SHAKING TABLE TEST OF LARGE SCALE BRIDGE MODEL CONSTRUCTED WITH NEW ADAPTIVE IMSO-SYSTEM FOR SEISMIC PROTECTION

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ABSTRACT

In the frame of recent innovative NATO SfP project, extensive research activity have been focused on development and experimental validation of new, highly efficient, bridge seismic response modification system. The proposed adaptive IMSO-system was developed based on integration of the innovative Multi-Level Multi-Directional Seismic Energy Dissipation concept into Globally Optimized Seismic Energy Balance (GOSEB) system. The created adaptive IMSO-system for seismic protection of bridges represents important technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control. With the achieved advanced seismic protection performances, in compliance with the actual seismic input energy, complete seismic protection of highway bridges is provided, even under the strongest earthquakes. In this paper briefly are shown the original results obtained from conducted extensive experimental and analytical research devoted to development and validation of the new advanced method for seismic upgrading of new and existing bridges, including practical application of the adaptive IMSO-system. The existing prototype bridge considered herein for innovative seismic upgrading represents typical classical system commonly used in south-east Europe during middle years of the 20th century, mostly designed without consideration of seismic loads. It was confirmed that, with installation of optimally designed new adaptive IMSO-system, the analyzed specific non-seismic bridge can be efficiently upgraded and converted to seismically resistant structure for expected seismic effects in its location. The actual nonlinear behavior features of all integrated components in the original IMSO-system have been successfully considered in the formulated advanced phenomenological analytical model.

Keywords: Seismic shaking table; Bridges; passive devices; seismic isolation; response modification

1. INTRODUCTION

The high seismic risk of transportation networks in South East Europe (SEE) is a serious threat to public safety, sustainable economic and social development and security in the region. This risk has not been quantified to this date and sound seismic risk mitigation concepts are not available. Most of the existing bridges are constructed as non-seismically resistant and are older than 40 years, so that they are highly vulnerable to seismic loads and require immediate, reliable and cost-effective seismic upgrading. Regarding this, large international NATO Science for Peace Project “Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)”, led by the third author, was carried out including realization of fundamental research devoted to development of an innovative

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technology for seismic protection of bridges. Extensive experimental quasi-static and shaking table tests have been conducted at the DYNLAB (Dynamic testing laboratory) of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University SS Cyril and Methodius, Skopje. The extensive research activity of this innovative NATO SfP project have been focused on development and experimental validation of efficient new bridge seismic response modification system. The proposed adaptive IMSO-system was developed based on integration of the innovative concepts of Multi-Level Multi-Directional Seismic Energy Dissipation and Globally Optimized Seismic Energy Balance (GOSEB) system. The created adaptive IMSO-system for seismic protection of bridges represents important technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control. With the advanced seismic isolation and seismic protection performances, in compliance with the actual seismic input energy, advanced seismic protection of bridge structures is provided, even under the strongest earthquakes. In this paper briefly are presented original experimental results from the conducted shaking table tests of large scale bridge model originally constructed with scaled prototype of new adaptive IMSO-system for seismic response modification and tested with simulated very strong real earthquakes. It was confirmed that the proposed seismo-safe IMSO-system is capable for efficient seismic protection of bridge structures under very strong future earthquakes. The realized long-term project resulted in creation of important innovative end-products, including: experimental verification of prototypes of seismic isolation devices, experimental verification of prototypes of energy dissipation components and devices and experimental verification of prototypes of displacement limiting devices. To demonstrate practical application capability of the developed IMSO system, in the paper are briefly presented the obtained results from conducted analytical study demonstrating seismic upgrading of an specific existing bridge constructed before 40 years as non-seismically resistant structure.

