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IMPROVING RELIABILITY OF UZBEKISTAN'S TRANSPORT INFRASTRUCTURE FACILITIES UNDER IMPACT OF NATURAL HAZARDS BY ANALYSIS OF ITS VULNERABILITY, MONITORING AND MODELING

Ulugbek Z. Shermukhamedov[1], **Zukhritdin Z. Ergashev**[1], **Shakhzod M. Takhirov**[2], **and Abdurakhim A. Abdullaev**[1]

[1] Tashkent State Transport University: Tashkent, Uzbekistan
e-mail: ulugbeksermuxamedov@gmail.com
ergashev33@gmail.com
abdurahim4095@gmail.com

[2] University of California, Berkeley: Berkeley, California, USA
e-mail: takhirov@berkeley.edu

Abstract

The paper is focused on the analysis of the vulnerability of the transportation infrastructure of Uzbekistan based on monitoring and modeling. The paper provides detailed information about the railroads and railway bridges of Uzbekistan. It also summarizes major natural hazards, the impact of which can lead to failures of the transportation infrastructure. The paper aimed at improving the performance of railroads and railway bridges based on comprehensive monitoring, subsequent modeling, and predictions of performance. An example of the application of seismic protection for bridge design in Uzbekistan is discussed. The bridge was recently constructed in an area with a seismic intensity of 9 on the MSK scale. Both damping and bearing systems were used in the design and construction of the bridge. Due to the damping effect, it was possible to reduce the seismic forces in the piers. At the same time, the rigidity of the connection between the superstructure and the pier has increased. This is critical for railway bridges in ensuring small relative displacements as opposed to regular seismic isolation systems.

Keywords: transport infrastructure facilities, natural hazards, vulnerability, railway bridge, earthquake engineering, seismic isolation, damping device.

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INTRODUCTION

A railway transportation infrastructure can be impacted by many natural hazards including but not limited to earthquakes, landslides, snowfalls, cave-ins, avalanches, mudflows, tsunamis, liquefaction, soil settlement, massive snowfalls, and many others. The consequences of train failures can be devastating and in the case of passenger trains, can lead to loss of life. For freight trains, failures can lead to significant environmental issues depending on the train's payload of the freight trains, as occurred in the recent train derailment in Ohio, USA [1]. Less severe natural disasters and hazards can lead to an interruption of transport services for the population and the economy, which results in productivity and monetary losses. Hence, continuous monitoring, modeling, and predictions of the railway infrastructure's performance under the impact of various natural hazards are important for ensuring the resiliency of the transportation network. The importance of this problem for Uzbekistan cannot be overestimated. Uzbekistan is one of only two doubly landlocked countries in the world. Hence, the resiliency of the railway infrastructure is a high priority. To mitigate the risk of failures, Uzbekistan focuses its attention on studying the vulnerability of the transport infrastructure under the impact of natural hazards during the design, construction, and usage phases.

STATE OF UZBEKISTAN'S RAILWAY INFRASTRUCTURE

Railway passenger and freight transportation are one of the highest priorities in the transport sector worldwide. Railways play a significant role in ensuring international trade and economic relationships. Since all countries of Central Asia are landlocked, the railways have a significant effect on the international trade among these countries [2, 3].

The overall length of the railway track in countries of Central Asia is more than 26,185 thousand km, the density of the network is equal to 6.53 km/km^2. By using a number of countries, S.P. Pershin [4] introduced an empiric relationship between the railway network density and the country's overall area:

$$\mathrm{G_c} = (\mathbf{23} + \mathbf{3,5} * \boldsymbol{S})/\boldsymbol{S} \tag{1}$$

where S is the country's overall area measured in millions of km^2.

For example, in Belarus this density is five times greater than that of Central Asia. In the case of Latvia the density is seven times greater than that of Central Asia. The low density of the railways is evidence of a significant lag in the development of the railway network. This lag is one of the reasons for the delay in growth of the region's wealth.

Table 1 shows the density of the railroad network of the Central Asian countries.

