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Application of Analytical Hierarchy Process for Structural Health Monitoring and Prioritizing Concrete Bridges in Iran

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Abstract: This paper proposes a method for monitoring the structural health of concrete bridges in Iran. In this method, the bridge condition index (BCI) of bridges is determined by the analytical hierarchy process (AHP). BCI constitutes eight indices that are scored based on the experts' views, including structural, hydrology and climate, safety, load impact, geotechnical and seismicity, strategic importance, facilities, and traffic and pavement. Experts' views were analyzed by Expert Choice software, and the relative importance (weight) of all eight indices were determined using AHP. Moreover, the scores of indices for various conditions were extracted from experts' standpoints. BCI defines as the sum of weighted scores of indices. Bridge inspectors can examine the bridge, determine the scores of indices, and compute BCI. Higher values of BCI indicate better conditions. Therefore, bridges with lower BCI take priority in maintenance activities. As the case studies, the authors selected five bridges in Iran. Successful implementation of the proposed method for these case studies verified that this method can be applied as an easy-to-use optimization tool in health monitoring and prioritizing programs.

Keywords: transportation infrastructure; concrete bridges; structural health monitoring; bridge condition index; analytical hierarchy process; mobility; multiple-criteria decision analysis; decision making; civil engineering; infrastructure

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1. Introduction

The quality of transportation systems directly affects the lives of urban residents. A large portion of the national resources of each country is invested in this area. As one of the most important parts of transportation systems, bridges have a critical role in urban development [1–5]. The bridge conditions in the transportation networks are so important that the costs incurred by out-of-service bridges are exorbitant. Therefore, bridge condition evaluation has crucial importance for the proper maintenance and management of transportation infrastructures. Another important factor that affects the maintenance process of infrastructures is budget constraints. Consequently, further attention should be paid to the development of a bridge management system (BMS) [6,7]. The first step in the BMS is to prepare a technical profile for all bridges in the network. This profile contains technical information such as the name of a bridge, its location, construction method, etc. It is, in fact, the starting point of BMS. The next step in BMS is assessment, including structural and seismic assessment, hydrological assessment, facility evaluation, safety assessment, and pavement and traffic evaluation [8]. Bridge inspection methods are divided into four general categories [9,10]: 1. Visual assessment; 2. Evaluation by non-destructive tests; 3. Sampling and destructive tests; and 4. Health assessment. Another major step of BMS is bridge maintenance. The maintenance involves a variety of operations that continuously ensure the safety and serviceability of bridges over their lifetime. The prioritization of bridge maintenance, including repairs or reinforcement, is the cornerstone of the BMS [8,11]. Traditionally, for small-sized bridges, the prioritization of bridge maintenance projects was carried out based on engineer's assessments. In large and old bridge networks, it was conducted in accordance with concepts and principles of optimization in project budget allocation. Today, the bridge condition index (BCI) is used for this purpose. BCI is a good benchmark for prioritizing BMS [12].

The service life of a bridge is divided into four different phases [13]:

- Design and construction;
- Start of damages (early damage stages);
- The spread of damages;
- The expansion of damages.

Under the famous Law of Five, each dollar spent on the first phase will equal $5 in the second phase, $25 in the third phase, and $125 in the fourth phase [13]. According to this law, any miscalculated decisions about maintenance, repair, and rehabilitation (MR&R) in bridges would incur surplus costs. With this in mind, there is a need for a decision support system (DSS). DDS aims at improving the bridge network condition and allocating the budget appropriately [14]. Most of BMSs are founded upon processes that optimize the cost of a lifecycle. They tend to overlook factors such as environmental impacts and social impacts. This gives rise to a number of problems, especially when the existing financial resources are higher or lower than the cost of the computational life cycle [15].

In this paper, the main goal is to present an applicable method for determining the condition index of the concrete bridges in Iran. For this purpose, firstly, eight critical indices were selected. These indices include structure, hydrology and climate, safety, load impact, geotechnical and seismicity, strategic importance, facilities, and traffic and pavement. Each index comprises a number of sub-indices. Next, the authors developed a questionnaire for surveying the views of experts. The questionnaire was about the relative importance of the indices and sub-indices. Moreover, examining various conditions of sub-indexes is another aim of this questionnaire. After that, this questionnaire was distributed among bridge experts. Then, experts' feedbacks about the relative importance of indices and some sub-indexes were analyzed by Expert Choice software. This software resulted in the relative weight of these indexes and sub-indexes using the analytical hierarchy process (AHP). For all sub-indexes, experts' views about conditions scores were gathered as well. The score of each index is the sum of condition scores assigned to its sub-indices. Finally, BCI is calculated as the sum of weighted scores assigned to indices. BCI is a value between 0 and 100, with higher values indicating a better bridge condition. Therefore, bridges with lower BCI take priority in terms of repair and maintenance. To test the proposed method in practice, five bridges in Semnan province, in Iran, were inspected and their BCI was determined to prioritize bridges in terms of maintenance requirements. This study is innovative because no comprehensive method has been proposed to evaluate and prioritize in-service bridges in Iran. Therefore, the proposed method helps Iranian engineers evaluate bridges and prioritize bridge maintenance operations more effectively.

This paper is organized as follows: Next section presents a literature review of BCI. Section "Method" introduces the study methodology, which is further divided into three general sub-sections entitled BCI, AHP, and sub-indices of BCI. The results are presented and discussed in section "Results and Discussion." The final section offers a summary of results and conclusions.

2. Background

The proper maintenance and management of bridges need the evaluation of safety and lifetime conditions. In recent years, there is an increasing number of studies on the BMS and BCI. This section presents a range of the most important methods used for determining BCI around the world.

2.1. India

In India, Sanjay and Kumar developed a bridge health index (BHI) using AHP. They divided elements of the bridge into seven categories, including approaches, substructure, waterway/channel, foundations, superstructure, appurtenances/auxiliary works, and bearings. Then, they drafted a questionnaire and distributed it among engineers and experts. The results of the questionnaire were incorporated in determining the relative importance and weight of diverse elements. They also considered a numerical value for each type of damage. The condition of various elements of a bridge is assessed by visual inspection. Finally, BHI was developed by summing the score of all bridge elements [16]. In Figure 1, the decision tree of this research is presented.

