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Analytical study of seismic isolation systems in bridge structures

M. Miralimov[1][a], R. Ospanov[1][b], R. Azamjonov[2][c]
[1]Tashkent state transport university, Tashkent, Uzbekistan
[2]National Research Institute for Seismic Safety and Resilient Construction under Tashkent Institute Architecture and Civil Engineer, Tashkent, Uzbekistan

Abstract: This article presents a comprehensive analysis of existing seismic isolation systems used for protecting bridge structures against seismic impacts. The role of antiseismic devices within bridge structures, as well as the possibilities of their implementation through connections between supports, superstructures, and structural elements, are thoroughly examined. The necessity of considering antiseismic devices as independent and essential structural components of bridges is scientifically substantiated. The strengthening methods employed to ensure the seismic resistance of bridges are classified into conventional and special categories, and their operating principles are analyzed in detail. Conventional methods are primarily based on the absorption and redistribution of seismic loads by the structural elements themselves, whereas special methods are aimed at reducing seismic effects by modifying the dynamic behavior and structural scheme of the bridge. Special methods include seismic isolation and seismic energy dissipation systems. The article also provides a detailed explanation of the concept of seismic isolation, its operating mechanism, and corresponding structural solutions. Seismic isolation systems are categorized into adaptive and stationary types, and the technical characteristics of rigid, flexible, sliding, elastic, and gravitational bearing components specific to each category are investigated. Furthermore, suspended and supported types of gravitational seismic isolation foundations are also analyzed. The research results demonstrate that seismic isolation systems represent one of the most promising seismic protection technologies for bridges constructed in regions with high seismic activity.
Keywords: seismic isolation, anti-seismic devices, bridge structures, seismic loads, adaptive systems, stationary systems, rubber–metal bearings, gravitational seismic protection

1. Introduction

Today, ensuring the seismic resistance of transport infrastructure located in seismically active regions of the world, particularly highway and railway bridges, is considered one of the most important scientific and technical challenges. Strong earthquakes generate significant inertial forces in bridge structures, which may lead to severe damage in supports, superstructures, and their interaction zones. Therefore, the application of antiseismic devices in modern bridge engineering has gained special importance.

Antiseismic devices can be integrated into bridge supports, superstructures, and bearing components, or implemented through structural connections between the main elements of the bridge system. In this context, the interaction between the superstructure and soil, between supports and superstructures, as well as between adjacent spans and supports, must be taken into account [1]. It is more appropriate to consider antiseismic devices not as auxiliary components, but as primary structural elements responsible for seismic protection.

2. Research methodology

To improve the seismic resistance of bridges, both conventional and special strengthening methods are applied. Conventional methods are based on strengthening structural elements or redistributing seismic loads among components. However, such approaches often lead to an increase in structural mass and stiffness.

Special methods, on the other hand, aim to reduce seismic actions by modifying the dynamic behavior of the structure. These methods include seismic isolation and seismic energy dissipation systems. In practice, seismic isolation is considered one of the most effective solutions [2]. This approach significantly reduces the overall seismic response of the bridge by decreasing the energy transmitted to the structure during seismic excitation.

Currently, seismic isolation systems are classified into adaptive and stationary types and are implemented using rubber–metal bearings, gravitational systems, and sliding bearing components. These systems are regarded as one of the most promising seismic protection solutions for bridges constructed in regions with high seismic activity, particularly in seismic zones exceeding intensity level 8.

Antiseismic devices may be incorporated into bridge supports, superstructures, and bearing elements. In addition, they can also be implemented through connections between the main structural components of the bridge (for example, between the superstructure and soil, between supports and superstructures, between adjacent spans, and between neighboring supports). Antiseismic devices should be considered as primary structural elements that perform the function of protecting the structure against earthquakes.

To ensure the seismic resistance of bridges, two main strengthening approaches are applied: conventional and special methods.

[a] https://orcid.org/0000-0003-2530-5516
[b] https://orcid.org/0009-0009-9996-1023
[c] https://orcid.org/0009-0003-8428-4716

Traditional seismic design methods must ensure the acceptance of seismic loads that act on the structure. This is achieved by developing and strengthening structural elements, or by distributing the acting loads among elements [2].

Special methods must ensure a reduction in seismic loads by changing the dynamic scheme of the structure; they are divided into seismic isolation and seismic damping (seismolysis and seismodamping). The overall classification of special seismic protection systems is shown in Figure 1.