№	Country	Area of the territory, S mln. km^2	Operational length of railroads, L, thousand km	Density of the rail network		G_{cc} / G_{ca}
				Actual, G_{cf}	Calculated, G_{cc}	
1	Uzbekistan	0,449	4,64	10,33	54,72	5,30
2	Kazakhstan	2,725	16,61	6,10	11,94	1,96
3	Kyrgyzstan	0,1999	0,424	2,12	118,56	55,90
4	Tajikistan	0,143	0,96	6,71	164,34	24,48
5	Turkmenistan	0,491	3,551	7,23	50,34	6,96
	Central Asia	4,008	26,185	6,53	9,24	1,41

Table 1. The density of the railroad network in the countries of Central Asia

Various engineering structures (ES) are being constructed on the railways of Central Asia, most of which are bridges. A large number of ES is located in seismically hazardous areas of Central Asia [6]. Figure 1 shows the railway network of Central Asia overlayed on a seismic hazard map expressed in earthquake magnitude (MSK scale).

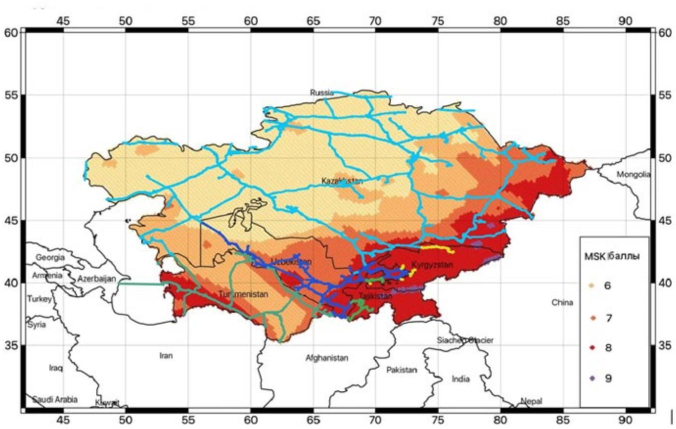


Figure 1. Seismic hazard map of Central Asia with railway network overlay

The railroad network of Uzbekistan is an integral part of the large railway network of the Central Asian countries. In recent years Uzbekistan has built a new railway network with a total length of more than 1,200 km, modernized and reconstructed more than 3,800 km of roads, and electrified almost 1,100 km of railways [3, 5]. Figure 2 shows a map of railways in Uzbekistan.

Figure 2. Map of railroads in Uzbekistan

Table 2 summarizes the railway network of Uzbekistan [5]. As presented in the table, the total length of the railroads is 9,925.8 km, of which 7,420.7 km are for general use.

№	Indicators	Length, km
1	The total length of railroads	9,925.8
	of which are for public use	7,420.7
2	Operating length	4,641.9
3	Length of electrified sections	3,728.6
	of which operational length	1,646.0
	including high-speed sections	718.6

Table 2. Network of railroads in Uzbekistan

Figure 3 shows a histogram of the development of construction and reconstruction of railroads in Uzbekistan presented for four time periods. The first time period covers railways constructed from 1888 to 1920 (1,049 km or 17.65% of the total). The second time period covers railways constructed from 1920 to 1950 (1,245 km or 20.95% of the total). The third time period covers railways constructed from 1950 to 1991 (1,278 km or 21.51% of the total). The fourth time period covers railways constructed from 1991 to 2001 (2,370 km or 39.89% of the total) [5].