2. GENERAL CONCEPT OF ADAPTIVE IMSO-SYSTEM

The basic concept of the adaptive seismic response modification IMSO-system, Figure 1, for improved seismic protection of bridges, Figure 2, is based on general globally optimized seismic energy balance (GOSEB-approach) including optimal integration of advantages of three basic devices: (1) Seismic isolation (SID); (2) Seismic energy dissipation (EDD) and (3) Displacement limitation devices (DLD). First, the optimized seismic isolation devices (SID) are used to achieve effective bridge isolation and essential seismic response modification. Scaled models of four different types seismic isolators have been constructed and experimentally tested under cyclic loads, including: circular laminated rubber isolation devices (CI-LRID), square laminated rubber isolation devices (SQ-LRID), double spherical sliding isolation devices (DSSID) and double spherical rolling isolation devices (DSRID). Each type can be practically adopted based on implementation of advanced design process. Applying expert knowledge, the designers will be able to perform successful selection of the appropriate types and characteristics of seismic isolators. Considered type in the present study is shown in Figure 3 and Figure 6. Second, scaled models of the new multi-level multi-directional energy dissipation devices (EDD) are constructed and experimentally studied with seven optional types (HC-EDD, HS-EDD, V-EDD, VM-EDD, C-EDD, SF-EDD and SB-EDD) and they are invented to achieve unique energy absorption features, i.e. to be capable of adapting their behavior to the actual intensity of seismic input energy.
Actually, the new hysteretic energy dissipation devices are able to provide the most innovative and advanced features of multi-level earthquake response in all directions considering adopted variable gap concept. Considered type in the present study is shown in Figure 2 and Figure 7. Third, the models of optimized displacement limitation devices (DLD) are constructed and experimentally studied with two optional types (hysteretic, H-DLD & rubber, R-DLD). Their application proved very effective and efficient limitation of excessive displacement of bridge superstructure under very strong earthquakes. Considered type in the present study is shown in Figure 5 and Figure 8.

3. SHAKING TABLE TESTS OF PROTOTYPE BRIDGE MODELS WITH IMSO-SYSTEM

The successfully realized extensive experimental shaking table test program included creation, construction and testing of various options of innovative large-scale bridge models on seismic shaking table with incorporated all related prototypes of innovative IMSO response modification systems for seismic protection of bridges. The results from the completed experimental seismic shaking table tests are considered as basic realistic data for experimental validation of the actual response modification performances and generated efficiency of the created different options of the innovative bridge.
systems applicable for seismic upgrading of existing bridges and seismic protection of new important and large bridge structures located in seismic active regions. The designed basic bridge model (BM) has been very successfully accommodated for specific and multi-purpose use providing very realistic results for full experimental validation of the proposed different response modification technologies for seismic protection of bridges. The model was constructed in the scale 1/9, and consequently for conducting planned seismic shaking table tests, the considered input earthquake record was time-compressed by scaling factor 1/3. The dynamic shaking table tests were carried out using selected records of the following earthquakes: (1) El Centro, (2) Landers, (3) Northridge and (4) Petrovac. The input records were scaled both in time and intensity according to the theory of similarity for physical models. On Figure 9 presented is selected representative acceleration time history response recorded at measuring channel ACC-01, from shaking table testing of Bridge Model-1 (BM1) with integrated seismic energy dissipation devices (EDD) of H-type, EDC type 1.2. The channel ACC-01 was used to record acceleration response at the top left side of the RC bridge deck, exactly in the direction of activation of the shaking table, i.e. under 45 degrees in respect to the bridge model. On Figure 10 presented is selected representative displacement time history response recorded at measuring channel LVDT-01, from shaking table testing of Bridge Model-1 (BM1) with integrated seismic energy dissipation devices (EDD) of H-type, EDC type 1.2. The channel LVDT-01 measured the displacement at the top left side of the RC deck, exactly in the direction of activation of the shaking table, i.e. under 45 degrees in respect to the bridge model. The shaking table input earthquake record Petrovac was scaled to maximal acceleration level of PGA=0.7g.

From the realized extensive experimental shaking table tests of large-scale bridge prototype models composed with different options of innovative response modification IMSO system, obtained are original, highly valuable and consistent results providing full evidence in advanced capabilities of the proposed IMSO technology for seismic protection of bridges.

