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DECIDING THE ORDER OF INTERVENTIONS ON THE STRUCTURE OF REINFORCED CONCRETE (RC) BRIDGES FOR EARTHQUAKE CONDITIONS

SUMMARY

A multitude of existing bridges fail to meet the criteria of seismic resistance, as designed according to inadequate regulations, which eventually led to the reduction in their resistance. This practice requires interventions (rehabilitation or strengthening) conducted on their structure, which in turn requires developing methods of assessment of seismic performances of existing reinforced concrete (RC) girder bridges. Due to budget constrains it is impossible to strengthen all the bridges, so that a list of priorities is necessary to be drawn. The rank of a specific bridge in this list is stated by the importance of the road, age of the bridge, technical regulations according to which the bridge was designed and the condition of vital support elements. Ranking requires conducting multi-criteria optimization. This paper is focused on overpass, which is used to demonstrate the developed methodology.

Key words: bridges, multi-criteria optimization, strengthening, seismic resistance

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1. INTRODUCTION

Assessing a bridge damaged by earthquake presents a complex engineering, technological and economic problem to be solved by analyzing a number of parameters in the process of making an optimum decision. Some of the key aspects of solving this problem are related to the creation of adequate numerical models of the damaged bridge structure and application of nonlinear methods, taking into account modern design rules and regulations. On the other hand, it is necessary to consider a substantial number of potential interventions on the bridge based on which the structure can be efficiently restored to its initial condition (rehabilitation) that preceded the incidental situation or improving the properties (strengthening) to meet the new requirements. However, in addition to the engineering aspects of this complex issue, the economic aspects have also particular importance; they are reflected through the effects of intervention costs, the choice of the method and analysis of the period of time required for interventions on the bridge structure. Taking into account the fact that the above parameters can be related to the attributes of "minimum", "maximum" as well as "optimum", several possible situations can be established, with the following being the most important: minimizing the intervention costs, maximizing the method's quality and implementation in order to increase the safety of the bridge structure. The relation between the method and costs of intervention, as well as the time required for implementation, is also optimized, and a combined model of relation between the above defined three parameters has been introduced.

If the problem is analyzed by considering a larger number of damaged bridges on roads of different categories, different service conditions and levels of maintenance, and if the bridges were designed according to regulations that have changed over time, a complex engineering and mathematical problem occurs with a large number of parameters. The solution to these problems can be found in the application of the MCDM approach (*Multi-Criteria Decision Making*). Given the almost omnipresent budget constraints, additional requirements occur when deciding on priorities and choosing the method of rehabilitating damaged bridges. Today, there are a considerable number of multi-criteria optimization methods in which the solution for a multi-criteria problem is obtained by choosing the best alternative from a set of predefined alternatives (multi-attribute decision making) or programming the best alternative (multi-objective decision making) (Kabir et al. 2014). Among the multi-attribute decision making methods, the most popular are the TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*), CP (*Compromise Programming*), VIKOR (*Multi-criteria Compromise Ranking*), ELECTRA (*Elimination Et Choix Traduisant la REalité*) and PROMETHEE (*Preference Ranking Organization METHod of Enrichment Evaluations*).

In (Yousefi et al. 2013) the VIKOR method had been used for determining the priority of earthquake-damaged bridges for strengthening based on the criteria: age of the bridge, average annual daily traffic, distance of alternative traffic routes, and connections with the other transportation infrastructure. Aiming at establishing the priority for rehabilitation of earthquake-damaged bridges using the TOPSIS multi-criteria optimization, (Yousefi et al. 2014) is based on the following criteria: structural vulnerability, seismic hazard, years of service, average annual daily traffic, connections with other transportation infrastructure, alternative routes and the importance of the bridge. Given that a large number of bridges were designed according to old regulations or without introducing aseismic design, (Bradshaw et al. 2011) discusses the MCDM method taking into account the increase in structural performance (ductility and capacity) along with the reduction in rehabilitation costs. Solutions obtained using the VIKOR and TOPSIS method and their applicability and effectiveness in assessing the structural rehabilitation are presented in (Caterino et al. 2009). The model of multi-parameter economic evaluation of the lowest price and the shortest time of rehabilitation/strengthening the earthquake-damaged bridges is analyzed in (Cheng and Wu 2007). A research project on multi-criteria optimization of the damage to bridges is presented in (Patidar et al. 2007), with the optimization being discussed for a single bridge and a group of bridges.

