-n-cage (RNC) isolator, and the analysis results show that RNC is able to protect cable-stayed bridges against seismic demand induced by near-fault ground motions. Furthermore, Ismail [8] demonstrated that the RNC isolator could be an efficient seismic design strategy particularly for structures located at the fault zones. Wanget et al., [9] numerically studied the sloped multi-roller isolation which was typically used to protect equipment and facilities, and the results show an excellent in-plane seismic isolation performance. Chunget et al., [10] suggested that an isolation system might not be very effective when an inappropriate damping is selected, and proposed a theoretical method that can be used to determine the optimal frictional coefficient of an isolation system. Ortiz, Magluta and Roitman [11] validated a numerical model developed for dynamic analysis of buildings with roller seismic isolation bearings against experimental results.

In addition, similar extensive series of research were conducted on rolling-based isolation devices. Jangid and Londhe [12] developed a theoretical formulation to obtain seismic responses of a multistory building supported by elliptical rolling rods in 1998, and analysis results show that the device is quite effective in reducing the seismic response of the system without undergoing large base displacements. Jangid [13] investigated the stochastic

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response to the earthquake motion of flexible multi-storey shear type buildings isolated by rolling rods with a re-centering device, and the research outcome continue to illustrate the effectiveness of the rolling rods in which help to reduce the stochastic dynamic response of the structure. In 2004, Antonyuk and Plakhtienko [14] analyzed the possible states of a system of interacting solids with rolling friction and unilateral sliding friction bonds, and considered that the proposed strategy can be utilized for seismic isolation purpose. In 2010, Lee [15,16] proposed a roller seismic isolation bearing for use in highway bridges which combined the rolling mechanisms, a self-centering capability, and some unique friction devices for supplemental energy dissipation. After investigating seismic behaviors of the proposed bearing through parametric studies, Lee suspected there was something wrong with the calculation method in AASHTO Specifications and suggested further investigations. In 2013, Harvey and Gavin [17] presented the modeling of a rolling isolation platform built from four pairs of recessed steel bowls, which could be used to protect objects from the hazards of horizontal shaking. The numerical results showed that uni-axial models could not be used to predict responses of these systems. Simultaneously, Harvey, Wiebe and Gavin [18] analyzed the chaotic response of a similar rolling-pendulum vibration isolation system. Rich chaotic behavior is exhibited in the case considering impacts of the ball-bearing with the bowl lip. As to isolate an entire raised floor in a building, Cui [19] performed a series of experiments on a concrete ball-in-cone isolator with solid rubber and polyurethane balls in 2012, and identified the practicability of the isolation system. Similarly, Luís Guerreiro [20] carried out a seismic test and a numerical modeling of a rolling-ball isolation system to protect some light structures in 2007, and the results showed an effective reduction of the acceleration levels induced in the isolation structures. For the purpose of prolonging the isolation system's life span of service, Tsai [21] proposed a static dynamics interchangeable-ball pendulum system (SDI-BPS) in 2010. Several general steel balls provided supports to long terms of service loadings. When an earthquake happened, these balls did not work any more, and a damped steel ball surrounded by damping materials began to uphold the vertical loads and supply additional damping to the bearing by deforming the damping material. Kurita [22] developed a similar device for seismic response reduction, and the peak acceleration amplitude was decreased by about 50–90%. In 2012, Nanda [23] considered that the base isolation in the form of pure friction (P-F), among all other isolation methods developed so far, was the simplest one, which could be easily applied to low cost brick masonry buildings. Furthermore, the P-F isolation is one of the best alternatives for reducing earthquake energy transferred to superstructure during strong earthquake.

In all these studies, although the rolling friction isolation device reduces structural damage caused by earthquakes, the induced structural displacement may be very large and difficult to control [24,25]. Therefore, some restoring devices, such as springs, are usually added to the isolation device to provide the restoring force, which can eliminate excessive relative displacement and reduce the structural residual displacement [26,27]. However, how to combine the spring device and the rolling friction device to obtain an optimum isolation performance needs further investigation. In addition, the previous researches and applications usually assume all of the rolling friction coefficients on the contact surface as a constant value, i.e. the distribution of rolling friction coefficient on the entire contact surface is absolutely uniform, to simplify the calculation process of the structural seismic response. But the assumption is not reasonable in some sense [28–30]. Because the contact surface is usually rough in fact, and the according rolling friction coefficient on the contact surface is uneven [31,32]. Theoretically, the uneven distribution of rolling friction coefficient may lead to great uncertainty in the structural seismic responses [33,34].

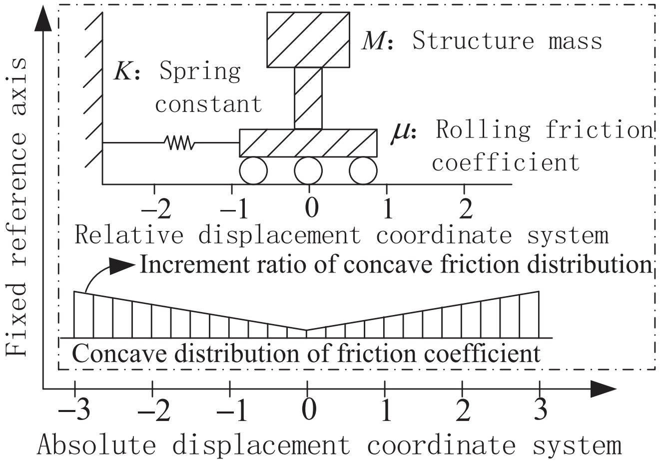

**Fig. 1.** The spring-rolling isolation system.

In view of this, how to use the uneven distribution of rolling friction coefficient to improve the isolation performance is an interesting topic. This paper artificially makes the uneven distribution of rolling friction coefficient to be concave as shown in Fig. 1. The rolling friction coefficient in the center of the contact surface is the smallest one, and it gradually increases when the relative displacement between the rolling ball and the ground increases. The friction coefficient increment of unit length is defined as the increment ratio of the concave friction distribution. A spring is added to a contact surface with this concave friction distribution to form a spring-rolling isolation system as shown in Fig. 1. Theoretically, based on the restoring force provided by the spring and the concave friction distribution, the isolation structure may not displace considerably during an earthquake, and the isolator may roll back to the original position without a significant residual displacement after an earthquake. The main purpose of this paper is to utilize a numerical analysis to detailedly analyze the impact of the concave friction distribution on the seismic performance of the spring-rolling isolation system under different ground motions.

## 2. Numerical analysis method

Based on the motion characteristics of a spring-rolling isolation system, this section establishes a numerical analysis procedure.

### 2.1. Movement characteristics

Fig. 1 schematically shows a SDOF pier system supported by spring-rolling device where the rolling ball isolates the superstructure from the ground. Simultaneously, the friction action of the rolling ball dissipates the seismic energy. The spring element represents the elastic restoring component which could help to avoid the excessive structural relative displacement and reduce the structural residual displacement. In this simplified system, three important design variables include the rolling friction coefficient $\mu$, spring constant $K$, and the increment ratio of the concave friction distribution. The system with different combination of these variables could result in three different scenarios with different characteristics as follows:

(1) A system with a significantly small $\mu$ and significantly large $K$. This indicates that the system has a large stiffness but significantly small friction force. In this regard, this system can be identified as a classic linear oscillator. This characteristic might