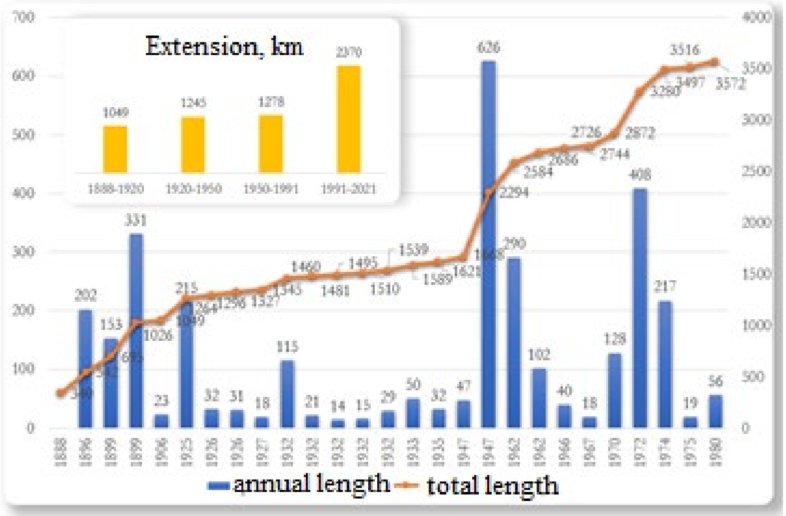


Figure 3. Development of the railroad network in Uzbekistan

As of 2019, there are 1,380 bridges on the main railway lines of Uzbekistan's railway company, Temir Yullari JSC. Of these 1,307 are reinforced concrete bridges, 48 are steel bridges, and 25 are combined or composite bridges. The engineering structures include: railway tunnels (2), pedestrian tunnels (10), footbridges (30), galleries (5), aqueducts (4), pipes (4420) pieces, flumes (386), and culverts (245). The total length of all bridges is approximately 41 km [7, 8]. Table 3 shows engineering structures classified by material and length. Figure 4 presents the same information in a graphical form.

<table>
<tr><th>№</th><th colspan="2">Name</th><th>Quantity, pcs.</th><th>Length, p.m.</th></tr>
<tr><td>1</td><td colspan="2">Total bridges on the main tracks including:</td><td>1,380</td><td>39,157</td></tr>
<tr><td></td><td colspan="2">steel</td><td>48</td><td>599</td></tr>
<tr><td></td><td colspan="2">reinforced concrete</td><td>1,307</td><td>30,014</td></tr>
<tr><td></td><td colspan="2">combined or composite</td><td>25</td><td>3,144</td></tr>
<tr><td>2</td><td colspan="2">Total reinforced concrete spans</td><td>2,511</td><td>-</td></tr>
<tr><td colspan="2">Basic schemes of reinforced concrete bridges</td><td>5 x 6,0 m</td><td>3x16,5 m,
11,5m+23,6m+11,5m</td><td>7x23,6 m,
16,5m+4x23,6m+16,5m</td></tr>
</table>

Table 3. Engineering structures on the railroads of the Republic of Uzbekistan

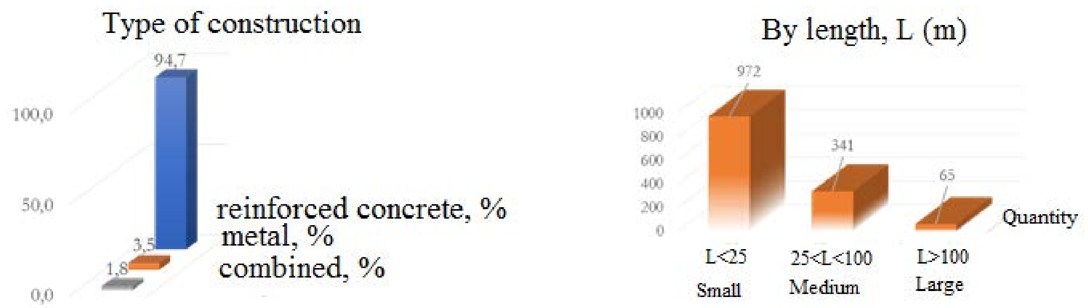


Figure. 4. Classification of engineering structures on the railroads of Uzbekistan

Since 1991, a large number of construction and rehabilitation projects have been conducted for the development of transportation and communication systems. Uzbekistan has ensured the independence of the transportation system and has created a national system linking all of the regions of Uzbekistan. The country's effective transportation system contributes to the development of international economic relations and strengthens integration with neighboring countries.

VULNERABILITY OF RAILWAY INFRASTRUCTURE DUE TO EARTHQUAKES

Uzbekistan is located in a seismically active region. Thus the issue of seismic protection is relevant [9]. Figure 5 shows a map of the general seismic zoning of the territory of the Republic of Uzbekistan.