Given that the problem of strengthening the structure of RC bridges can be taken into consideration and presented as a discrete mathematical problem, this research is based on the VIKOR method. The multi-parameter analysis was conducted in order to determine priority bridges as well as methods for their rehabilitation, taking into account the aspects of minimum costs and time required for rehabilitating/strengthening.

2. ENGINEERING AND SOCIO-ECONOMIC PARAMETERS AND CHOOSING THE METHOD OF BRIDGE REHABILITATION

The development of methodology of multi-criteria analysis in the rehabilitation/strengthening of damaged RC bridge structures is based on taking into account some relevant parameters, such as: bridge database, base of geotechnical, geophysical and seismic soil data on which bridges are built. It is necessary to collect data about the bridges in service conditions (measurements and tests), to provide a description and classification of damage to the structure, and conduct numerical analyses for getting an insight into their condition situation and making decisions on interventions. Furthermore, a detailed description of the developed methodology is provided. The target group of RC bridges analyzed in the present research were overpass (over roads and railways), damaged by earthquake conditions. For this purpose multiple databases were used.

The database of RC bridges for which the monitoring is conducted and decisions made about interventions:

- database created in an object-oriented software environment with the possibility of intervening on existing conditions and introducing new conditions in bridges,
- a brief presentation of the technical documentation of RC bridge structures along with technical reports;
- visual presentation of bridges with details on location, GPS coordinates, *Google* Maps, and local and global coordinates of road infrastructure,
- photo documentation of bridge structures in service conditions,
- damage to bridge structures shown in the layout drawings,
- details on damaged bridge structures (photographs and technical drawings),
- possibility of exchanging data with the existing bridge databases.

Base of geo-technical, geo-physical and seismic data on soil where the RC bridges were built:

- data from geo-technical and geo-physical studies on micro locations where the bridges were built: geo-technical soil profiles, mechanical properties of the soil by layers, geo-seismic properties of the soil (velocity of wave propagation by soil layers, etc.),
- data on micro-seismic reionization,
- seismic hazard maps for the areas where the bridges are located,
- data from the project documentation of importance for the seismic of bridges: maximum design ground acceleration at the surface and on the bedrock, design response spectra, regulations based on which the bridges were designed, and the like.

Detailed visual macroscopic inspections with photographic documentation of bridges (collecting data about the bridges in service conditions):

- detailed visual macroscopic inspections: transport infrastructures of bridges, drains and drain pipes, protective fencing, final asphalt road surfaces, insulation, bridge access structures, traffic profiles, expansion joints, base plates and supports,
- detailed visual inspection of protective concrete layers and preliminary in situ tests,
- detailed visual macroscopic inspections: span structures-deck (beams, plates, stiffeners), vertical elements (columns), abutments, foundations, head plates, piles (if visually available) of the bridge.

Measurements and tests (preliminary non-destructive testing):

- *Ambient Vibration Tests*,
- measuring horizontal and vertical bridge deformations in service and in unloaded conditions for their implementation in numerical models through the initial bridge imperfections and initial node displacements,
- *Pile Integrity Tests*.

Description and classification of damage to bridge structures and possibly foundations:

- damage identification and classification: no damage, minor damage, significant damage, major damage, local/global fracture/collapse (Cooper et al. 2006),
- damage description: barely visible cracks, visible cracks, larger cracks with concrete spalling, very large cracks with extended zones of concrete spalling, visible deformations in the bridge structure (Cooper et al. 2006).

Numerical analyses of bridge structures:

- selecting accelerograms from the database,
- generating and processing artificial and/or synthetic accelerograms,
- scaling and spectral matching of accelerograms and response spectra,
- modelling bridge structures based on the collected data, taking into account the damage to the existing bridges,
- numerical tests of ambient vibrations,
- *Linear Dynamic Analyses* of individual bridge structure eigenforms (damage assessment by eigenforms in the time domain),
- *Spectral-Modal Analyses* of bridges,
- *Incremental Nonlinear Dynamic Analyses* (assessing the current state of bridge structures for earthquake conditions up to the collapse level in time and capacitive domain),
- *Nonlinear Static Pushover Analyses* (assessing the current state of bridge structures for earthquake conditions up to the collapse level in capacitive domain),
- analyses of performance states of damaged elements and the complete bridge structure,
- analysis of vulnerability and reliability of damaged bridge structures on probabilistic level.