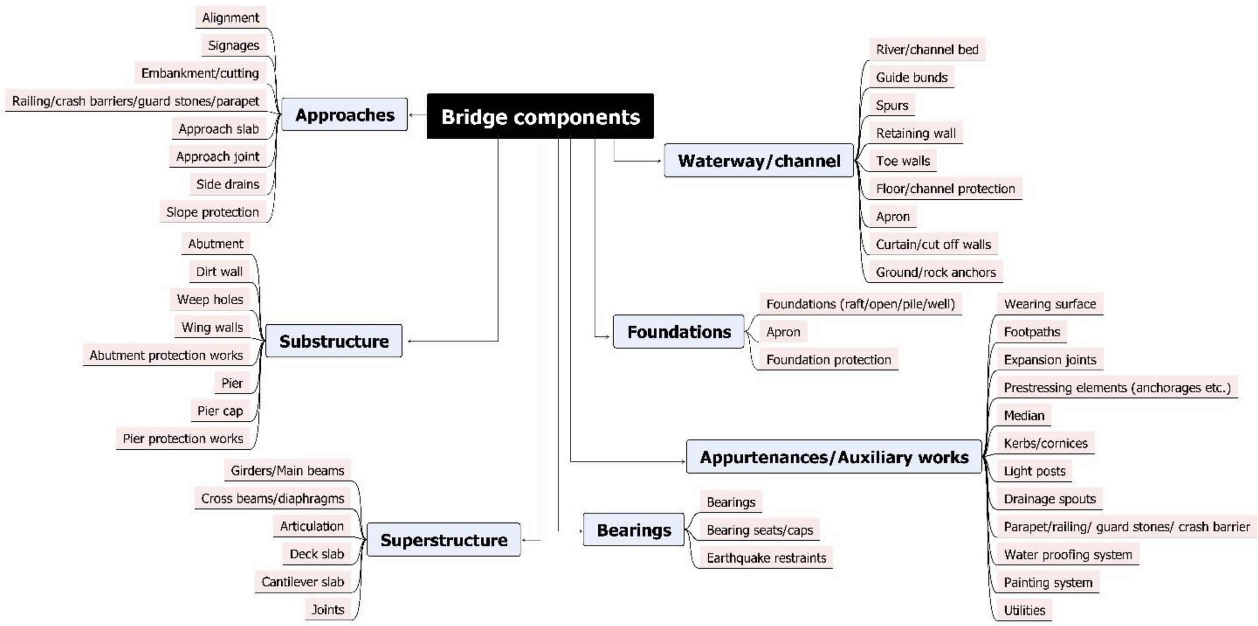

Figure 1. Decision tree in Sanjay and Kumar research.

2.2. China

In China, there are two main indexes for assessing bridge conditions. The Ministry of Transport of the People's Republic of China uses the Dr index to assess the conditions of a bridge [17]:

$$D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB}, \quad (1)$$

where D_r is bridge condition rating, BDCI is bridge deck condition index, SPCI is bridge superstructure condition index, SBCI is bridge substructure condition index, W_D, W_{SP}, and W_{SB} are the weight of BDCI, SPCI, and SBCI indicators, respectively. On the other hand, the Ministry of Housing and Urban-Rural Development of China has also provided a definition identical to Equation (1) for assessing bridge conditions [18]:

$$BCI = BCI_d \times \omega_d + BCI_{sp} \times \omega_{sp} + BCI_{sb} \times \omega_{sb}, \quad (2)$$

where BCI is bridge conditions index, BCI_d is bridge deck condition index, BCI_{sp} is bridge superstructure condition index, BCI_{sb} is bridge substructure condition index, and ω is the weight of a bridge element. Table 1 presents the assessment approach based on D_r and BCI.

Table 1. Assessment of bridge condition in China.

D_r		Condition
$95 \leq D_r < 100$	$90 \leq BCI$	Perfect
$80 \leq D_r < 95$	$80 \leq BCI < 90$	Good (minor damage)
$60 \leq D_r < 80$	$66 \leq BCI < 80$	Pass (mediate damage)
$40 \leq D_r < 60$	$50 \leq BCI < 66$	Unqualified (great damage)
$0 < D_r < 40$	$BCI < 50$	Dangerous

2.3. Japan

In Japan, no specific formula or equation is used to evaluate the condition of a bridge. For each bridge, first, one of the statuses shown in Table 2 is assigned to each element based on the assessment of the bridge inspector, and then the bridge general conditions are described in accordance with Table 3 [19].

Table 2. Assessment of maintenance urgency for bridge element in Japan.

Rate	Condition
A	No repair needed
B	No immediate repairs needed
C1	Immediate repairs needed from standpoint of preventative maintenance
C2	Immediate repairs needed from standpoint of structural safety
E1	Immediate actions needed from standpoint of structural safety
E2	Immediate actions needed in tandem with other factors
M	Repairs needed during regular maintenance work
S1	In-depth investigations needed
S2	Follow-up investigations needed

Table 3. Bridge soundness in Japan.

State	Condition	Description
1	Good	No problems in bridge's functions
2	Preventative maintenance	No problems in bridge's functions but maintenance required from standpoint of preventive maintenance
3	Early action	Possibility of problems in bridge's functions, need for early action
4	Emergency action	Possibility of problems or existing problems in bridge's functions, need for emergency actions

2.4. Korea

In Korea, a damage index (DI) is used to assess bridge conditions. It is the normalized index obtained from the evaluation of all bridge elements. The DI index is shown in Equation (3) [20]:

$$DI = \sum(CR_i \times WF_i)/100, \quad (3)$$

$$\sum(WF_i) = 100,$$

where DI is damage index, CR_i is condition evaluation of ith element, and WF_i is the weight factor of ith element. Based on the DI index, a bridge condition could be described with grades A to E (Table 4).

Table 4. Assessment of bridge condition in Korea.

Rate	DI	Description
A	$0 \leq \text{DI} < 0.13$	Perfect
B	$0.13 \leq \text{DI} < 0.26$	Minor problem in secondary elements
C	$0.26 \leq \text{DI} < 0.49$	Minor problem in primary elements
D	$0.49 \leq \text{DI} < 0.79$	Problem in primary elements
E	$0.79 \leq \text{DI}$	Serious problem in primary elements

2.5. United States

In the United States, there are various approaches to assess the condition of the bridge. For example, the California Department of Transportation defines BHI based on Equation (4). This index varies from 0 for the worst bridge condition to 100 for the healthiest bridge condition [21].

$$\text{BHI} = \left[\sum(\text{CEV})/\sum(\text{TEV})\right] \times 100, \quad (4)$$

where BHI is bridge health index, CEV is current element value, and TEV is total element value.

CEV and TEV can be calculated according to the following equations [21]:

$$\text{CEV} = \sum(\text{QCS}_\text{i} \times \text{WF}_\text{i}) \times \text{FC}, \quad (5)$$

$$\text{TEV} = \text{TEQ} \times \text{FC}, \quad (6)$$

where TEQ is total element quantity, FC is failure costs of element, QCS_i is quantity in condition state i, and WF is weight factor.

In the United States, transportation departments report a set of data called national bridge inspection (NBI). Based on the physical condition of the bridge, the bridge is assigned a score in the range of 0 to 9 [22]. The assessment procedure is presented in Table 5.

