

## New advances on rolling-type isolation systems

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### Abstract

Rolling-type base isolation as a means of earthquake protection has been recognized for over a century, yet it has advanced rapidly in recent years due to increased research interest. Significant developments in the modeling and experimental testing of rolling-type isolators have broadened both the understanding and acceptance of this concept. This study focuses on recent models of rolling-type isolation that capitalize on the rolling mechanism's ability to convert translational motion into rotational motion, thereby reducing the accelerations and forces transmitted to the superstructure. Among these developments is the patented 3-Dimensional Geared Rocking/rolling Inverse Pendulum System (3DGRIPS), which was specifically conceived to address limitations of conventional rolling isolators. The 3DGRIPS system is designed to protect lightweight, high-value assets—such as museum exhibits, servers, and hospital or telecommunications equipment—by employing a toothing geometry at its contact surfaces to prevent slippage and enhance energy dissipation. In addition, the inclusion of a flat resting surface reduces stress concentrations, provides impact-related damping, and ensures complete recentering of the isolated system to its original equilibrium position following seismic excitation.

**Keywords:** Rolling isolation system, base isolation, inverse pendulum, museum artefacts.

### 1- INTRODUCTION

Seismic isolation is an effective method of protection against earthquakes, which has been known for a long time. In addition to theoretical knowledge, this method now has a number of applications in real structures. Instead of increasing the strength of a structure, the purpose of seismic isolation is to reduce the seismic forces acting on it. The seismic isolation systems provide (or should provide) the following key components:

(a) The separation of the superstructure from the underlying formation (usually the ground), using flexible elements, which increases the fundamental oscillation period of the system and leads it away from the range of values in which seismic excitations have a strong effect.

(b) The use of damping, in order to keep the displacements within acceptable limits.

(c) The use of some elements of lateral stiffness, which will prevent the significant activation of the system under service loads (as in the case of wind pressure on the superstructure, or weak seismic excitations).

Apart from the common base isolation systems which use elastomer or spherical friction bearings, the rolling-type base isolation systems are well-known for over 150 years and offer certain advantages. In 1870, J. Touaillon with U.S. Pat. No 99973 patented the seismic isolation system shown in Figure 1. The building is based on rolling metal spheres and therefore during seismic excitation there is no significant acceleration. Similar patents have been awarded to P. Seiler (US846249 – 1907), F. Schär (US951028 – 1910), F.D. Cummings (US1761659 – 1930) and J.F.J. Bakker (US2014643 – 1935). Instead of spheres, cylindrical elements have also been used in one or both dimensions, e.g., the patent awarded to G. C. Lee et al. (US6971795 – 2005). Rolling isolation systems have the advantage of simplicity but also the significant disadvantage of low damping. Consequently, the displacement requirements are generally excessive. In addition, if the rolling surface is flat, the system does not fully return to the initial position after a dynamic event. This is problematic for the performance of the system in the event of successive seismic excitations. Finally, if the spheres and / or the surfaces on which they roll are made from a soft deformable material such as rubber or polyurethane, to increase damping, the change of shape due to the vertical loads needs attention.

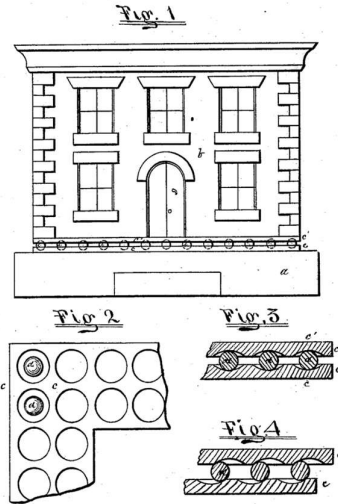


**Figure 1- U.S. Pat. No 99973 by J. Touaillon (1870) [1]**

## 2- SMALL-SCALE BASE ISOLATION

While seismic isolation of newly constructed buildings is very common, e.g., the new Stavros Niarchos Foundation Cultural Center in Athens (SNFCC) [2], it is generally considered difficult to implement in existing structures. In the latter case, individual seismic protection of the most valuable objects is the most cost-efficient method, e.g., the seismic protection of the statue of Hermes of Praxiteles at the Museum of Olympia [3]. Apart from museum artefacts, sensitive equipment or whole areas in hospitals, laboratories or data centers can also be seismically protected to ensure their resilience.