Assessing the state and making decisions on interventions to be made on bridge structures:

- pointing out the defects (errors) in the design, construction, and as a result of inadequate maintenance and use,
- analyzing the compliance of the state of existing bridges with current regulations in the area of bridge structure design,
- assessing the state of bridges by identifying their bearing capacity and deformations up to the level of collapse,
- creating an algorithm on the state and interventions to earthquake-damaged RC bridge structures,
- deciding on interventions: no rehabilitation required, local-level repairs can be carried out, rehabilitation to a lower extent, significant rehabilitation required, part of the structure or the entire structure need to be replaced,
- deciding on additional strengthening or changing the static systems of bridge structures: application of FRP strips, increasing the cross-section, introducing pre-stressing, additional reinforcement, adding new elements, setting dampers and/or base isolation, strengthening foundations and walls, replacing bearings, constraining/preventing displacement,
- recommendations for executing planned works on bridge structures and foundations,
- recommendations for monitoring the existing untreated and subsequently rehabilitated bridges using modern information technologies.

Socio-economic aspects of interventions on bridge structures:

- socio-economic description of the state of bridge structures: in a fully serviceable state, generally serviceable state, state of the bridge where it is necessary to further ensure that human lives are not at risk, state close to collapse of the bridge structure, collapse state of the bridge structure,
- interventions on damaged bridges: executing works on rehabilitation of bridge structures with minimum traffic disruption, in significantly damaged bridge structures interventions should be executed such to ensure the traffic of emergency vehicles (fire trucks, ambulance, police, etc.), optimizing the number of days required for the rehabilitation of totally damaged bridge structures or structures where the traffic is disabled,

- economic analyses and effects of bridge rehabilitations.

The final assessment of the state of the bridge structure is made based on the analysis of actual damage and numerical simulations which indicate the progression of damage if adequate rehabilitation/strengthening measures are not promptly carried out.

3. VIKOR METHOD OF DECISION MAKING IN THE ANALYSIS OF BRIDGE REHABILITATION/STRENGTHENING

3.1. Mathematical formulation of the VIKOR method

Due to spatial constraints for a detailed presentation of the problem and the complexity of the methodology which is conceptually presented in this paper, the research is focused on multi-criteria optimization using the VIKOR method. The VIKOR method was developed for the purpose of multi-criteria decision making in strategic projects (Opricović and Tzeng 2004), by first identifying the best (compromise) solution in a multi-criteria sense from a set of *J* permissible alternatives evaluated based on a set of *n* criteria functions. This method requires knowing the values of all criterion functions for all alternatives in the form of a matrix $\| f_{ij} \| n\text{x}J$, where f_{ij} denotes the value of *i*-th criterion function for the *j*-th alternative. The compromise solution $F^c=(f_1^c,\ldots f_n^c)$ is the permissible solution that is the closest to the ideal solution F^* (best values of criteria functions). Here, compromise implies an agreement reached by mutual trade-offs, represented by $\Delta f_i=f_i^*-f_i^c$, $i=1,\ldots n$. The VIKOR method is carried out in several steps:

- determining the ideal point based on the values of criteria functions using the following relation:

$$f_i^* = ext_j\, f_{ij} \qquad i = 1,...n\,, \tag{1}$$

  where *ext* indicates maximum if the *i*-th criterion function represents benefit or profit, or minimum if the *i*-th criterion function represents damage or costs,
- transformation of various criteria functions (different measures of value):

$$d_{ij} = (f_i^* - f_{ij})/(f_i^* - f_i^-)\,, \quad i = 1,...n\,, \quad j = 1,...J\,, \tag{2}$$

  where f_i^- indicates the worst criteria functions,
- assigning criteria weights w_i, i=1,...n, representing the relative importance of the criterion that is based on the preference of decision-maker,
- determining S_j, R_j, Q_j, j,...J based on the following relations:

$$S_j = \sum_{i=1}^{n} w_i d_{ij} \quad \text{(weighted and normalized \textit{Manhattan} distance)}, \tag{3}$$

$$R_j = \max_i (w_i d_{ij}) \quad \text{(weighted and normalized \textit{Chebyshev} distance)}, \tag{4}$$

$$S^* = \min_j S_j\,, \quad S^- = \max_j S_j\,, \tag{5}$$

$$R^* = \min_j R_j\,, \quad R^- = \max_j R_j\,, \tag{6}$$

$$QS_j = (S_j - S^*)/(S^- - S^*)\,, \quad QR_j = (R_j - R^*)/(R^- - R^*)\,, \quad Q_j = v \times QS_j + (1 - v) \times QR_j\,, \tag{7}$$

  where $v=(n+1)/2n$, while some studies apply v=0.5.