Table 5. Assessment of bridge condition based on NBI.

Rate	State	Description
9	Excellent	A new bridge
8	Very good	No problems noted
7	Good	Some minor problems
6	Satisfactory	Structural elements show some minor deterioration
5	Fair	All primary structural elements are sound but may have minor section loss, deterioration, spalling or scour
4	Poor	Advanced section loss, deterioration, spalling, scour
3	Serious	Loss of section, etc., has affected primary structural components; Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present
2	Critical	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed structural support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken
1	Imminent failure	Major deterioration or loss of section in critical structural components or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic but corrective action may allow it to be returned to light service
0	Failed	Out of service. Beyond corrective action

The US departments of transportation often use a computer program to assess bridge conditions. This program is based on Equation (7) [22].

$$\text{SR} = \text{S}_1 + \text{S}_2 + \text{S}_3 - \text{S}_4, \quad (7)$$

where SR is Sufficiency rating, S_1 is the parameter related to structural safety, S_2 is the parameter related to bridge serviceability and functionality, S_3 is the parameter related to user requirements, and S_4 is the parameter related to reductive coefficients based on structure type and traffic safety.

SR indicates the bridge sufficiency to remain in service, where SR has a maximum rating of 100%, indicating complete bridge sufficiency, and a minimum rating of 0%, indicating complete bridge deficiency. The parameters S_1, S_2, S_3, and S_4 have weight importance of 55%, 30%, 15%, and 13%, respectively. FHWA uses SR to allocate rebuilding funds so that [22]:

- If SR < 50, the bridge is eligible for replacement;
- If 50 < SR < 80, the bridge is eligible for rehabilitation.

2.6. Australia

In Australia, Rashidi et al. presented an overall working framework for bridge infrastructure management. This framework had two phases, including project ranking and remediation planning. The engaged factors of this framework were weighting by expert judgments and employing AHP [23]. In phase project ranking, they presented a model for prioritizing based on priority index (PI). A bridge with higher PI takes priority for maintenance [24]:

$$PI = 0.6(SE) + 0.2(FE) + 0.2(CIF), \tag{8}$$

where PI is priority index, SE is structural efficiency index, FE is functional efficiency, and CIF is the client impact factor.

In phase remediation planning, the problem was modeled in a hierarchical order by a simplified hierarchical analysis process (S-AHP). This hierarchy consists of at least three main levels: goal, criteria, and alternatives. The goal is the remediation strategy. The criteria require to be broken down into more specific sub-criteria introduced as attributes in an extra level of the hierarchy. Each criterion has a weight indicating its importance. These weights are defined by the decision makers. The final level is added for the remediation treatment alternatives. This procedure is flexible and can vary for different projects. Therefore, criteria, rehabilitation strategies, and even the number of levels can be different in various cases [25,26].

2.7. Turkey

In Turkey, the following technique is used for the assessment of bridge condition and its elements [27]:

$$CR\ (e)_{element,W} = \sum j((\sum(WP_{dt,i,j} \times r_j))/(\sum\sum(WP_{dt,i,n} \times r_n))),\ j = 1, \ldots, S;\ i = 1, \ldots, d;\ n = 1, \ldots, S \tag{9}$$

$$CR\ (b)_{bridge,W} = \sum (W_e \times CR\ (e)_{element,W})/100,\ e = 1, \ldots, n_e \tag{10}$$

where $CR(e)_{element,W}$ is weighted assessment of conditions for element e, n_e is total number of bridge elements, $WP_{(dt,i,j)}$ is weighted percentages for damage type i under condition j, s is total conditions, d is total number of damages, r_j is damage impact distribution coefficient, $CR(b)_{bridge,W}$ is weighted assessment of bridge b, and W_e is weight importance of r_j element. In Figure 2, the weight importance of elements for a conventional concrete bridge is shown.

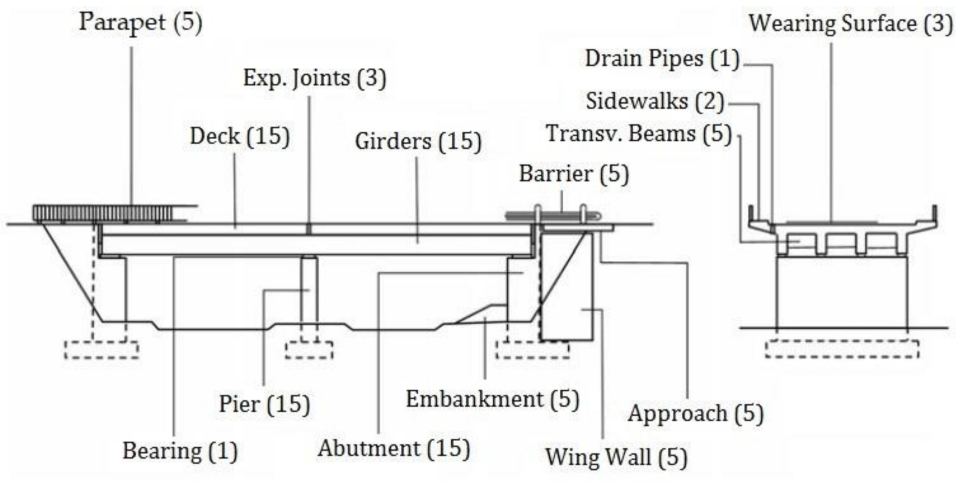

Figure 2. Weight importance of elements for a conventional concrete bridge.

2.8. Concluding Remarks

In previous parts of this section, an overview of the most important studies is relating to methods of assessing the condition of bridges in different countries is presented. After reviewing these works, the authors found that the main gap in these methods is: almost all methods/models only focus on the structural condition of bridges. Of course, considering the structural condition is logical and essential because the structural elements play the most key role in bridge serviceability. However, disregarding other important factors, including hydrology, climate, safety, load impact, etc., can decrease the quality of monitoring, assessing, and prioritizing bridges. Another key point that can be found from the background is the attempt of some researchers and organizations to resolve the mentioned gap. By applying some new factors such as safety, seismic evaluation, and hydrology, they tried to remove/moderate the impact of the gap. This is a valuable attempt and a helpful step in eliminating the mentioned gap. But, the authors think that these attempts can be more extended and with more details. As a result, the authors aim to present a new method that includes a wide range of the affecting factors in evaluating bridges condition. Indeed, this study presents a method for monitoring, assessing, and prioritizing bridges that is not confined to structural condition and considers other affecting factors. Moreover, all these factors are examined in detail as much as possible. The method includes hydrology and climate index, safety index, load impact index, geotechnical and seismic index, mechanical/electrical facilities quality index, strategic importance index, and traffic and pavement index. Another gap that has been followed in this study is the lack of a comprehensive, practical, scientific method for bridge networks in Iran. Although there are attempts in the field of developing health monitoring methods for various infrastructures in Iran, such as [28–37]; however, the absence of a full detailed, efficient, specialized method for bridges can be felt. Consequently, the authors also tried to fill the later gap, and therefore, the proposed method is based on the condition of bridges in Iran.