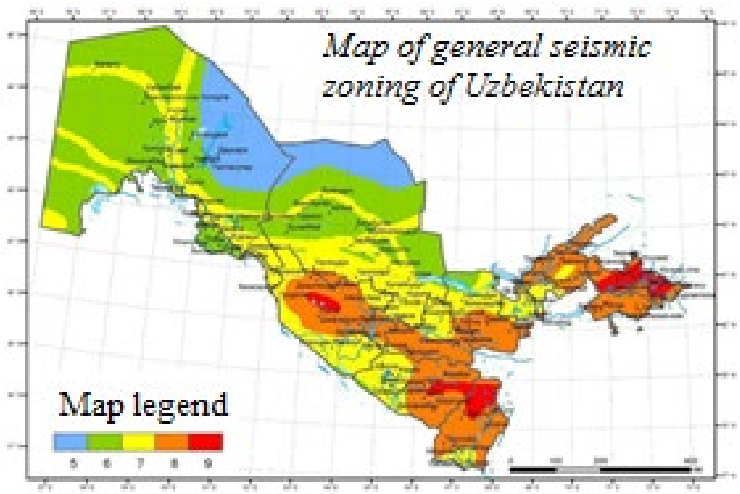


Figure 5. Seismic hazard map of Uzbekistan

Earthquakes are usually caused by tectonic strains in the earth's crust. These strains can accumulate over years. At some point, the tectonic plates slip in respect to each other, resulting in the sudden release of a large amount of strain energy. As a result, seismic waves propagate in all directions. When the waves reach the earth's surface, they cause vibrations in the upper part of the soil layer [10] and thus in all above-ground and underground buildings and structures.

The problem of seismic resistance of bridges and bridge structures is extremely important due to the fact that severe earthquakes can cause damage so they cannot function normally. Depending on the severity of the earthquakes and the construction design bridges can be even destroyed. The bridges and bridge structures are constructed of many elements, the most important of which are piers and bearing parts [6, 10-12].

In Uzbekistan, there are a few natural hazards (related to earthquakes) that can cause the destruction of bridges. These include the discontinuous tectonic displacement of the crust, seismic ground vibrations, landslides, cave-ins, avalanches, mudflows, liquefaction, soil settlement, and many others.

Based on post-earthquake analysis of several severe earthquakes, a few mitigation measures were developed for incorporation into construction practice in order to improve the seismic stability of buildings and structures [13].

Analysis of various data allows us to distinguish two major groups of damage to bridge structures [11, 13-16]:

– *damage to span structures*: their shift on bridge seats, or falling from supports under relatively minor damage to the support.

– *destruction or severe damage to the supports*: resulting in the complete or partial collapse of the bridge.

Worldwide the field of seismic resistance of bridges is in a process of continuous development because humankind learns from each new earthquake, especially from those similar to the February 6, 2023 earthquake in Turkey [17]. The methods of seismic strengthening of bridges are being added to regulatory documents to ensure the bridges' seismic resistance, durability, and reliability. Uzbekistan is part of this worldwide development although its construction code is slightly lagging and does not contain the recent developments in this field (as does the US construction code, for example). This paper is focused on the utilization of seismic protection devices in bridge engineering to stimulate code development.

To facilitate the development of modern construction code and improve design and construction practices, a large research center in Uzbekistan is under consideration. The center will address the infrastructure resiliency in all major transportation-related fields of Uzbekistan: railways, automotive roads, and aviation. In addition to other issues, it will focus on improving the performance of railroads and railway bridges based on comprehensive monitoring, experimental studies, subsequent modeling, and performance predictions via computational simulations. The center will utilize the best practices worldwide, including US practices for the development and validation of measures improving seismic stability. To create a reliable numerical model, the seismic protection device and the design approaches need to be studied in experimental studies. Figure 6 shows an example of component testing of a damping device in the US being evaluated for use as seismic protection [18].