3.2. Analysis of bridge priority for rehabilitation/strengthening

The priority list of bridges for rehabilitation/strengthening was defined and decided based on the following activities:

- forming a list of bridges on various travel routes,
- forming the criteria for multi-criteria optimization,
- numerical procedure of multi-criteria optimization using the VIKOR method in the *LingV* software (Opricović 2015),
- evaluating the solutions formed in accordance with the adopted criteria,
- ranking alternative solutions,
- analyzing and selecting priority bridges for rehabilitation/strengthening.

A total of 12 bridges were taken into consideration (M1,...M12) on various first and second order travel routes, and seven criteria were selected for multi-criteria optimization:

- importance of the bridge c_1,
- years of service c_2,
- average annual daily traffic c_3,
- infrastructure passing through the bridge structure c_4,
- alternative travel routes c_5,
- structural vulnerability c_6,
- seismic hazard c_7.

The criterion *importance of the bridge* (c_1) represents its strategic importance, ranging from regional to international. Three bridge importance categories were considered: strategic, critical and standard. The criterion *years of service* (c_2) refers to the time elapsed since the beginning of operation of the bridge to the time the data was collected for the research presented in this paper. The criterion of *average annual daily traffic* (c_3) represents the average daily flow of vehicles over the bridge on annual level. The criterion *infrastructure passing through the bridge structure* (c_4) represents an additional infrastructure which is mounted on the bridge structure. The criterion *alternative travel routes* (c_5) refer to alternative routes that can be used in the case when the bridge is damaged to such an extent that disables the undisturbed flow of traffic. The criterion of *structural vulnerability* (c_6) refers to performances of the bridge structure and the level of vulnerability in the case of earthquake conditions. Bridges in poor condition have a higher level of vulnerability and they are given a higher priority for rehabilitation/strengthening. The criterion of *seismic hazard* (c_7) is a function of two factors: intensities of ground displacement and ground amplification, which can be displayed as the product of maximum ground acceleration for the bedrock and ground seismic coefficient.

In the next step, each alternative solution was evaluated individually based on the corresponding criteria, forming thereby the initial (non-normalized) decision matrix. For the purpose of this study five possible scenarios were defined for which various weight coefficient values w_i were taken into consideration across the criteria. Table 1 shows the decision matrix and the predefined scenarios along with the weight coefficients. Scenarios S1 and S2 refer to the situation when higher weight coefficients values are taken into account for seismic hazard and structural vulnerability. In scenarios S4 and S5, more importance is attributed to average annual daily traffic and importance of the bridge, while minimizing the impact of seismic hazard. The scenario S3 is a transitional category between the above defined scenarios.

After defining the (non normalized) decision matrix and forming the predefined scenarios with weight coefficients, the decision matrix was normalized, while in the next step was consisted of calculating the weight coefficients that determine the relative importance of each criterion in the criteria order formed. Then the final decision matrix was calculated and the ranking procedure conducted based on the solution obtained from multi-criteria optimization. Due to the volume of calculations and spatial constraints for the presentation of the intermediate solution obtained using the VIKOR method, only the ultimate solution is presented in the form of a ranking chart of priority bridges for rehabilitation/strengthening (Figure 1). In case of the first two scenarios (S1, S2) with higher weight coefficients for seismic hazard and structural vulnerability, bridge M5 has the priority for rehabilitation/strengthening. On the other hand, in the case of last two scenarios (S4, S5), there is M3 a priority bridge, while in the case of scenario S3 the priority bridge is M1. After examining the rank of trade-off solutions, bridges M7 and M8, ranked second and third in four scenarios, were proposed for rehabilitation/strengthening (if there are funds available) immediately after the rehabilitation of bridges M5 and M3. The level of seismic hazard of bridge M5 is almost identical to that of bridges M3, M7 and M8, while its annual average daily traffic is significantly lower; however, its level of structural vulnerability is slightly higher compared to the vulnerability of bridge M3.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
M1	1	25	22555	3	6	1	0.375
M2	2	9	13108	2	3	3	0.25
M3	1	35	40537	2	2	6	0.275
M4	3	18	11157	1	3	1	0.35
M5	2	55	15288	2	2	8	0.3
M6	2	40	19872	3	4	4	0.25
M7	1	48	30985	3	2	2	0.3
M8	1	20	52873	3	4	2	0.3
M9	3	52	7862	1	2	2	0.3
M10	3	35	9352	1	1	3	0.45
M11	2	48	19285	2	3	5	0.3
M12	3	42	7408	1	2	4	0.4
	w_1	w_2	w_3	w_4	w_5	w_6	w_7
S1	5	3	4	2	1	6	7
S2	4	5	3	1	2	7	6
S3	6	3	5	1	2	4	7
S4	7	3	6	2	1	5	4
S5	6	4	7	5	2	3	1