3. Method

3.1. Bridge Condition Index (BCI)

One of the major concerns of organizations in charge of bridges is that repairs and maintenance of bridges should be implemented with respect to financial constraints. Bridge maintenance is a costly and long-term project, which has led to the development of various scientific tools and methods for optimal budget allocation [38]. Before allocating any budget, it is necessary to determine the current condition of the bridge and its present and possible future needs. The key to the successful assessment of a bridge condition is to recognize various damages. Bridge damage is a slow, progressive, and continuous process that is influenced by the imposing load, conditions of various bridge components, environmental factors, and the properties of materials [16].

Many researchers have argued that the damage process is a blend of several mechanisms, such as corrosion, creep, shrinkage, cracking, fatigue, etc. [39]. The bridge damage is induced by a host of factors such as traffic, rainfall, freezing and melting cycles, climate change, and pollution, which can eventually lead to bridge failure [16]. The bridge failure can be either structural or functional. The methods for assessing various components of a bridge and their relative significance are key concepts in BMS [40].

Different countries employ diverse methods to evaluate bridges so that they can develop a priority plan for bridge repair and maintenance with respect to budget constraints. Using a series of indicators is one of the most commonly used decision-making methods to prioritize maintenance. One perquisite of such indicators is determining the relative importance of different bridge components. Indicators can be categorized into two broad categories [16]:

1. Bridge Health Index (BHI);
2. Maintenance Priority Index (MPI).

The BHI is generally calculated as follows [16]:

$$\mathrm{BHI} = \sum \mathrm{W_i} \times \mathrm{C_i},\ \mathrm{i} = 1, \ldots, \mathrm{n} \tag{11}$$

where BHI is bridge health index, W_i is the weight of ith element, C_i is the condition of ith element, and n is the number of bridge elements.

Moreover, MPI is usually calculated using the following equation [41]:

$$\mathrm{MPI} = \sum \mathrm{K_i} \times \mathrm{F_i}(\mathrm{a}, \mathrm{b}, \mathrm{c}, \ldots), \tag{12}$$

where MPI is maintenance priority index, K_i is the weight of ith damage, F_i is ith damage and a, b, c, etc., are damage characteristics.

The above indicators, BHI and MPI, aim to determine the condition of the in-service bridges. In fact, both these indicators are somehow the same as the BCI. In this study, a method of BCI determination is proposed that is structurally similar to BHI.

3.2. Analytical Hierarchy Process (AHP)

Introduced by Thomas Satty in 1980, the analytic hierarchy process (AHP) provides a mechanism for switching the criteria rating into weights [4,42]. AHP is an effective and powerful tool for multi-criteria decision-making approaches. In fact, it is a powerful technique for solving complicated problems that may have correlations and interactions among different goals. When using in multi-criteria problems, AHP breaks down these problems into multiple levels of hierarchy. The goal or objective seats in the top level. Intermediate levels include the criteria and sub-criteria, and the lowest level can provide alternatives. AHP then develops priorities among all the criteria and sub-criteria within each level of the hierarchy [43,44]. The basis of AHP can be both experts' judgments and predetermined measurements. Experts are interviewed, and pair-wise comparison judgments are applied to pairs of criteria. Eventually, priorities will be determined. AHP is easy to apply and helps engineers obtain the final ranking from the individual evaluations, and finally, select an optimal alternative [45]. Because of these features, AHP has been used in bridge engineering in the past decades. Generally, the AHP can be included in the following steps [46]:

1. Constructing the pair-wise comparison judgment matrix.
2. Determining the weight of decision elements.
3. Controlling the compatibility index.

The purpose of this study is to present a simple, applicable methodology for the health monitoring and prioritizing of bridges. This methodology works based on calculating the bridge condition index (BCI). For the determination of BCI, the methodology uses AHP. In cases where AHP is used for decision making, a proper hierarchy tree should be designed. This hierarchy tree has different levels depending on the type of problem under investigation. As mentioned earlier, the first level of this tree is goal or objective. In this study, the goal is to determine the BCI of the bridge. In intermediate levels, first, criteria are located. These criteria are eight indices affecting the quality of a bridge, including structural index, hydrology and climate index, safety index, bridge performance index (load impact), geotechnical and seismic index, strategic importance index, facilities index, and traffic and pavement index. Sub-criteria are set in the next level. The sub-criteria, in fact, are sub-indexes of eight indexes of the previous level. Figure 3 shows the hierarchy tree of this research.

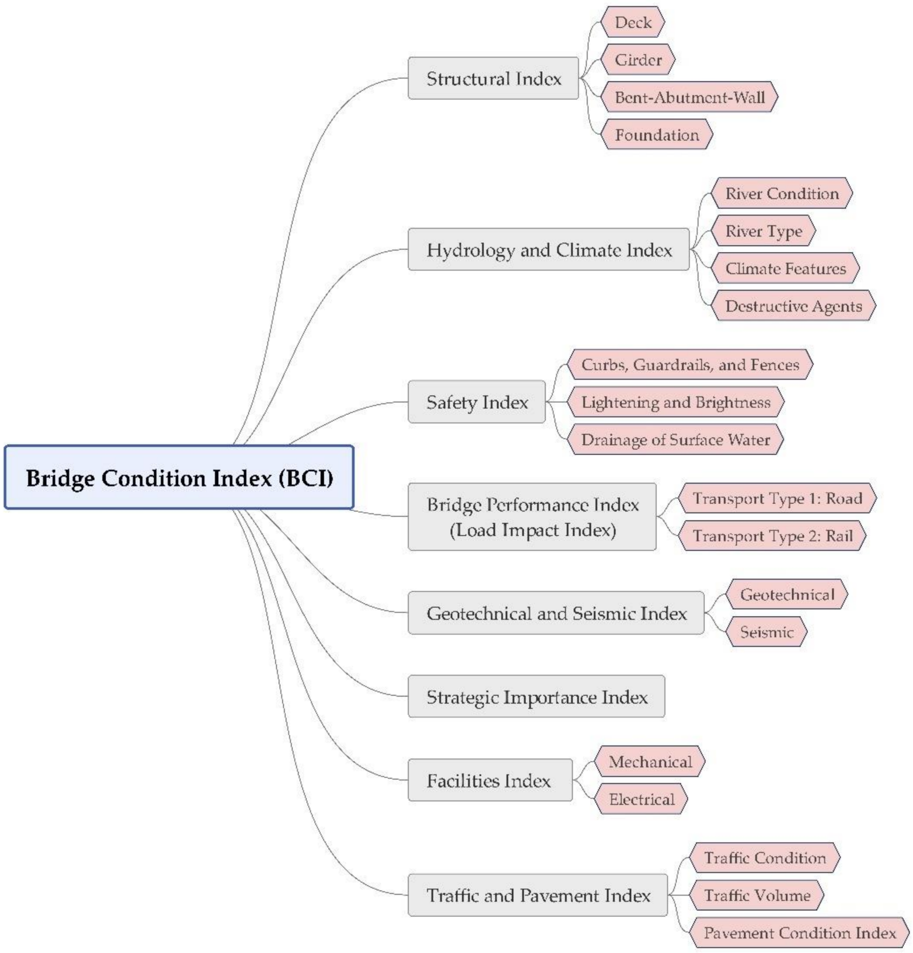

Figure 3. Hierarchy tree in this study.