4. MODELING AND SEISMIC EVALUATION OF EXISTING PROTOTYPE BRIDGE

4.1 Description of the selected bridge structure

The selected representative structure is a reinforced concrete viaduct with five spans and total length of L=2*16.9+3*21.1m=97.1m. The viaduct is located at km 10+524.85 of the М-26 road, section Gostivar-Kicevo, Figure 11 and 12. According to the project documentation, the bridge is constructed as a classical frame structural system cast in place. The superstructure of the bridge consists of two main longitudinal girders with height h=1.40m constructed at a distance of e=6.10m, secondary transverse girders (located at every support and also three or four along spans) and reinforced concrete slab with width b=9.6m and thickness of dp=0.18 m. The longitudinal section of the bridge is shown on Figure 12, while in Figure 11 is given bridge view.
The bridge substructure includes box type abutments cast in place and middle supports each consisting of two RC piers with circular cross section, $D=1.0\,\text{m}$, founded with single footings, Figure 12. The pier heights vary between 10.1m and 17.9m. Both end supports of the bridge are movable bearings in longitudinal direction, while middle piers at both ends are with fixed connection. In plane, the bridge forms a horizontal curve with small radius of $R=70.0\,\text{m}$. The transverse slope of the bridge deck is 6.4%. The vertical alignment of the bridge deck has a small gradient also. The piers and the abutments of the bridge are founded on stiff rock foundation with bearing capacity of $\sigma_0=3.5\,\text{MPa}$. The RC structure is constructed with concrete grade MB30, except for the wing walls which are built with concrete grade MB45 and the footings which are built with concrete grades MB10 and MB22. The reinforcement steel used for the structure is of grade C240/360. The selected existing viaduct considered in this study is about 40 years old and presently is in regular traffic function.

### 4.2 Modeling and seismic evaluation of existing prototype bridge

To achieve advanced seismic safety evaluation of the existing structure formulated was 3D nonlinear mathematical model incorporating the real geometrical, physical and material characteristics of the bridge.

![Computed interaction relation moment-axial force (M-N) for piers S2 and S5](image)

![Moment-curvature (M-\(\phi\)) relations for piers S2 and S5 under different axial (N) forces](image)

![Dynamic characteristics of the bridge structure: a) Mode shape 1 and b) Mode shape 2](image)
The RC deck was modeled with shell finite elements while for the bridge girders, beams and columns were used 3D beam finite elements. The connection between the super and sub-structure was modeled as fixed while end supports where considered as movable bearings. Potential plastic hinges were modeled as non-linear at both ends of middle piers (two cross-sections, one at the foundation level and one at contact with longitudinal and transverse beams of the superstructure). Nonlinear behavior of the cross-sections representing potential plastic hinges was modeled based on specified family of moment-curvature (M-\(\phi\)) relations, Figure 14, defined for several levels of axial forces in order to include variation effect of axial forces and also based on computed axial force-moment (N-M) interaction diagrams, Figure 13. Boundary conditions of middle piers and abutments were considered fixed due to high bearing capacity of the foundation soil, while the end supports of the superstructure upon abutments was modeled by springs realistically simulating behavior of the RC movable bearings. The main objective of the analysis was realistic evaluation of seismic resistance of the structure, defining the minimal seismic intensity expressed by PGA level, at which total failure of the structure occurs. From the analysis of the dynamic characteristics defined are periods and mode shapes of the bridge. Mode shape-1 with period \(T_1=0.850\)sec has vibrations dominantly expressed in transverse direction of the bridge, Figure 15a. Mode shape-2 with period \(T_2=0.778\)sec, has vibrations dominantly expressed in longitudinal direction, Figure 15b. Mode shape-3 with period \(T_3=0.517\)sec, has vibrations dominantly expressed as torsion representing rotation of the bridge superstructure. In the second phase, conducted was respective study of seismic resistance capacity of the structure by implementation of several earthquake records and iterative nonlinear analysis procedures. For each earthquake record, defined was maximum level of peak ground acceleration (PGA) for which the structure remains non-collapsed, i.e., defined was structural state just before total failure.