Such small-scale applications pose a significant challenge to common seismic isolators due to the following reasons:

- (a) Common isolators are not fit for small gravity loads.
- (b) Although most seismic isolators exhibit some kind of restoring force, in reality, this is weak near the center of the system. Thus, the devices fail to recenter properly and need to be recentered manually. This may not be feasible in time, as it is common for earthquake events to occur in a sequence, one after another, separated by a time span of some minutes or hours. For example, in the recent events in Turkey (6/2/2023), two major earthquakes (Mw 7.8 and Mw 7.5) occurred within 9 hours with an epicentral distance of only 100 km. The subsequent events commence with the system off-center, which may endanger the safety of the objects under protection. As the implementations of seismic isolation grow in number, a system with precise automatic recentering capability is clearly in advantage.

(c) The vertical component of the seismic excitation is typically not handled by the common isolation devices, as they only work in the horizontal directions.

To address these shortcomings, a new patented bearing design, called 3-Dimensional Geared Rocking/rolling Inverse Pendulum System (3DGRIPS) [4] is presented herein, which was specifically developed to mitigate these issues.

## 3- 3DGRIPS

3DGRIPS uses a rocking/rolling inverse pendulum to achieve the separation of the superstructure from its foundation. The defining characteristics which set it apart from other base isolation systems are the following:

- (a) The system can be implemented with both a ball-like element (to create a compact bearing of small height, see Figure 2a) or a column element (Figure 2b).
- (b) The rolling surfaces in contact feature deep and robust 3D teeth which interlock and ensure that no sliding occurs whatsoever (Figure 3). The depth is sufficient to compensate for potential relative movement in the Z dimension. The engagement of the teeth causes friction and damping, which can be enhanced by proper coating of the involved surfaces with elastomeric or TPU-based materials.
- (c) The central part of the bearing is flat which ensures stress alleviation and shape retention, additional impact-related damping, stability under small lateral loads (i.e., no activation under wind loads or small seismic events), and full recentering after a strong dynamic event (see area 5 of Figure 3).