In this work, the problem is to calculate BCI. For solving this problem, the authors must provide the relative importance of all indexes and sub-indexes. The relative importance values depend on weights which are measured using the AHP method. AHP is an analytical method that allows making appropriate decisions by considering qualitative, quantitative, and mixed criteria. This process is based on a dual comparison system [47]. For this reason, a questionnaire (Appendix A) is designed and distributed among experts. The experts' group comprises several specialists and advisors involved in the maintenance and reinforcement of bridges, also, university professors with relevant expertise. In this questionnaire, firstly, experts are asked to determine the relative importance of eight indices of Figure 3. Table A1 was designed for this purpose. In each cell of Table A1, experts assigned a value between 0 and 10 based on their technical experience and expertise. In fact, this table is a dual comparison between all indices. In this table, if a row index outweighs a column index, experts assigned a value between 1 and 10. If the column index outweighs the row index, a value between 0 and 1 was assigned by experts. Of course, the value of 1 was used at the diameter of the table. Table 6 shows the final results. In fact, the numbers in Table 6 are the average of experts' viewpoints. After this step, the values of Table 6 were entered in Expert Choice software, and the relative weights of all eight indexes were calculated (Table 7).

Table 6. Relative importance of indices based on a survey of experts.

Index	**Structural**	**Hydrology and Climate**	**Safety**	**Bridge Performance (Load Impact)**	**Geotechnical and Seismic**	**Strategic Importance**	**Facilities**	**Traffic and Pavement**
Structural	1	5.271	3.152	4.581	1.877	3.13	6.075	3.578
Hydrology and Climate		1	1.037	1.382	0.788	1.377	1.871	0.941
Safety			1	2.613	1.633	1.489	3.318	2.074
Bridge Performance (load impact)				1	0.761	1.164	2	1.154
Geotechnical and Seismic					1	2.859	3.133	2.216
Strategic Importance						1	2.766	1.75
Facilities							1	0.975
Traffic and Pavement								1

Table 7. Relative weights of indices and compatibility rating.

Index	**Structural**	**Hydrology and Climate**	**Safety**	**Bridge Performance (Load Impact)**	**Geotechnical and Seismic**	**Strategic Importance**	**Facilities**	**Traffic and Pavement**
Relative weight	0.331	0.097	0.146	0.080	0.143	0.088	0.046	0.068
compatibility rating	0.03							

As indicated in Table 7, the relative weight of indices was calculated. This table contains additional information called compatibility rating. It is the mechanism that determines the adaptability of comparisons, indicating the extent to which the priorities selected by the group or the priorities of the mixed table are reliable. According to the experience, if the compatibility rate is less than 0.1, the adaptability of comparisons is acceptable; otherwise, the comparisons need be repeated [46].

The next step is to examine all indices in detail. In Figure 3, each index is divided into some sub-indices. In this step, the relative importance/weight of all sub-indices must be determined. Figure 3 shows that the structural index consists of four sub-indices. These four sub-indices have various relative importance. Therefore, Table A2 in the questionnaire was assigned to the relative importance of these four sub-indices. In other indices of Figure 3, all sub-indices have the same importance/weight. By determining the relative importance/weight of all indices and sub-indices, it is time to determine the score of each sub-index in various conditions. Tables A3–A10 were designed for this purpose. In these tables, experts rated sub-indices in different states. Considering the given explanations, they filled the blank cells of the tables with a number in the range of 0 to 100. Details of this step are presented in the next sections of the paper. Figure 4 depicts the flow chart of AHP in this study.

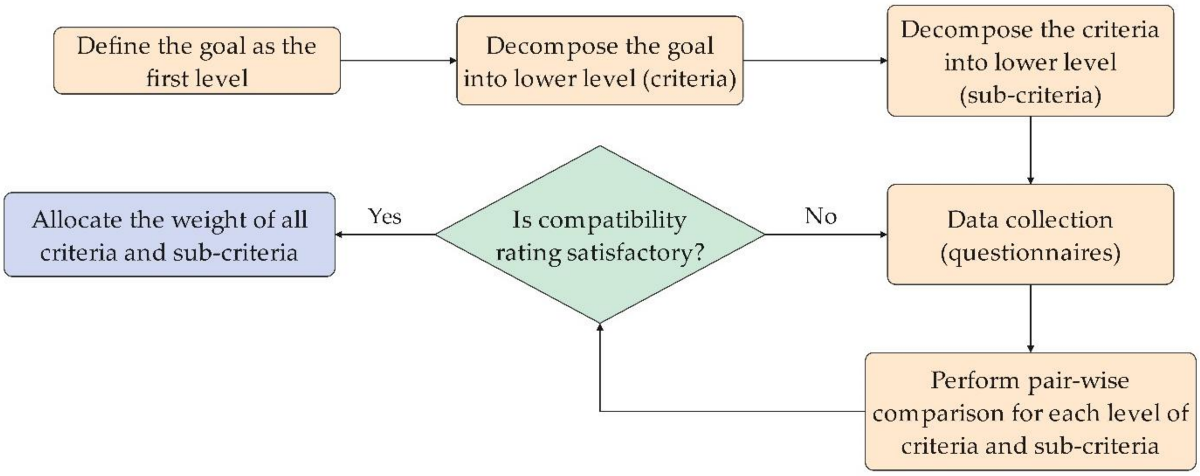

Figure 4. The flow chart of AHP used in this study.

Now, the BCI can be calculated. For each bridge, first, the score of each sub-index is determined based on the bridge inspection. After that, the score of each index is computed as the sum of weighted scores of its sub-indices. Finally, BCI can be determined based on Equation (13):

$$BCI = \sum (X_i \times W_i), i = 1, \ldots, 8 \quad (13)$$

where BCI is the bridge condition index, X_i is the score of ith index, and W_i is the weight of ith index.