![Time history response of displacement dx of top of pier S4L in longitudinal direction](image16)

![Time history response of axial force N (kN) at the bottom of pier S5D](image17)

![Hysteretic response MX-\(\phi\)X of pier S5L, bottom section, in T-direction (no failure)](image18)

![Hysteretic response MX-\(\phi\)X of pier S5L, bottom section, in T-direction (failure)](image19)

In this paper are included only selected characteristic results obtained from the performed iterative nonlinear analysis of the bridge under real Ulcinj-Albatros earthquake record recorded during the Montenegro earthquake of 1979. In this case, obtained are the following main findings: (1) Complete failure of the structure occurs only if maximum acceleration level in global direction is PGA_{gl}>0.14g,
(2) If maximum acceleration level is PGA_{gl}<0.14g, failure of the structure does not occur, and (3) For PGA=0.14g reached is stage just prior to total failure. Such seismic intensity was simulated by simultaneous application of two scaled identical acceleration records in transversal x-direction and longitudinal y-direction of the bridge, as projections from global direction considered at angle 45°. It means that the stage just prior to failure is reached for applied seismic input with PGA_{x}=PGA_{y}=0.10g, simultaneously in longitudinal (x) and transversal (y) direction. In Figure 16 shown is the time history response of displacement dx(m) at the top of pier S4L in longitudinal direction of the bridge for Ulcinj-Albatros earthquake input with PGA=0.14g. The obtained maximum displacement is dx,max=0.032m. From time history response of acceleration ay (m/sec²) at the top of pier S4L in the transverse direction, also under Ulcinj-Albatros earthquake with PGA=0.14g, stage just prior to failure, defined is maximum acceleration ay,max=1.39m/s². In Figure 17 is shown the time history response of the axial force N (kN) at the base of pier S5D, under the effect of the Ulcinj-Albatros earthquake with PGA=0.14g. The values of the axial force range from N_{min}=-1280.60kN to N_{max}=-2523.79kN. Shear force FX (kN) at the base of pier S5L in L-direction, is ranging from FX_{min}=-387.45kN to FX_{max}=289.91kN, for the same earthquake input. Finally, in Figure 18 is shown hysteretic responses of the bottom cross-section of the middle pier S5L in T-direction just prior to failure due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.14g, demonstrating that total collapse does not occur. Comparatively, in Figure 19 is shown hysteretic responses of the bottom cross-section of the middle pier S5L in T-direction due to Ulcinj-Albatros earthquake record scaled to PGA=0.15g, demonstrating now total pier collapse and most probably the whole structure.

5. SEISMIC EVALUATION OF UPGRADED BRIDGE WITH IMSO-SYSTEM

5.1 Seismic upgrading concept of prototype bridge with IMSO-system

Modification of the bridge structural system begins with separation of the bridge superstructure and substructure and formation of a seismic joint in which seismic isolation and seismic energy dissipation devices are built-in. With the separation of the superstructure and the substructure of the bridge, the boundary conditions of the middle piers are changed from a double fixed to a single fixed, i.e. cantilever system. To get an insight into the effects of the new IMSO-system for seismic upgrading of the “non-aseismic” structural system of the previously analyzed existing bridge, an optimal concept for defining an adequate IMSO-system was implemented. Taking in consideration the specific characteristics of the existing bridge, the IMSO-system was formulated as follows (Figure 20 & Figure 21):

1. Basic seismic isolation system was formed by installation of two seismic isolators over each of the six supports. This system consists of seismic sliding bearings (DSSID) with two spherical surfaces with large radius and minimal friction for the purpose of minimizing the friction force and protect the weak middle piers that are characterized by quite low (limited) moment bearing capacity of the fixed to support critical cross-sections;
(2) Seismic energy dissipation system was incorporated with special treatment of the supports considering different characteristics of the middle piers and the end supports, (Figure 20, Figure 21, Figure 22 & Figure 23), as follows: I. “Strong” seismic energy dissipation devices of HC-type with higher yielding capacity with two levels of activation were used above the bridge abutments S1 and S6. The seismic energy dissipation components at both levels were appropriately designed to safely receive the generated horizontal forces and to provide required level of seismic energy dissipation in accordance with the earthquake intensity; II. “Weaker” seismic energy dissipation devices of HC-type with lower yielding capacity, with two levels of activation were used above the shortest middle piers S2 and S5. The seismic energy dissipation components at both levels were appropriately designed to sustain large generated horizontal forces that could cause failure of the short middle piers; III. No seismic energy dissipation devices were used above the longest middle piers S3 and S4 in order to prevent increase of the horizontal forces transferred to the central piers in which case present is only the low isolator friction force that will not cause failure of the longest and the most flexible piers.