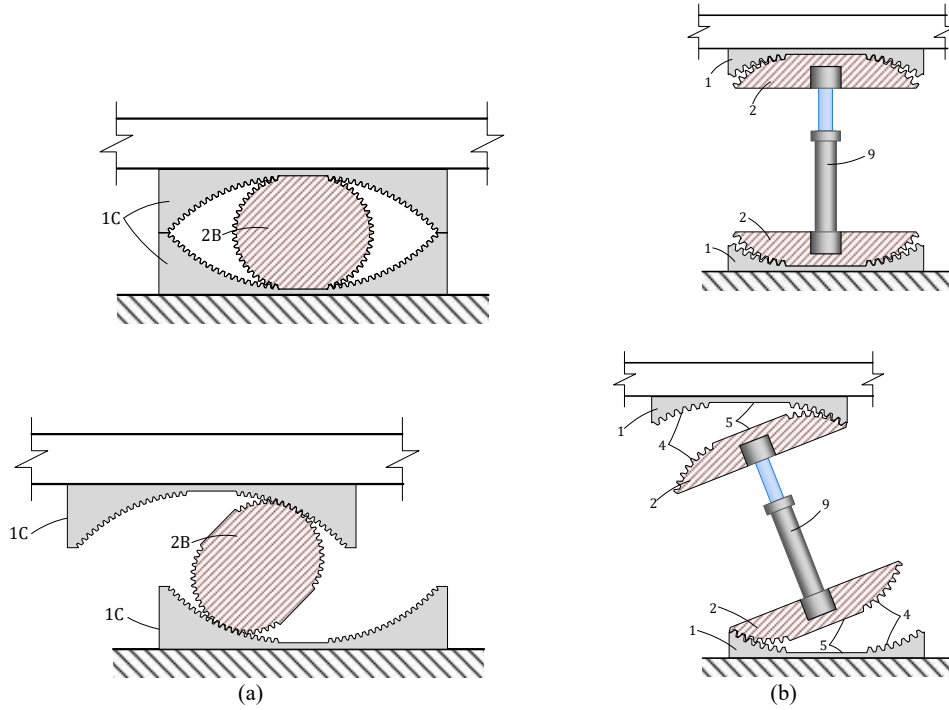


**Figure 2- 3DGRIPS [4] with (a) rocking/rolling ball element and (b) rocking/rolling column element with absorber**

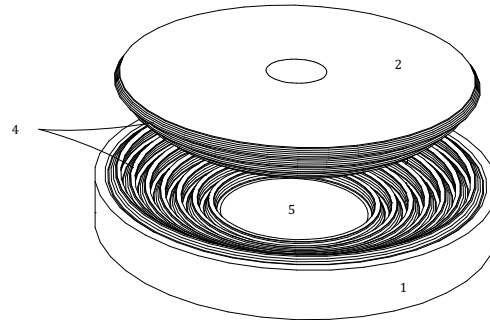


**Figure 3- 3D geared contact surfaces of 3DGRIPS [4]**

Contrary to other rolling-type isolators which use deformable TPU balls to increase damping, the present bearing is designed to deform minimally. For this reason, all the kinematic equations can be defined accurately using geometry, and there is no need for complex analyses to account for the deformed shape of the balls and their rolling behavior. The kinematic non-sliding nature of the proposed isolation system also ensures long-term reliability, in contrast to sliding systems where the temporal evolution of the friction coefficient due to aging and contamination should be investigated.

As shown in Figure 2, the deflection of the system from the equilibrium position entails the elevation of the superstructure. Therefore, the gravity loads provide the restoring force, while the curvature of the geared surfaces mainly controls its aggressiveness, just as in spherical friction systems. When the seismic event is over and the bearing is relatively centered, the central flat surfaces act to achieve the completion of the full recentering process. The size of the central flat surface also dictates accurately the threshold, in terms of acceleration, over which the system is activated, just as in rocking systems.

Damping is achieved through the interlocking motion of the gears and the impacts on the central areas. Finally, the displacement capability of the device is similar to a double concave FPS system of equal size.

#### 4- 3DGRIPS BEARING DESIGN

The design of the 3DGRIPS bearing allows for various isolator configurations based on the geometry of the central flat areas. No-slip conditions are always assumed and the gear teeth are omitted from Figure 4 for visual clarity. In all configurations, the orange bases maintain a central flat area identical to that of the corresponding roller. The cases are as follows:

Type-S (Figure 4a): A purely rolling, simple spherical roller with no flat contact surface.

Type-A (Figure 4b): Combines rolling and impact. It is derived by dividing the circular section of a Type-S isolator into two semi-circles, displacing them by  $\pm a$  in the horizontal direction, and revolving the resulting ovaloid around the vertical axis of symmetry. The resulting central flat area is a circle of radius  $a$ .

Type-B (Figure 4c): Combines rocking/rolling and impact. It is formed by removing horizontal slices from the top and bottom of a full sphere. The central flat area is a circle of radius  $b$ .

Type-C (Figure 4d): Combines rocking/rolling and impact. This configuration integrates the design features of both Type-A and Type-B, resulting in a central flat area with radius  $c = a + b$ .