3.3. Sub-Indices of BCI

3.3.1. Structural Index

The structural index describes the bridge condition in terms of the damages in the structural elements. In other words, it evaluates the structural condition of the bridge. Figure 4 shows that the structural index consists of four sub-indices, including deck, girder, bent-abutment-wall, and foundation. It should be noted that the joints are classified under the deck sub-index and bearing and support in the sub-index of bent-abutment-wall. These four sub-indices have various relative importance. Table A2 in the questionnaire was designed for determining the relative importance of these four sub-indices. Similar to Table A1, the experts were asked to conduct a dual comparison between the four sub-indices and assign a value between 0 and 10 in cells of Table A2. Table 8 presents the averaged viewpoints of experts. By inserting these values into Expert Choice software, the authors calculated the relative weights of the sub-indices. Table 9 indicates these relative weights. Next, these four sub-indices must be assessed for different states of damages. Table A3 had been designed for this purpose. Experts were asked to enter the appropriate scores in the blank cells based on their views about the various damage intensity in each sub-index. Their scores were a number in the range of 0 to 100. A score of 100 is related to the best condition, and a score of 0 is related to the worst condition. Table 10 shows the assigned score of each sub-index for different conditions. These scores are the average of experts' viewpoints.

Table 8. Relative importance of sub-indices in structural index.

Sub-Index	Deck	Girder	Bent-Abutment-Wall	Foundation
Deck	1	1	0.84	1.476
Girder		1	1.644	1.94
Bent-abutment-wall			1	3.204
Foundation				1

Table 9. Relative weight of sub-indices in structural index (Results of Expert Choice software).

Sub-Index	Deck	Girder	Bent-Abutment-Wall	Foundation	Compatibility Rating
Relative weight	0.247	0.32	0.297	0.136	0.04

Table 10. Scores of sub-indexes in structural index.

Damage Intensity	Sub-Indexes Scores			
	Deck	Girder	Bent-Abutment-Wall	Foundation
Low	95	95	90	95
Mediate	70	65	60	75
High	30	30	25	35

The structural index score is the sum of weighted scores of its four sub-indices. In the bridge maintenance program, usually, more attention was allocated to structural sub-indices, and they were included with more details in the assessment. In other indices, however, evaluations were more general.

3.3.2. Hydrology and Climate Index

One of the affecting factors in the condition of a bridge is hydrology and environmental factors. The hydrology and climate index focuses on four factors, including river conditions, river type, climatic features, and the concentration of destructive matters (such as sulfates) in the water, soil, and air. Based on the explanation of Table A4, experts provided the appropriate scores in the range of 0 to 100 for various conditions of this table. A score of 100 is related to the best conditions, and a score of 0 is related to the worst conditions. These scores are shown in Table 11. The score of hydrology and climate index is the average value of these scores, with identical weight. It should be noted that if there is no river in the path under the bridge, the sub-indices of river conditions and destructive matters would be removed.

3.3.3. Safety Index

This index includes parameters that affect the safety of the bridge. These parameters include the beauty and proper serviceability of curbs, absence of crack/fracture/delaminated curbs, proper functioning of the guardrails/fences, lighting and brightness, and the efficiency of the drainage system to provide sufficient friction coefficient. Table A5 in the questionnaire was designated for the safety index. Based on the explanation of Table A5, experts were asked to assign the relevant score for various conditions of safety equipment. These scores are in the range of 0 to 100. Again, the scores of 100 and 0 are related to the best and worst conditions, respectively. Table 12 shows the average scores based on the experts' scores. The safety index score is the average value of scores of these three sub-indexes, with identical weight.

Table 11. Scores of sub-indexes in hydrology and climate index.

Sub-Indexes Scores			
River Conditions		**River Type**	
Description	**Score**	**Type**	**Score**
There is no erosion in the riverbed or the erosion is trivial. The amount of sedimentation and debris is negligible	98	Area under the bridge is not a river path	98
The riverbed has eroded slightly. There are signs of depositions in the upstream and downstream. Further analysis is required to detect failures	58	There is seasonal river flowing under the bridge.	59
The erosion of the riverbed is critical and concerning. There are enormous amounts of sedimentations around the bridge. Serious measures have to be taken.	14	There is permanent river flowing under the bridge.	8
Climatic Features		**Destructive Agents**	
Description	**Score**	**Quality of Protection against Destructive Matters**	**Score**
Mild (there are no invasive agents such as moisture, transpiration, freezing and melting cycle, corrosive substances, etc.)	93	Very good	95
Medium (conditions that are occasionally exposed to moisture and transpiration, and elements that are permanently exposed to non-invasive soils and water, or underwater with a pH > 5)	80	Good	76
Severe (extreme humidity or transpiration, or freezing and thawing cycle, elements immersed in water, such that one surface is exposed to air, elements in chlorine ion air, elements exposed to corrosion caused by the use of anti-freezing agents)	54	Medium	49
Extremely severe (conditions that are exposed to gases, water and static sewage with a pH of up to 5, corrosive matters, moisture with extreme icing and melting)	35	Bad	14
Exceptionally severe (conditions subject to extreme erosion, flowing water and sewage with a maximum pH of 5)	20	-	-

Table 12. Score of sub-indexes in safety index.

Sub-Indexes Scores					
Curbs, Guardrails and Fences		**Lighting and Brightness**		**Drainage of Surface Water**	
Description of Defects	**Score**	**Conditions**	**Score**	**Drainage Condition**	**Score**
No repair is needed	98	Trivial dazzling, excellent color rendering, broad sight	94	Perfect drainage, adequate friction coefficient	96
Partial repair is needed	67	Slight dazzling, color rendering and sight are relatively desirable	66	Drainage for securing desirable friction	68
Major repair is required	14	Extreme dazzling, low color rendering and limited sight	23	Improper drainage, undesirable friction coefficient	27

3.3.4. Load Impact Index

In bridges that are under heavy loads or dynamic loads, damages are more common. The dynamic load imposed on a railway bridge is higher than that of a road bridge. Moreover, bridges for which use crossing heavy vehicles, such as a trailer or trucks, are more likely to be damaged than bridges used for light traffic. These points are considered in the impact load index. Table A6 in the questionnaire was designated for this index. In this table, experts assigned their scores for various classes and types of the transport system that the under-investigation bridge belongs to it. These scores are in the range of 0 to 100. Table 13 shows the final results of Table A6 that is the average value of experts' scores.

Table 13. Load impact score.

Class	Transport Type	
	Car	Train
Freeway	40	30
Highway and major road	45	40
Minor road	70	60
Rural road	85	-
Metro and monorail	-	70

3.3.5. Geotechnical and Seismic Index

The quality of soil under the bridge foundation, seismicity of the region, and its geological structure affect the behavior of the bridge during an earthquake and its settlement, which consequently affect the bridge condition. For considering these points, Table A7 was designed to determine the geotechnical and seismic index. According to the earth and the seismic area type, experts filled the blank cells with numbers from the range of 0 to 100. The better conditions take higher scores and vice versa. The average values of Table A7 are presented in Table 14. Based on Table 14, each bridge takes two scores: Geotechnical score and seismic score. The score of the geotechnical and seismic index is obtained by averaging these two scores.