(3) Displacement control system was not herein introduced explicitly, but its role was given to the stronger energy dissipation components from the second level of the energy dissipation devices installed on the abutments S1 and S6.

5.2 Modeling and seismic evaluation of upgraded bridge with IMSO-system

The nonlinear behavior of cross-sections representing potential plastic hinges was modeled in the same way as previously, using the same specified moment-curvature (M-ϕ) relations for different levels of axial forces in order to include variation effect of axial forces, Figure 14 and the same axial force-moment (N-M) interaction diagrams. Figure 13. The only difference in this case was the location of the potential plastic hinges, actually they were considered only at the bottom critical cross-sections of the middle piers. From the new analysis of the dynamic characteristics defined are periods and mode shapes of the modified bridge structure. Mode shape-1 with period $T_1=0.914s$ has dominant vibrations in transverse direction of the bridge, Figure 24a. Mode shape-2 with period $T_2=0.773s$, has dominant vibrations in longitudinal direction, Figure 24b. Mode shape-3 with period $T_3=0.546s$, has dominant vibrations expressed as torsion representing rotation of the bridge superstructure.
With the performed analytical research implementing the formulated phenomenological nonlinear analytical model, it was derived that the new modified bridge system could sustain the increased Ulcinj Albatros earthquake intensity, i.e., it remained stable under the defined earthquake level reaching the value of even PGA=0.42g. In this way, the modified structural system with the built-in IMSO-system becomes seismically resistant to a satisfying level, without any need for strengthening of its substructure. The state of the modified structural system of the bridge defined with performed nonlinear analysis of the seismic response to the Ulcinj Albatros earthquake with peak acceleration of PGA=0.42g is presented further in the text through the selected characteristic results. In Figure 25 shown is the time history response of displacement dx(m) at the top of pier S4L in longitudinal direction of the bridge for Ulcinj-Albatros earthquake input with PGA=0.42g. The obtained maximum displacement is dx,max=0.073m. In Figure 26 shown is the time history response of acceleration ay (m/sec^2) at the top of pier S4L in the longitudinal direction of the bridge, also under Ulcinj-Albatros earthquake with PGA=0.42g. The obtained maximum acceleration is ax,max=9.03 m/s^2.

Figure 25. Time history response of displacement dx (m) at the top of pier S4L in longitudinal direction

Figure 26 Time history response of acceleration ay of top of pier S4L in longitudinal direction

Figure 27 Hysteretic response MX-ϕX of bottom plastic hinge of pier S5L in L-direction (no failure)

Figure 28 Hysteretic response MX-ϕX of bottom plastic hinge of pier S5L in T-direction (no failure)
In Figure 27 and Figure 28, respectively are shown hysteretic responses of the bottom cross-section of the middle pier S5L in longitudinal direction and S5L in transversal direction due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g, demonstrating that collapse does not occur.

In Figure 29 is shown hysteretic response of seismic isolator above abutment S1L in longitudinal direction of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g. The obtained maximal force equals to FXmax=120 kN, and the maximal value of the displacement Dmax=5.4 cm. In Figure 30 is shown hysteretic response of seismic isolator above shortest middle pier S5L in transversal direction of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g. The obtained maximal force equals to FXmax=120 kN, and the maximal value of the displacement is Dmax=2.8 cm.

In Figure 31 and Figure 32, respectively, are shown hysteretic responses of seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above abutment S1 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g. The obtained maximal axial force for the component HC1 from level-1 equals to Nmax=676.7 kN, with maximal value of the displacement of Dmax=2.3 cm. The obtained maximal axial force for the component HC1 from level-2 equals to Nmax=1411.6 kN, with maximal value of the displacement of Dmax=0.97 cm.

In Figure 33 and Figure 34, respectively, are shown hysteretic responses of seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above shortest middle pier S5 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g.
The obtained maximal axial force for the component HC1 from level-1 equals to Nmax=5.0kN, with maximal value of the displacement of Dmax=0.18 cm. The obtained maximal axial force for the component HC1 from level-2 equals to Nmax=1.7kN, with maximal value of the displacement of Dmax=0.026 cm. In Figure 35 and Figure 36, respectively, are shown gap-hook responses for seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above the abutment S1 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGA=0.42g. The obtained maximal axial force for the gap-hook element for component HC1 from level-1 equals to Nmax=7535.4kN, with maximal value of the gap designed to equal Dmax=1.5 cm. The obtained maximal axial force for the gap-hook element for component HC1 from level-2 equals to Nmax=2785.9kN, with maximal value of the gap designed to equal Dmax=3.0 cm.