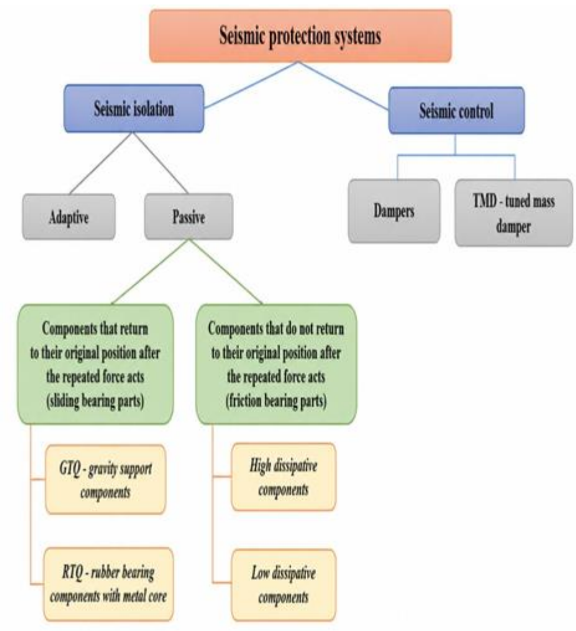

Fig. 1. Classification of special seismic protection method

Worldwide practice widely uses the seismic isolation method for protection against seismic effects.

Seismic isolation means, in our context, systems that reduce the energy affecting structures during the seismic vibration process by installing elements with a higher degree of flexibility at certain levels. Thus, any seismic isolation system must consist of three main components: a rigid structure, a seismic-isolating element, and a supporting (load-bearing) structure.

Seismic isolation systems are classified into adaptive and stationary systems.

Adaptive systems. The adaptive seismic isolation systems consist of coupled support structures of intermediate devices and are divided into rigid or flexible support parts. The rigid support parts are designed to carry operational loads with a certain reserve. Under extreme loads, the rigid support parts fail, and the second group of support parts—flexible elements—comes into operation.

Stationary systems. Stationary seismic isolation systems include four groups of technical solutions. The first two groups of solutions are “flexible” support parts, in which the restoring force arises from elastic forces (rubber-metal bearings (RTQ)) or from the force of gravity (gravitational bearings (GTQ)). The issue of protecting bridges from seismic effects is an important scientific and practical task for ensuring the reliability and continuous operation of transport infrastructure worldwide. For this reason, in many countries numerous constructive and technological solutions have been developed and implemented aimed at improving the effectiveness of seismic isolation systems [12].

Rubber-metal bearings are currently widely used in bridges located in seismically active regions such as Japan, the United States, New Zealand, and Italy. These systems consist of elastomer layers and steel plates, providing high flexibility in the horizontal direction and sufficient stiffness in the vertical direction. Lead-rubber bearings (LRB) additionally have an energy-dissipation capability, so during seismic vibrations the inertia forces are significantly reduced. Gravitational seismic isolation systems are used as an effective solution for bridges in the United States and European countries. In these systems, the intermediate part moves along spherical sliding surfaces, and the restoring force is generated by gravity.

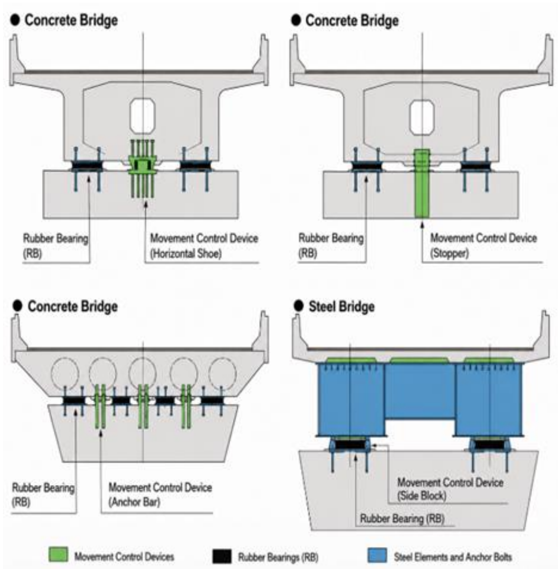

Fig. 2. Lead Rubber Bearings (LRB) used in bridge structures for seismic isolator

The presented figure illustrates the fundamental mechanical behavior, analytical relationships, and seismic performance characteristics of damping systems used in bridge isolation and vibration control engineering. These systems are essential components in modern earthquake-resistant bridge structures because they reduce seismic forces, dissipate input energy, and improve structural stability during dynamic loading conditions [6]. The diagram integrates several important concepts of structural dynamics, including hysteretic energy dissipation, damping ratios, force–displacement relationships, seismic response spectra, and equivalent viscous damping models. Each subfigure represents a specific analytical or mechanical characteristic of bridge isolation devices such as rubber bearings, viscous dampers, hysteretic dampers, and friction-based seismic isolation systems [7].