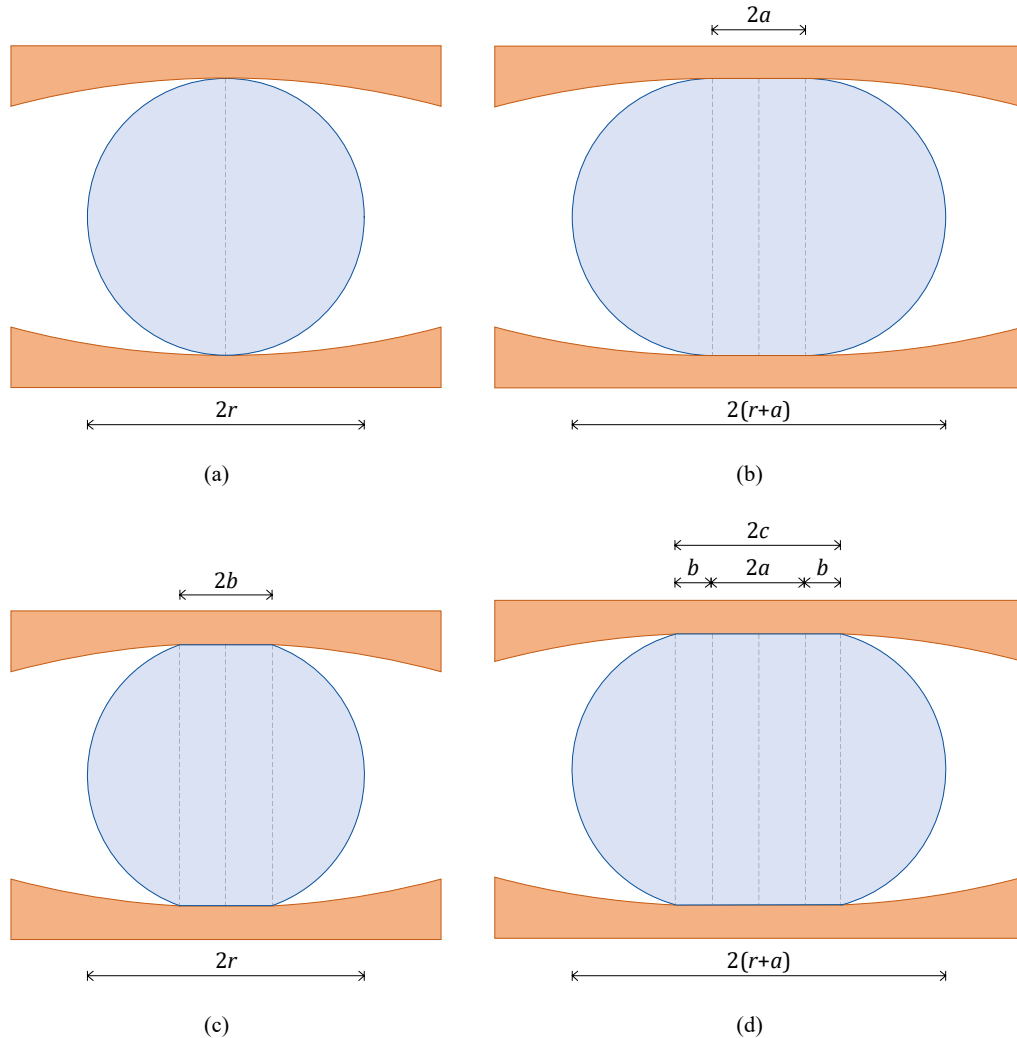


**Figure 4- Isolator types (a) Type-S (spherical, purely rolling isolator) (b) Type-A (rolling isolator with impact) (c) Type-B (rocking/rolling isolator with impact) (d) Type-C (rocking/rolling isolator with impact, a combination of Type-A and Type-B).**

## 5- TYPE-S ISOLATOR

It is insightful to analyze the behavior of the common spherical roller (type-S) before moving to the next types.

### 5-1- KINEMATICS

Figure 5a shows a 2D section of a spherical roller of radius  $r$ , rolling onto a flat surface. After the roller has rotated by  $\theta$ , the center point  $C$  has moved to point  $C_3$  and the contact point  $A_2$  is directly below it, due to the flat horizontal rolling surface.