Table 1. Decision matrix and predefined scenarios with the weight coefficients when deciding on priority of bridges for rehabilitation/strengthening

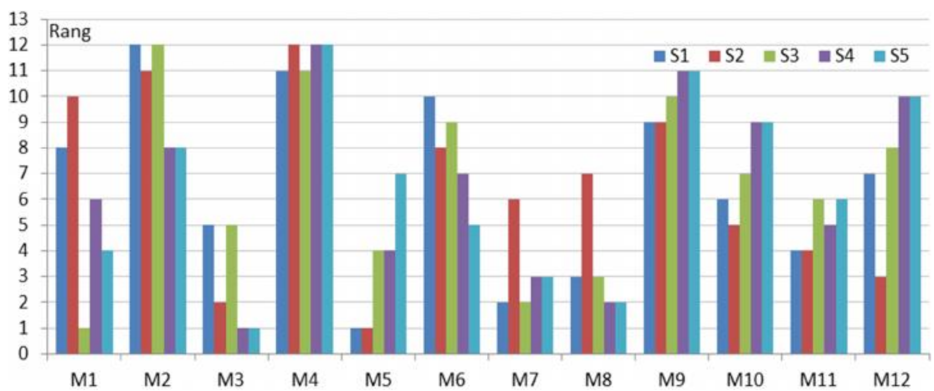

Figure 1. Ranking/priority chart of bridges for rehabilitation/strengthening

3.3. Analysis of priority of bridge rehabilitation/strengthening methods

The priority list of methods of bridge rehabilitation/strengthening was defined and decided based on the following activities:

- forming a list of methods of rehabilitation/strengthening,
- forming criteria for multi-criteria optimization,
- numerical procedure of multi-criteria optimization based on the VIKOR method using the *LingV* software (Opricović 2015),
- evaluating the solutions formed in accordance with the adopted criteria,
- ranking the alternative solutions,

- analyzing and selecting the priority methods of bridge rehabilitation/strengthening.

In the preliminary stage, a number of rehabilitation/strengthening methods were taken into consideration, which in the final stage were reduced to a total of 8 methods (Met1,...Met8), according to (Folić et al. 2015): refurbishing rehabilitation, cross-section strengthening, adding stiffeners, rehabilitation using FRP strips, adding dampers, installing base insulation, changing the static system, and strengthening foundation with piles, while 6 criteria being selected for multi-criteria optimization:

- capacity c_1,
- ductility c_2,
- deformation c_3,
- global stability c_4,
- rehabilitation costs c_5,
- time needed for rehabilitation c_6.

The criterion of *capacity* c_1 refers to the increase in structural resistance of the bridge to earthquakes effects as a function of the rehabilitation/strengthening method applied. The criterion of *ductility* c_2 is related to increasing the ratio of maximum deformations and deformations on the yield limit as function of the applied methods of rehabilitation/strengthening. The criterion of *deformation* c_3 is a function of the ratio of deformation of the rehabilitated/strengthened and the earthquake-damaged. The criterion of *global stability* c_4 is a function of increased global stability of rehabilitated/strengthened bridge in earthquake conditions. The criterion of *rehabilitation costs* c_5 refers to the overall rehabilitation/strengthening costs, while the criterion of *time needed for rehabilitation* c_6 refers to the cumulative time from the outset of rehabilitation to the normalization of traffic over the bridge. Values of coefficients c_1,...c_6 are shown as normalized. For the purpose of this study eight possible scenarios were defined for which different values of weight coefficients w_i were considered across the criteria. Table 2 shows the decision matrix and the predefined scenarios along with the weight coefficients.