The first graph presents the hysteretic behavior of elastomeric rubber bearings under cyclic shear loading. When seismic excitation occurs, the bridge deck experiences repeated lateral displacements. Rubber bearings deform in shear and generate a hysteresis loop due to the viscoelastic behavior of rubber material. The enclosed area inside the hysteresis loop represents dissipated seismic energy [8].

$$\mathbf{K} = \frac{\tau}{\gamma}$$

Where:
K = Shear stiffness ,τ = Shear stress ,γ = Shear strain
A wider hysteresis loop indicates higher energy dissipation capacity, greater damping performance, reduction in seismic response amplitude, and improved bridge survivability during earthquakes.

During earthquake excitation, the bridge superstructure experiences repeated horizontal displacement. The rubber layers inside the bearing deform in shear, producing cyclic stress–strain loops. Because rubber exhibits viscoelastic behavior, loading and unloading paths do not coincide, creating a hysteresis loop. modern earthquake engineering, seismic isolation design, nonlinear structural dynamics, and bridge vibration control analysis. These equations form the theoretical foundation for evaluating damping behavior, energy dissipation mechanisms, and seismic performance of isolated bridge systems.

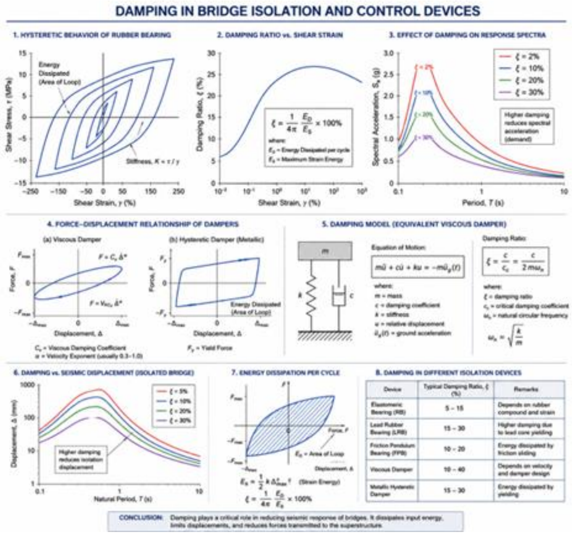

Fig. 3. Analytical Representation of Damping and Energy Dissipation in Bridge Seismic Isolation Devices

The next two groups of solutions are “sliding” support elements. Based on their operating principle, they can be divided into two categories: those with low friction and those with high friction. In the first case, the intermediate devices are connected in the form of a chain, and movable (“sliding”) support elements are installed on the intermediate bearings [6].

The stationary seismic isolation systems can also be classified according to whether they have a restoring force or not. In turn, seismic isolation systems with a restoring force are divided into elastic and gravitational systems. In the former, the restoring force is provided by elastic forces, whereas in the latter, it is provided by the force of gravity [9].

Gravitational seismic isolation foundations can be divided into suspended foundations and supported (bearing) foundations. In suspended foundations, the upper foundation slab is installed on a frame structure that is rigidly connected to the lower foundation slab and is suspended using hangers (ties/supporting rods). The seismic isolation foundation of F. D. Zelenkov constructed in the city of Ashgabat was the first such type of foundation of its kind in the USSR [10].

In supported foundations, the upper foundation slab rests on kinematic bearings. The scheme of the gravitational bearing foundation is shown in Figure 4.

At present, it is reasonable to consider seismic isolation of buildings and structures—including bridges constructed in regions with seismicity greater than 8— as the most promising means of seismic protection. Worldwide, thousands of seismic-isolated buildings and structures have been constructed [11].

In gravitational seismic isolation foundations of the bearing type, the upper foundation slab rests on special kinematic bearings. These bearings have spherical or curved sliding surfaces, ensuring a controlled displacement of the structure during seismic effects. During the displacement process, the restoring force is generated mainly due to the weight (gravity) of the structure [3].

Bearing gravitational foundations have high stability and keep the displacement amplitude within predetermined limits. These systems are widely used in modern global practice, and their developed forms operate on the basis of the Friction Pendulum System. Such systems maintain high reliability even under conditions of large seismic loads.

Scientific evaluation. Gravitational seismic isolation foundations are an effective means of seismic protection for structures and bridges in regions with high seismic activity. Their main advantage is explained by the fact that the restoring force depends not on the stiffness of structural elements, but primarily on the force of gravity, which ensures a stable and predictable dynamic behavior of the system. The research results indicate that applying seismic isolation systems to bridges built in highly seismic regions is appropriate and highly promising as a means of seismic protection.