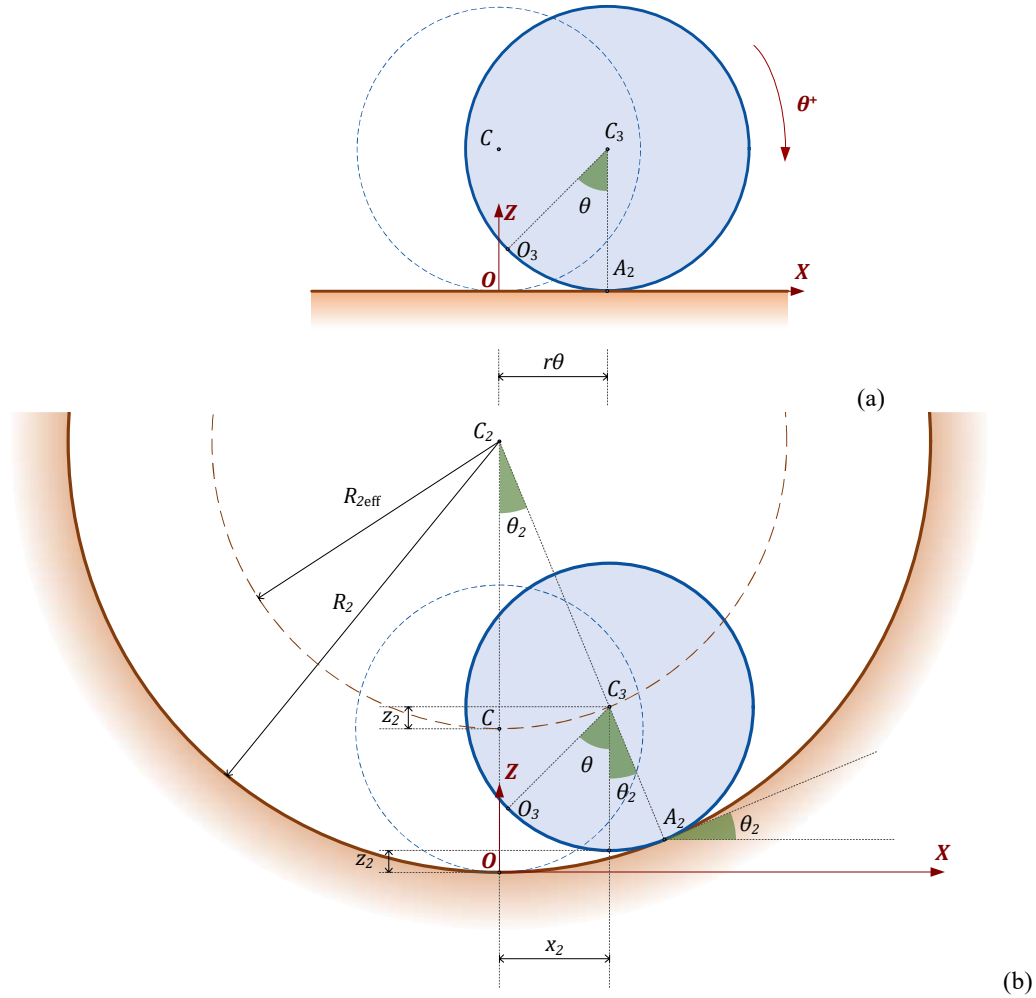


Figure 5- Type-S isolator rolling on (a) flat surface and (b) spherical surface of radius  $R_2$ .

However, when rolling occurs on a spherical surface of radius  $R_2$  (Figure 5b), the contact point  $A_2$  is further to the right, forming an angle  $\theta_2$  with the vertical axis. This angle is additional to the self-rotation angle  $\theta$ . The difference between angles  $\theta$  and  $(\theta + \theta_2)$  is the root cause of the famous “coin paradox”. Note that the angle  $\theta_2$  also indicates the rotation of the CG of the roller with respect to point  $C_2$ .

Since there is no sliding, the arc length  $O_3A_2$  must be equal to the arc length  $OA_2$ , which leads to

$$r(\theta + \theta_2) = R_2\theta_2 \quad (1)$$

By considering the effective radius  $R_{2eff} = R_2 - r$  [5], which is the radius of the circle on which the center of the roller is moving (Figure 5b), and by setting

$$\kappa_2 = \frac{r}{R_{2eff}} = \frac{r}{R_2 - r} \quad (2)$$

Equation 1 becomes

$$\theta_2 = \kappa_2 \theta \quad (3)$$

Note that  $\kappa_2$  is a measure of the relative curvature of the bottom base with respect to the roller radius  $r$  (Figure 6). When  $\kappa_2 \rightarrow 0$ , the bottom base is flat. The displacement of the roller center (i.e., from point  $C$  to point  $C_3$ ) in the x-direction is of interest and is evaluated as

$$x_2 = (R_2 - r) \sin \theta_2 = \frac{r}{\kappa_2} \sin(\kappa_2 \theta) \quad (4)$$

Similarly, in the z-direction

$$z_2 = (R_2 - r)(1 - \cos \theta_2) = \frac{r}{\kappa_2} (1 - \cos(\kappa_2 \theta)) \quad (5)$$

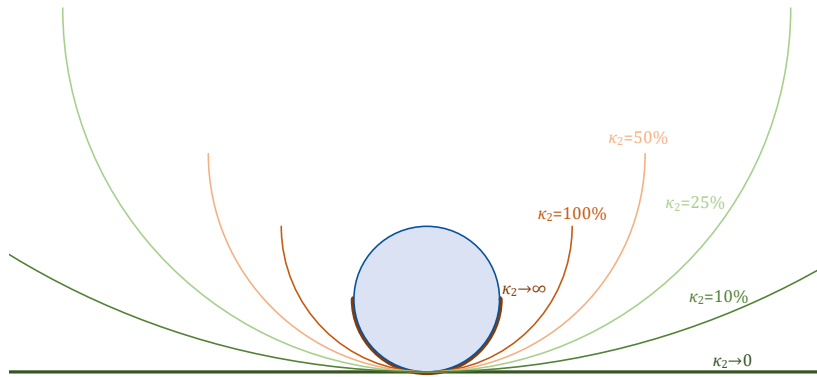


Figure 6- Physical representation of curvature parameter  $\kappa_2$ .