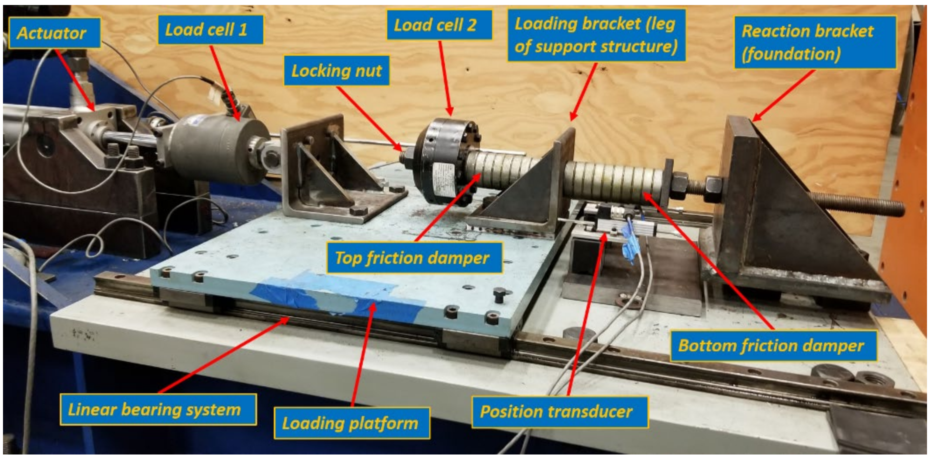
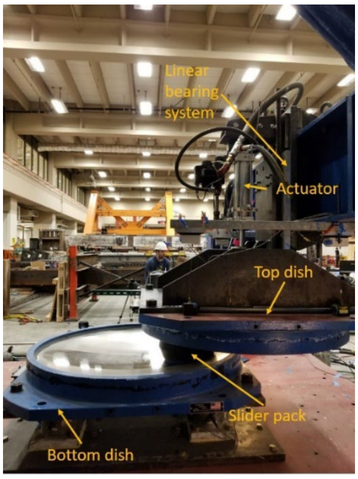
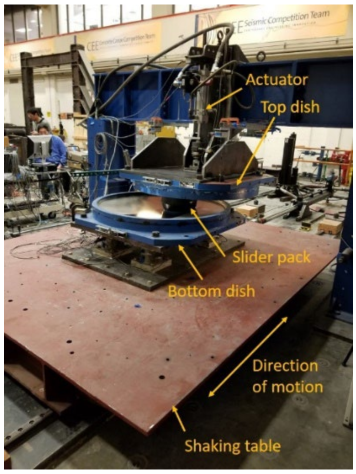


Figure 6. Example of experimental validation of damping device [18]

An example of full-scale component testing of a seismic isolator in the US to be utilized as a seismic protection device [19] is shown in Figure 7.



a) Testing at large displacement cycles



b) Weight of the superstructure is imposed by an actuator

Figure 7. Example of experimental validation of seismic isolation [19]

New damping devices for bridges are continuously being developed and they cannot be used in practice without a validation test (see [20] for example). The design approaches cannot be adopted to practice without rigorous testing to ensure their optimum performance (see [21] for example).

SEISMIC ISOLATION SYSTEM

Seismic isolation is currently one of the main means of ensuring the seismic resistance of bridges, especially for an earthquake intensity of 8 and greater (MSK scale). In this case, compliant or sliding seismic isolation bearings are installed between the superstructure and the support. This solution is well known, however, its application is limited to road bridges at this time.

The limited application is related to concerns over the failure of the track structure on the bridge [12, 14] due to the high buckling of the support parts and the high horizontal forces of the braking load. Nevertheless, there are a few cases of the successful application of seismic insulation of railway bridges in bridge construction practice. Here we can highlight the seismic insulation of the Las Piedras Bridge in Spain and the Northern Railway Bridge in Budapest as well as the Maurer Sohnes Bridge in Greece [16]. Providing a railway bridge with seismic insulation leads to very significant savings in areas with seismic intensity of 8 or more, and the cost of the support construction can be reduced by 40-50 %.

In the bridge construction industry of Uzbekistan, the supports of railway bridges are designed to withstand seismic loads, which in turn leads to both increased loads and the expediency of applying special seismic protection methods. A typical example is the bridges on the Sochi-Adler line designed by OJSC "Transmost" with the seismic insulation system carried out by CJSC "Stroykompleks-5". This is the seismic isolation system considered here, which is represented by the photo and diagram of the supporting part (Figure 8) [6, 22, 23].

This paper examines the longitudinal behavior of a Stroycomplex-5 seismically insulated railway bridge against earthquakes of varying severity and recurrence.

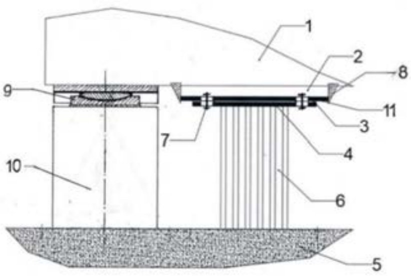


Figure 8: Stroycomplex-5 seismic isolation support system: left - placement of support elements on one of the bridges in Sochi; right - seismic isolation flexible rod package

A movable ball bearing element (9) is installed between the span structure (1) and the support (5) via the sub-bearer (10). Parallel to the support element (9), a seismic bar shock absorber (6), connected via a friction cover (FC), is installed. The complementary sheet (11), freely moving along the vertical axis of the sheet, is connected to the stops (8), which are mounted on the spanning structure (1). In doing so, there is a gap (2) between the seismic isolating element and the superstructure. This approach eliminates the transmission of the vertical load from the superstructure, which is fully absorbed by the movable support element [24].