Table 14. Scores of sub-indexes in geotechnical and seismic index.

Sub-Indexes Scores			
Geotechnical		Seismic	
Earth Type	Score	Seismic Area Type	Score
I	92	Low relative risk	80
II	71	Medium relative risk	63
III	47	High relative risk	40
IV	26	Very high relative risk	23

3.3.6. Strategic Importance Index

This index indicates the importance of the bridge location in terms of regional, strategic, and political considerations. Strategic areas include hospitals (with more than 500 beds), military centers, crisis management centers, and fire stations. The experts were asked to write their scores in Table A8. They used the numbers from the range of 0 to 100. Table 15 indicates the final scores that are the average values of experts' scores.

Table 15. Scores of the strategic importance index.

The Strategic Importance of Bridge	Score
High importance (links two strategic areas)	89
Medium importance (links streets and non-strategic arterial)	55
Low importance (other bridges)	29

3.3.7. Facilities Index

This index is composed of two parts, including mechanical facilities and electrical facilities. The facilities index demonstrates the need for repairing the electrical or mechanical facilities of the bridge. Table A9 in the questionnaire was designed for this index. Experts scored various conditions of these facilities from the range of 0 to 100. Scores of 100 and 0 are related to the best and the worst conditions, respectively. The average values of these scores are presented in Table 16. It is important to point out that both sub-indexes of Table 16 have the same importance. Therefore, the overall score of the facilities index concludes from averaging of sub-indexes scores with equal weights.

Table 16. Scores of sub-indexes in facilities index.

Sub-Indexes Scores			
Mechanical Facilities		**Electrical Facilities**	
Drainage System	**Score**	**Lighting Condition**	**Score**
Fair	97	Good	92
Critical	62	Medium	62
Inappropriate	30	Unfair	29

3.3.8. Traffic and Pavement Index

Two other affecting parameters in bridge serviceability are traffic and pavement condition. For considering these parameters, the authors designed Table A10 in the questionnaire. Traffic effects are determined according to traffic volume and traffic condition. Pavement effects are considered as the pavement condition index (PCI). Therefore, the traffic and pavement index has three sub-indexes. Experts scored in the blank cells of Table A10 with the numbers from the range of 0 to 100. Furthermore, PCI is a number between 0 and 100. Table 17 shows the average of experts' views. Accordingly, the inspector needs three scores for each bridge: Traffic conditions score, Traffic volume score, and PCI. Finally, by averaging these three numbers, the score of traffic and pavement index will be obtained. It is important to point out that all sub-indexes (traffic condition, traffic volume, and pavement condition index) have the same importance.

Table 17. Scores of traffic sub-index.

Traffic Sun-Indexes Scores			
Traffic Conditions	**Score**	**Traffic Volume**	**Score**
Very good (traffic facilities are perfectly working, full sight distance and the number of lanes is standard)	95	Low	89
Good (traffic facilities are in relatively good condition, sight distance is desirable in most areas and the number of lanes is appropriate)	74	medium	68
Moderate (Some of traffic facilities are in bad conditions and the bridge has an undesirable curve)	51	Heavy	51
Bad (lanes are not enough, traffic facilities are not working, the bridge has a horizontal and vertical curve together, the sight distance is not appropriate).	12	Very heavy	26

4. Results and Discussion

The theoretical method needs to test in the real world to be more reliable for engineers. For this purpose, in this study, five bridges in Semnan province in Iran have been selected and implemented the proposed method for them. These bridges as following:

- Bridge No. 1: The bridge of Shahmirzad road intersection,
- Bridge No. 2: The bridge of Sari road intersection,
- Bridge No. 3: The bridge on 73rd km of Semnan-Damghan road,
- Bridge No. 4: The bridge on 6th km of Semnan-Jandaq road,
- Bridge No. 5: The bridge on 12th km of Semnan-Jandaq road.

First, all bridges are inspected by the authors. After that, the BCI of all bridges was determined based on the proposed method in this study. Finally, the prioritization of all bridges was conducted. The results of inspection and rating of bridges are given in the following subsections.

4.1. Determination of BCI in Bridge No. 1

The bridge of Shahmirzad road intersection is located in the city of Semnan, at the beginning of the Semnan-Shahmirzad road (Figure 5). This bridge has two spans and acts as the overpass of the Mashhad-Tehran highway. The bridge is forty-five meters in length, twenty-three meters in width, and has three lanes in each direction.

As shown in Figures 6 and 7, the structural elements of this bridge were in satisfactory conditions. Mostly, these elements were in low-distress conditions and rarely had medium-distress conditions. Hydrology and climate condition was good. The safety of the bridge was moderate. This bridge is part of the highway network, and the load impact score was forty-five. Earth type is II, and the seismic area type is high relative risky. The strategic importance of the bridge is medium. Bridge facilities were in weak condition. The drainage system and the electrical facilities were in inappropriate and medium conditions, respectively. Some of the traffic facilities were in bad condition, traffic volume was medium, and PCI was 76 (Figure 8). After completing the inspection and determination of all indices scores, BCI can be calculated (Table 18).

Figure 5. The bridge No. 1 on Google Earth (Latitude: 35°36′15″ N, Longitude: 53°22′16″ E).

Figure 6. The structure of the bridge No. 1.

Figure 7. An example of minor cracking in the wall of the bridge No. 1.

Figure 8. The pavement condition in the bridge No. 1.

Table 18. Calculation of BCI in bridge No. 1.

	Index	W_i	X_i	$W_i \times X_i$	BCI = $\sum (W_i \times X_i)$
1	Structural	0.331	93.765	31.036	72.849
2	Hydrology and Climate	0.097	95.5	9.264	
3	Safety	0.146	66	9.636	
4	Bridge Performance (load impact)	0.08	45	3.6	
5	Geotechnical and Seismic	0.143	55.5	7.937	
6	Strategic Importance	0.088	55	4.84	
7	Facilities	0.046	46	2.116	
8	Traffic and Pavement	0.068	65	4.42	

4.2. Determination of BCI in Bridge No. 2

The bridge of Sari road intersection is located in Damghan, at the cross of Damghan-Semnan and Damghan-Sari roads (Figure 9). The bridge has two spans and two lanes and is twenty-five meters in length and nine meters in width. After inspecting, the structural elements of this bridge, including deck, girder, bent-abutment-wall, and foundation, received the highest possible score because of their health conditions (Figure 10). In hydrology and climate examinations, there was no problem. The only problem of safety was related to lighting and brightness. The scores of the load impact, geotechnical and seismic, and strategic importance indices were similar to bridge No. 1. Another issue was related to the mechanical facilities of the drainage system that was inappropriate (Figure 11). Traffic condition was very well, volume traffic was medium, and PCI was 100. A summary of the BCI calculations in this bridge is presented in Table 19.