When concurrently rolling onto two surfaces of different radii (Figure 7), a curvature coefficient  $\kappa_1$  needs to be defined in similar fashion.

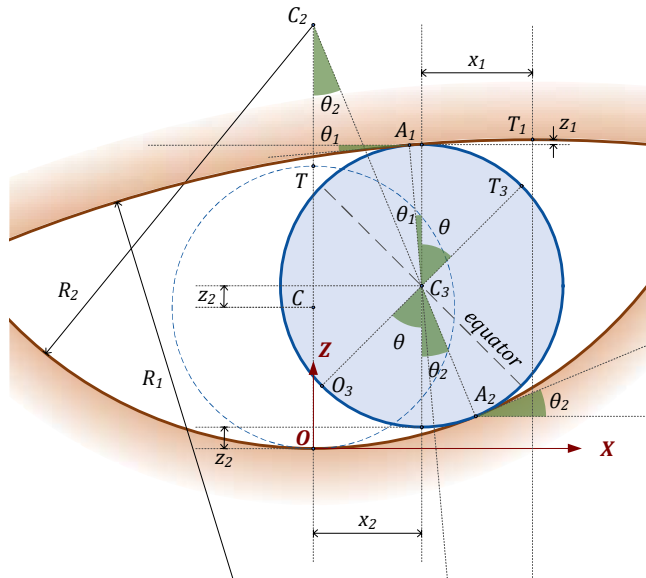


Figure 7- 2D section of a spherical roller rolling onto two spherical surfaces of different radii.

The total horizontal displacement of the isolator (i.e., the horizontal distance of point  $T_1$  with respect to point  $T$ ) is given as

$$x_b(\theta) = x_1 + x_2 = r \left( \frac{1}{\kappa_1} \sin(\kappa_1 \theta) + \frac{1}{\kappa_2} \sin(\kappa_2 \theta) \right) \quad (6)$$

The total vertical displacement (uplifting) of the isolator (i.e., the vertical distance of point  $T_1$  with respect to point  $T$ ) is given as

$$z_b(\theta) = z_1 + z_2 = r \left( \frac{1}{\kappa_1} (1 - \cos(\kappa_1 \theta)) + \frac{1}{\kappa_2} (1 - \cos(\kappa_2 \theta)) \right) \quad (7)$$

## 5-2- EQUATION OF MOTION

Following Wang [6], we perform a force analysis of the different bodies of the isolator, where  $M$  is the mass of the superstructure,  $m$  is the mass of the roller,  $I_3$  is the moment of inertia of the roller about its CG,  $N_1$  and  $N_2$  are the normal forces at the points of contact, and  $F_{f1}$  and  $F_{f2}$  are the necessary frictional forces to maintain the non-slip condition (Figure 8).

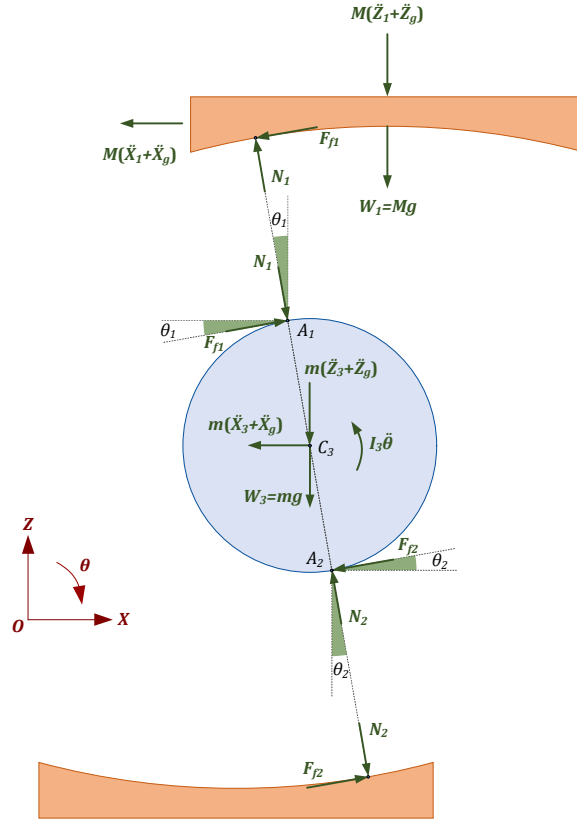


Figure 8- Force analysis for the bodies of the Type-S isolator.