	c_1	c_2	c_3	c_4	c_5	c_6
Met1	1	1	1	1	1	1
Met2	4	2	3	4	3	5
Met3	5	3	4	5	4	5
Met4	2	4	3	3	4	4
Met5	2	2	3	4	5	4
Met6	2	3	3	4	6	5
Met7	7	5	5	6	5	5
Met8	4	3	4	4	7	8
	w_1	w_2	w_3	w_4	w_5	w_6
S1	6	5	3	4	1	2
S2	5	6	3	4	1	2
S3	5	3	6	4	1	2
S4	5	4	3	6	1	2
S5	4	3	1	2	6	5
S6	2	1	3	4	6	5
S7	4	3	1	2	5	6
S8	2	1	3	4	5	6

Table 2. Matrix decision and predefined scenarios along with the weight coefficients in the analysis of priority methods of bridge rehabilitation/strengthening

The first four scenarios (S1, S2, S3, S4) are related to situations when higher weight coefficients values were taken into account in order to increase the quality of behaviour of bridge structural system. In the case of the remaining four scenarios (S5, S6, S7, S8) higher importance is attributed to the economic effects and the time needed for rehabilitation/strengthening of the bridge. The ultimate solution obtained using the VIKOR method is shown in the form of priority ranks of bridge rehabilitation/strengthening methods (Figure 2). In the case of the first four scenarios (S1, S2, S3, S4) with higher values of weight coefficients, in order to improve the quality of behaviour of the bridge structural system, the method of changing the static system Met7 is the priority approach to rehabilitation/strengthening. In the case of the last four scenarios (S5, S6, S7, S8), with the emphasis on economic effects and the time needed for rehabilitation/strengthening, Met1 (refurbishing rehabilitation) is the priority approach. However, in specific cases, the method of refurbishing rehabilitation is insufficiently adequate for bridge rehabilitation, so when considering the rank of trade-off solutions the Met3 approach (adding stiffeners) is obtained as optimal solution.

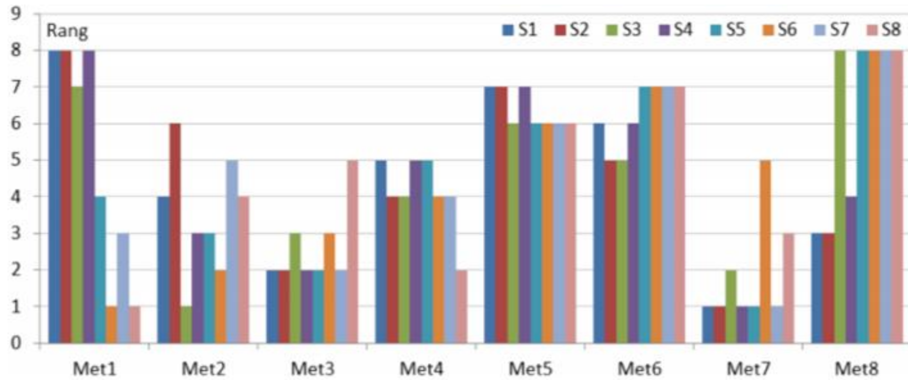

Figure 2. Ranking/priority chart of bridge rehabilitation/strengthening methods

4. CONCLUSION

The research presented in this paper is based on multi-criteria optimization in decision theory of analyzing the priority of bridges for rehabilitation/strengthening of their structures and foundations. Based on the selected 12 bridges, 7 defined criteria and 5 scenarios, the analysis of priority of bridges for rehabilitation/strengthening yielded compromise solution, according to which bridges M5 and M3 have the priority to be rehabilitated/strengthened, followed by bridges M7 and M8.

The study has shown that the bridge with a significantly lower annual average daily traffic have the priority to be rehabilitated/strengthened over bridges of strategic importance and a much higher flow of traffic. This can be justified by the fact that the level of vulnerability of this bridge is higher than that of the first four high ranking bridges, despite the almost identical seismic hazard levels. Based on the 8 methods selected, 6 criteria defined, and 8 scenarios, the analysis of priority bridge rehabilitation/strengthening methods yielded a compromise solution that improving the structural behaviour of the bridge requires changing the static system. When the economic effects and the time needed for rehabilitation/strengthening are of primal concern, then a trade-off solution is obtained based on refurbishing rehabilitation of adding stiffeners.

The research has shown that the VIKOR method presents a powerful engineering and scientific tool in decision theory based on multi-criteria optimization. Based on a number of alternative solutions, criteria and scenarios, trade-off solutions were obtained which can serve some practical engineering purposes.

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