6. CONCLUSIONS

Concluding remarks regarding innovative NATO project: From the conducted research activities in the frame of the realized innovative long-term NATO SIP research project, the following end products and goals have been successfully achieved: (1) Developed is a new highly efficient bridge seismic protection system (IMSO-System), with efficient 56 technological options, based on innovative integration of concepts of Multi-Level Seismic Energy Dissipation and Globally Optimized Seismic Energy Balance; (2) Mobilized is scientific potential in the region for advanced solving of NATO and society policy related complex safety problems including the actual topic of seismic upgrading of existing bridges; (3) Created is improved Cross-Border cooperation and regional approach for realization of development projects; (4) Promoted is application of the advanced technologies for seismic protection of bridges; (5) Achieved is reduction of the necessary financial resources; (6)
Promoted is harmonization of safety and security level; (7) Promoted is concept for successful and application of European standards; (8) Provided is own innovative scientific contribution to seismic protection of bridges; (9) Contributed is to motivation of end users toward application of innovative technologies; (10) Provided is strong impetus to scientific staff and young researchers toward development and application of advanced technologies through successful international cooperation, using recently established ReSIN Laboratory in Skopje.

**Concluding remarks regarding seismic safety of existing classical bridge:** From the performed detailed nonlinear analyses of the existing bridge designed with application of a classical structural system, the following important remarks and conclusions can be drawn: (1) The classical structural system of the analyzed existing bridge is characterized by very low seismic resistance, or more precisely, it shows a very high and economically unacceptable seismic risk due to the high level of vulnerability to earthquake effects; (2) Under the effect of the Ulcinj-Albatros earthquake, the classical structural system experiences total failure at unacceptably small PGAs. More precisely, under all levels higher than $\text{PGA} > 0.14g$, i.e., $\text{PGA}_x > 0.10g$ and $\text{PGA}_y > 0.10g$, the structure experiences failure in the shortest pair of middle piers, as presented on Figure 12 and Figure 13. The failure occurs when the PGA of the Ulcinj-Albatros earthquake is $\text{PGA} = 0.15g$, i.e., $\text{PGA}_x = \text{PGA}_y = 0.106g$. The maximal value of the bending moment at the bottom critical cross-section at the moment of failure is $M_{\text{max}} = 2097.8 \text{kNm}$; (3) With such realistic insights, it can be concluded that many infrastructure networks in the Balkan region and Southeast Europe are characterized with high to very high seismic risk since most of the existing bridges are designed as classical structural systems and do not possess a satisfying level of seismic safety and (4) To reduce the high seismic risk of existing bridge structures, it is necessary to perform detailed reevaluation of their seismic resistance levels in order to define optimal measures for conducting of their efficient and highly needed seismic revitalization and upgrade activities.

**Concluding remarks regarding seismic safety of upgraded IMSO-bridge:** Based on the derived and presented results from the carried out extensive analytical research, one could get a clear insight into the seismic response characteristics of the modified existing bridge by installation of the new IMSO-system. The most important conclusions can be summarized as follows: (1) The installation of the new IMSO-system into the existing traditional structural system enables a very important modification of the seismic response of the new system in a positive and desired way; (2) The existing structural system of the bridge characterized by very low seismic resistance was successfully seismically upgraded by installation of the optimal IMSO-system to the extent that it can remain seismically safe even under the effect of strong earthquakes with peak accelerations of up to $\text{PGA} = 0.42 \text{g}$; (3) The optimal design of the seismic isolation and seismic energy dissipation devices and their adequate distribution over the structural system enabled their adaptable activation and generation of several lines of defense leading to improvement of the seismic safety of the integral structural system and (4) The application of the new IMSO-system in the design procedure of new bridge structures will enable extraordinarily qualitative success. Actually, it will highly increase the level of bridge seismic protection since all the components of the system can be optimally designed.

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8. REFERENCES