The following set of equations are derived.

$$(N_1 \sin \theta_1 - N_2 \sin \theta_2) + \text{sign}(\dot{x}_b) (F_{f1} \cos \theta_1 - F_{f2} \cos \theta_2) - m(r\ddot{\theta} \cos \theta_2 + \ddot{X}_g) = 0 \quad (8)$$

$$-N_1 \cos \theta_1 + N_2 \cos \theta_2 + \text{sign}(\dot{x}_b) (F_{f1} \sin \theta_1 - F_{f2} \sin \theta_2) - m(r\ddot{\theta} \sin \theta_2 + \ddot{Z}_g + g) = 0 \quad (9)$$

$$-I_3\ddot{\theta} + r \text{sign}(\dot{x}_b) (F_{f1} + F_{f2}) = 0 \quad (10)$$

$$-N_1 \sin \theta_1 - F_{f1} \cos \theta_1 \operatorname{sign}(\dot{x}_b) - M(r\ddot{\theta}(\cos \theta_1 + \cos \theta_2) + \ddot{X}_g) = 0 \quad (11)$$

$$N_1 \cos \theta_1 - F_{f1} \sin \theta_1 \operatorname{sign}(\dot{x}_b) - M(r\ddot{\theta}(\sin \theta_1 + \sin \theta_2) + \ddot{Z}_g + g) = 0 \quad (12)$$

The system of five equations, i.e., Equations 8 to 12, is solved and after some simplifications and substitutions,  $\ddot{\theta}$  is found to be

$$\ddot{\theta} = - \frac{(g + \ddot{Z}_g)(\sin(\kappa_1 \theta) + (1 + \frac{m}{M}) \sin(\kappa_2 \theta)) + \ddot{X}_g(\cos(\kappa_1 \theta) + (1 + \frac{m}{M}) \cos(\kappa_2 \theta))}{\frac{I_3}{rM} + (2 + \frac{m}{M} + 2 \cos(\kappa_1 \theta - \kappa_2 \theta))r} \quad (13)$$

Solving the previous equation numerically for  $\theta = \theta(t)$  allows for the evaluation of any other quantity of interest, as well as simulating the motion of the isolator for validation purposes, as will be demonstrated.

### 5-3- LINEARIZED EQUATION OF MOTION

We can linearize Equation 13 for small angles and obtain

$$\ddot{\theta} = - \frac{(g + \ddot{Z}_g)(\kappa_1 + (1 + \frac{m}{M})\kappa_2)\theta + \ddot{X}_g(2 + \frac{m}{M})}{\frac{I_3}{rM} + (4 + \frac{m}{M})r} \quad (14)$$

Regarding the undamped free vibration, the previous equation becomes

$$\left(\frac{I_3}{rM} + \left(4 + \frac{m}{M}\right)r\right)\ddot{\theta} + g\left(\kappa_1 + \kappa_2\left(1 + \frac{m}{M}\right)\right)\theta = 0 \quad (15)$$

From which the natural period of oscillation is evaluated as

$$T_n = 2\pi \sqrt{\frac{\frac{I_3}{rM} + (4 + \frac{m}{M})r}{g(\kappa_1 + \kappa_2(1 + \frac{m}{M}))}} \quad (16)$$

If we further simplify the previous equation for  $I_3 \ll rM$  and  $m \ll M$ , and assume that the curvature of the top and bottom plates are the same ( $\kappa_1 = \kappa_2 = \kappa$ ), we obtain

$$T_n = 2\pi \sqrt{\frac{2r}{g\kappa}} \quad (17)$$

Which is equivalent to the corresponding equation of the double spherical sliding system since  $R_{\text{eff}} = r/\kappa$ . Solving the last equation for  $\kappa$  we derive

$$\kappa = \frac{8\pi^2 r}{gT_n^2} \quad (18)$$

Which yields the necessary parameter  $\kappa$  for a given target period of oscillation.