The developed seismic isolation device provides three degrees of protection for the load-bearing structures of the bridge, shown in Figure 9.

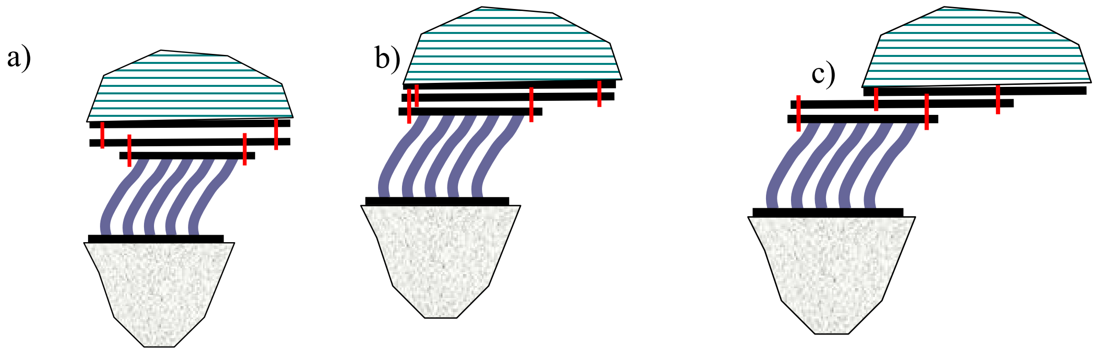


Figure 9: Behavior of seismic protection levels a) level one; b) level two; c) level three

The first level of protection ensures an elastic behavior of all bridge elements under the action of the design earthquake, while the second and third levels of protection do not work during the vibration of the structure. The flexibility of the rod spring can be specified with the guarantee of a limit displacement from the braking load of the rolling stock T_{BRAKE}, equal to U_{lim}. When the seismic load exceeds the elastic capacity (i.e. when plastic deformation takes place) of the rod spring, the second level of seismic protection is activated.

Seismic protection at the second and third levels of protection is provided by friction pendulum bearing connections in the form of bolted connections with oval bolt holes. The operation of these connections is described in detail in publications [25-27]. The difference between the second and third level of protection is the value of the bolt friction force [24]. The friction force of the second level of protection is less than the elastic limit of the stem spring and the support itself. If the seismic load is greater than the above-mentioned friction force value, the bolts of the second level connection start to slide along the oval holes and reduce the peak accelerations in the structure.

DESCRIPTION OF THE BRIDGE DESIGN. RESULTS AND DISCUSSION

This paper considers the technical implementation of a seismic protection for a bridge in the seismic regions of Uzbekistan. The 5-span (5x23,6m scheme) railway bridge with a total length of 128.9 m constructed in the Namangan region, an area with an estimated seismic intensity of 9 (MSK scale), is considered. The scheme of the bridge is shown in Figure 10. It has tall solid supports on a natural base and relatively small and light spans. Since the bridge is sectional, each column operates independently. The seismic protection of the supports in the most dangerous longitudinal direction is considered. In a conventional support solution, a significant horizontal load is transmitted to each support.