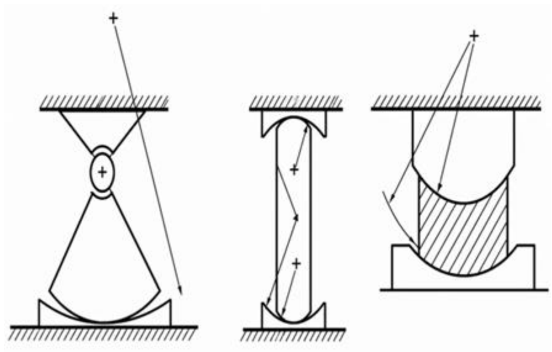

Fig. 4. Schematic diagram of gravitational bearing components (GB)

It should be noted that the sliding of this intermediate device relative to the support ensures the appearance of a gravitational restoring force. At the end of the 1970s, similar solutions were also proposed by Z. G. Khuchbarov and V. P. Chudnetsov.Gravitational seismic isolation foundations (GSIF – Gravitational Seismic Isolation Foundations) are systems intended to protect buildings or bridges from earthquake effects. Their main principle is based on the fact that the restoring force depends on gravity, i.e.,

In traditional elastic foundations and seismic isolation, the restoring force in the elastic foundation is determined primarily by the stiffness of the system. In a gravitational foundation, the restoring force arises from the weight (gravity) of the system, which ensures a stable and predictable dynamic response.As a result, in such systems the restoring force mainly depends on the stiffness of structural components (rubber, steel, concrete), where the restoring force is governed by gravity rather than by the elastic element stiffness alone.

The first concept is probably the simplest seismic design approach: the structure is designed to operate under the expected seismic load level without structural damage. During an earthquake, however, there are many unknown factors that affect the structural response, for example: the level of external loading, material properties, construction errors, and other factors.

Stability: The system may move under dynamic effects, but the restoring force remains constant and can be calculated in advance.

Simple structure: It does not require complex elastic or adaptive elements.

A seismic isolation system (SI system) consists of two main elements:

1. a flexible mounting/isolator that supports the superstructure, and
2. an energy-dissipating device (a dissipator).

The purpose of these two elements is to separate the vibration period of the structure from the dominant horizontal period of earthquakes, prevent large seismic energy from entering the structure due to resonance, and dissipate seismic energy, thereby reducing structural displacements.

Although the seismic isolation system must be sufficiently flexible during an earthquake to reduce the transfer of inertia forces from the foundation to the superstructure, it must also be stiff enough under service loads such as minor earthquakes or wind.

The use of mechanical energy-dissipation devices provides the advantage of seismic isolation in that it significantly reduces the probability of structural damage during strong earthquakes and ensures economic benefits over the entire service life of the structure.

Self-centering is one the most important characteristics of a modern earthquake resistant structural system. Several attempts have been done to design such a system which meets the desired performance objective. Up to now, modern proposed structural systems contain isolation devices or unbounded post-tensioned tendons or combination of them to dissipate energy. Post-tensioning technology is used to design self-centering bridge piers while preventing excessive rocking that cause instability. In this study instead of using special devices or technology, it has been focused on the inherent self-centering due to gravity acceleration to introduce a simple earthquake resistant scheme. This bridge structural system can rock during earthquakes [11].

High load-carrying capacity: Since the system operates based on gravity, it is suitable for heavy bridge or building structures.

The operating mechanism of gravitational seismic isolation foundations may include the following elements:

- **Gravitational bearing:** generates the restoring force due to the structure's weight.
- **Suspended or balanced (equilibrium) systems:** when the foundation moves, the displacement of the structure is smooth and stable.
- **Control of dynamic response:** the displacement amplitude and velocity are controlled according to the system design.

These systems are especially useful for bridges because the length of bridges and the role of intermediate supports are significant in reducing dynamic loads.

3. Conclusion

Within the framework of this study, the efficiency and practical application of seismic isolation systems in bridge structures were comprehensively analyzed. The obtained results demonstrate that seismic isolation systems, particularly elastomeric and hydraulic devices, effectively protect bridge structures from the adverse effects of seismic loading. The operation of these systems enhances the overall structural safety by re

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In general, seismic isolation systems play a significant role in improving the seismic safety of bridge structures and minimizing earthquake-induced damage. Therefore, scientifically and technically justified approaches should be applied during the design, analysis, and calculation processes of bridge seismic isolation system.

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Information about the author

Mirzokhid Miralimov	Tashkent state transport university, Doctor of Technical Sciences (DSc). E-mail: mirzakhid_miralimov@yahoo.com/ Tel.:+998977250924 https://orcid.org/0000-0003-2530-5516
Ruslan Ospanov	Tashkent state transport university, Graduate student Email: Jandos_Chingis@mail.ru
	Tel.: +998933601335 https://orcid.org/0009-0009-9996-1023
Ruziboy Azamjonov	National Research Institute for Seismic Safety and Resilient Construction under Tashkent Institute Architecture and Civil Engineering, Doctoral researcher E-mail: rozixojaazamjonov@gmail.com Tel.: +998909564684 https://orcid.org/0009-0003-8428-4716

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