### 6- VISUAL SEISMIC SIMULATIONS

The previous equations of motion for the Type-S bearing have been coded in Mathematica [7] to visually simulate seismic events. The response of the bearing is displayed along with the ground movement and graphs of all relevant metrics to ensure that motion is natural and no significant error exists.

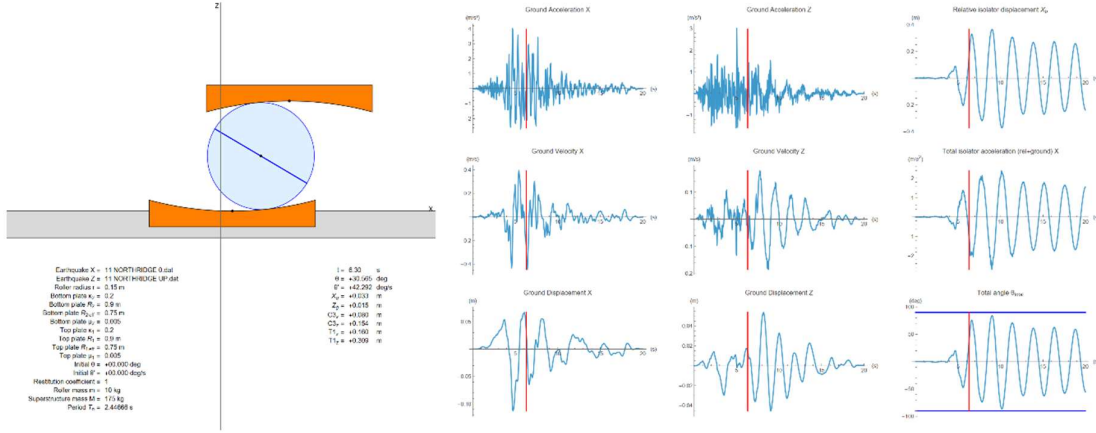


Figure 9- Visual seismic simulations in Mathematica [7].

## 7- SMALL-SCALE EXPERIMENTS

Preliminary small-scale experiments with 3D printed Type-B isolators in a small shake table confirm that the isolator behaves very satisfactorily. In particular, it is activated after a certain threshold, it prevents free-standing slender specimens from toppling and fully recenters at the end of the event. Interestingly, there also appears to be a significant level of damping due to the impacts and the interlocking motion of the gear teeth.



Figure 10- Small scale experiments of Type-B isolators.

Several free-standing wood specimens ( $B = 120$  mm  $\times$   $D = 60$  mm) of various heights  $H$  were tested against strong seismic records. Small indentations on the top plate prevented sliding, although it is uncertain if they were necessary at all. Under unfavorable conditions (flexible top plate, unprepared wood surfaces, small depth  $D$ ), specimens with  $H/B = 6$  reliably remained intact after all available strong motions, while in certain cases even specimens with  $H/B = 10$  also did not topple.

## 8- CONCLUSIONS

The 3DGRIPS system presents a promising advancement in the seismic isolation of lightweight, high-value assets, successfully addressing several limitations inherent in conventional isolation technologies. By integrating geared contact surfaces with a central flat resting area, the design eliminates slippage, provides impact-related damping, and ensures precise automatic recentring following seismic excitation. Preliminary small-scale experiments, conducted with 3D-printed prototypes on a shake table, have confirmed the system's

effectiveness; tested specimens remained stable and intact under strong seismic records, demonstrating the bearing's reliability and its ability to fully recenter even under unfavorable conditions.

Furthermore, because the 3DGRIPS bearing is designed for minimal deformation, its kinematic equations can be formulated with high accuracy using geometric principles, bypassing the need for complex, computationally intensive modeling. This geometric precision, combined with the system's inherent non-sliding nature, suggests superior long-term reliability compared to traditional sliding isolators, which often require careful investigation into the temporal evolution of friction coefficients due to aging and environmental contamination. As the implementation of seismic isolation for sensitive equipment continues to expand, the 3DGRIPS system offers a robust, advantageous solution that ensures both enhanced resilience and operational continuity for high-value protection applications.

3DGRIPS is an ongoing project. More up-to-date information can be found at <https://3dgrips.eu>.

## 9- ACKNOWLEDGMENT

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