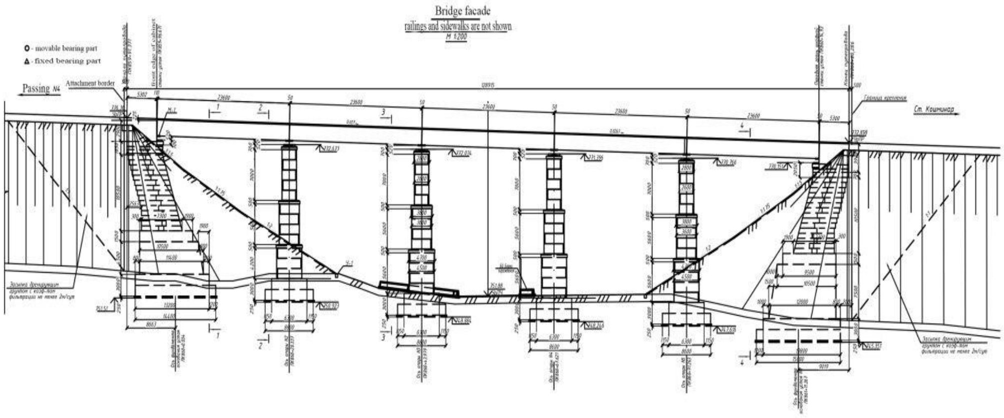


Figure. 10. General view of the bridge

The protection system is applied to the design of bridges with heavy spans [28]. It is impossible to use the superstructure as a dynamic vibration damper (DVD) for the piers because the superstructure's mass exceeds the critical value [14, 29], above which the dampening effect disappears. However, in many cases the DVD effect can be realized. Figure 11 shows the support of a small railway bridge in Uzbekistan under the span L=23 m and mass m=27.5 t.

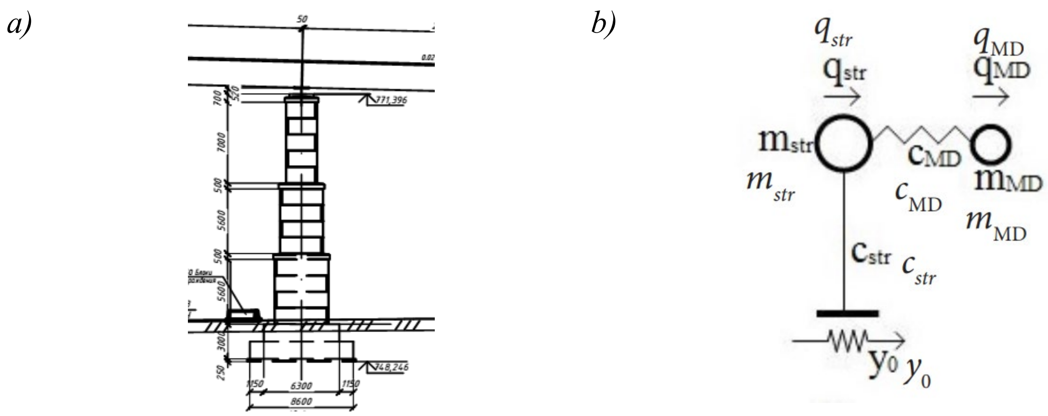


Figure 11. Diagram of railroad bridge support under span L=23,6 m: a) scheme; b) calculation scheme

Since the bridge consists of a few sections, each section works independently. Seismic protection of supports in the most dangerous longitudinal direction is considered. In a traditional bearing design, a significant horizontal load is transferred to each support. Some results of calculations by the linear spectral method (LSM) are given below. For the calculation, a version of the LSM was used which includes corrections to seismic loads due to modal damping [30-32].

The design of the seismic insulation was carried out at Stroykompleks-5 under the supervision of S.A. Shulman. The paper [24] describes the basic provisions of a seismic-isolated bridge design with calculations by the linear spectral method (LSM). Two options of seismic isolation are considered.

In the first type of seismic isolation, the optimum stiffness setting of the superstructure is ensured for its operation in the DVD mode. However, this stiffness setting violates the regulatory requirement limiting the displacement of the span ends from the operational load (braking).

$$u < 0.5\sqrt{L} \tag{2}$$

where L is the span of the bridge in meters and u is the offset of the span in centimeters.

In our case, the limit displacement is approximately 2.5 cm.

SELECTION OF SEISMIC ISOLATION PARAMETERS

The selection of the seismic isolation parameters was carried out by varying the shear stiffness of the supporting part. The dependence of the moment along the foot of the support, calculated using the LSM by taking into account damping, is shown in Figure 12. A case of zero rigidity of the supporting part corresponds to a support without a superstructure. Alternatively in the case when the rigidity is infinitely high corresponds to a traditional support with a rigid supporting element. It is important to note that in this case the effect of dynamic damping of support oscillations occurs. As a result the superstructure acts as a dynamic vibration damper (DVD). The effect is achieved when GF is close to 1000 T. At the same time, the moment along the foot of the support decreases to 1494 Tm. For comparison, the moment M along the foot of the support free from the superstructure reaches 1940 Tm, and with a rigid supporting part, M = 2870 Tm.

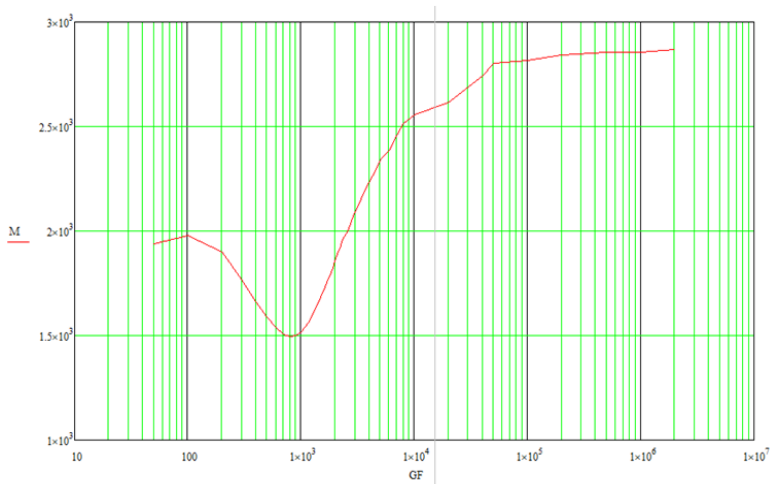


Figure 12. Dependence of the moment along the foot of the support on the shear stiffness of seismic isolation

The graph of the superstructure displacements relative to the support under operational loads are presented in Figure 13. The plot shows te relationship between these displacements and the period of the first fundamental mode of the support vibration.

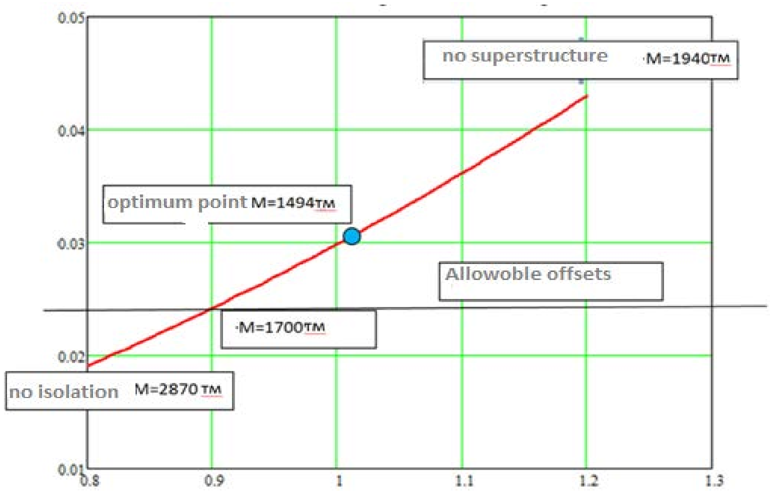


Figure 13. Dependence of the superstructure displacements on the braking load on the seismic isolation rigidity (period of fundamental mode)

Unfortunately, the displacements of the superstructure on the compliant support part exceed the permissible standards in accordance with formula (1). The calculations performed earlier [23, 31, 32] show that it is possible to safely increase the permissible displacement by a factor of two.

CONCLUSION

At present, the worldwide practice of earthquake-resistant construction applies a multi-level approach to the design of seismic-resistant structures. In accordance with this approach, the structure is calculated for several levels of seismic impact at the corresponding limit states. This approach is adopted in Eurocode-8, where it is recommended to consider at least two levels of impact and two limit states: (1) an interruption of normal operation (serviceability limit state (SLS)) and (2) a collapse of the structure (ultimate limit state (ULS)).

The work performed herein shows that the use of seismic protection devices is very effective for railway bridge structures constructed in earthquake-prone areas. Based on the results of this paper it was concluded that for girder railway bridges the most effective seismic protection is a combination of elastic elements with friction pendulum bearings. In this case, the spans are supported by the friction pendulum bearings, and seismic elastic elements reduce the demand in both horizontal directions. Hence, due to the use of seismic isolation devices, it is possible to increase the reliability of the bridge under seismic impact. Moreover, the use of seismic isolation devices results in a reduction in use of basic building materials by about 30% and as such, can result in a reduction of the construction cost by about the same percentage.

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