Figure 9. The bridge No. 2 on Google Earth (Latitude: 36°10′35″ N, Longitude: 54°18′17″ E).

Figure 10. The structural elements of bridge No. 2.

Figure 11. An example of block in the facilities of drainage system (bridge No. 2).

Table 19. BCI calculation of the bridge No. 2.

	Index	W_i	X_i	$W_i \times X_i$	BCI = $\sum (W_i \times X_i)$
1	Structural	0.331	93.765	31.036	73.221
2	Hydrology and Climate	0.097	95.5	9.264	
3	Safety	0.146	63	9.198	
4	Bridge Performance (load impact)	0.08	45	3.6	
5	Geotechnical and Seismic	0.143	55.5	7.937	
6	Strategic Importance	0.088	55	4.84	
7	Facilities	0.046	30	1.38	
8	Traffic and Pavement	0.068	87.67	5.962	

4.3. Determination of BCI in Bridge No. 3

This bridge is located at 73rd km of Semnan-Damghan road (Figure 12). The bridge has five spans, a total length of sixty meters, a width of ten meters, and two lanes. Similar to the two previous bridges, this bridge had low damage in its structural elements. Figures 13 and 14 show the structure and the example of the structural damage in this bridge, respectively. In hydrology and climate index, status was moderate. The most important issue was about the quality of protection against destructive matters. Lighting and brightness conditions were not proper and can cause safety issues in the bridge. This bridge is part of the highway network, and therefore the score of the load impact index was forty-five. Earth type is II, and the bridge is located in a high relative risk region. The strategic importance of the bridge is medium. The drainage system was another issue in this bridge because of its critical condition. Traffic facilities acted perfectly, sight distance was fully covered, and the number of lanes was standard. The traffic volume was medium, and the pavement was in very good condition with some minor distresses in the shoulder (Figure 15). A summary of the BCI calculation of this bridge is presented in Table 20.

Figure 12. The bridge No. 3 on Google Earth (Latitude: 35°57′22″ N, Longitude: 54°01′54″ E).

Figure 13. The structure of bridge No. 3.

Figure 14. An example of structural damage in bridge No. 3.

Figure 15. The pavement condition of bridge No. 3.

Table 20. BCI calculation of the bridge No. 3.

	Index	W_i	X_i	$W_i \times X_i$	BCI = $\sum (W_i \times X_i)$
1	Structural	0.331	93.765	31.036	73.193
2	Hydrology and Climate	0.097	66	6.402	
3	Safety	0.146	72.33	10.56	
4	Bridge Performance (load impact)	0.08	45	3.6	
5	Geotechnical and Seismic	0.143	55.5	7.937	
6	Strategic Importance	0.088	55	4.84	
7	Facilities	0.046	62	2.852	
8	Traffic and Pavement	0.068	87.67	5.962	

4.4. Determination of BCI in Bridge No. 4

This bridge is located at 6th km of Semnan-Jandaq road (Figure 16). It has one span, a length of eight meters, a width of seven meters, and two lanes. All structural subindexes were in low damage condition, except the bent-abutment-wall that had mediate damage intensity (Figure 17). Although this bridge is exposed to invasive agents (look at Figure 16), there was not appropriate protection against this issue. For this reason, the score of hydrology and climate index decreased into the moderate range. The safety of the bridge was not in a satisfactory status. Safety equipment needed repair, lighting condition is critical, and drainage condition was not very well (look at Figure 18). This bridge services as a member of a minor road, and therefore, the score of the load impact index is seventy. Earth type is III, and the bridge is located in a region with high relative risk. Based on Table 15, the score of strategic importance is twenty-nine because this bridge does not link the strategic areas, streets, and non-strategic arterials. In this bridge, there were no electrical facilities, and mechanical facilities were not in appropriate condition. Therefore, the score of the facilities index was thirty. Traffic volume was very low, traffic condition was very bad, and also, the pavement had not satisfactory status, and PCI was thirty-four (Figure 19). Table 21 shows a summary of the BCI calculation of this bridge.

Figure 16. The bridge No. 4 on Google Earth (Latitude: 35°32′28″ N, Longitude: 53°29′49″ E).

Figure 17. The structural damage in bridge NO. 4.

Figure 18. Safety and drainage issues in bridge No. 4.

Figure 19. Condition of pavement distresses in bridge NO. 4.

Table 21. BCI calculation of the bridge on 6th km of Semnan-Jandaq road.

	Index	W_i	X_i	$W_i \times X_i$	$BCI = \sum (W_i \times X_i)$
1	Structural	0.331	86.355	28.583	62.172
2	Hydrology and Climate	0.097	62.75	6.087	
3	Safety	0.146	52.67	7.69	
4	Bridge Performance (load impact)	0.08	70	5.6	
5	Geotechnical and Seismic	0.143	43.5	6.22	
6	Strategic Importance	0.088	29	2.552	
7	Facilities	0.046	30	1.38	
8	Traffic and Pavement	0.068	45	3.06	

4.5. Determination of BCI in Bridge No. 5

This bridge is located at 12th km of Semnan-Jandaq road (Figure 20) and has three spans, a length of twenty meters, a width of eight meters, and two lanes. Due to problems in the wall and foundation (Figures 21 and 22), the score of the structural index decreases to 83.635. Invasive agents caused erosion, and protection against them is weak. Safety equipment required major repair, lighting and brightness condition was in a bad status, and drainage condition could not provide the desired friction (look at Figure 23). Because of being in the same region and transport network, bridges No.4 and No. 5 have similar scores in the load impact index, geotechnical and seismic index, and strategic importance index. The mechanical facilities of the drainage system were improper. The volume of traffic was at a level of low. There are no proper traffic horizontal/vertical signs. The pavement had various distresses, and PCI was thirty-six. BCI in this bridge is calculated in Table 22.

Table 22. BCI calculation of the bridge on 12th km of Semnan-Jandaq road.

	Index	W_i	X_i	$W_i \times X_i$	$BCI = \sum (W_i \times X_i)$
1	Structural	0.331	83.635	27.683	56.768
2	Hydrology and Climate	0.097	52.75	5.117	
3	Safety	0.146	35	5.11	
4	Bridge Performance (load impact)	0.08	70	5.6	
5	Geotechnical and Seismic	0.143	43.5	6.22	
6	Strategic Importance	0.088	29	2.552	
7	Facilities	0.046	30	1.38	
8	Traffic and Pavement	0.068	45.67	3.106	

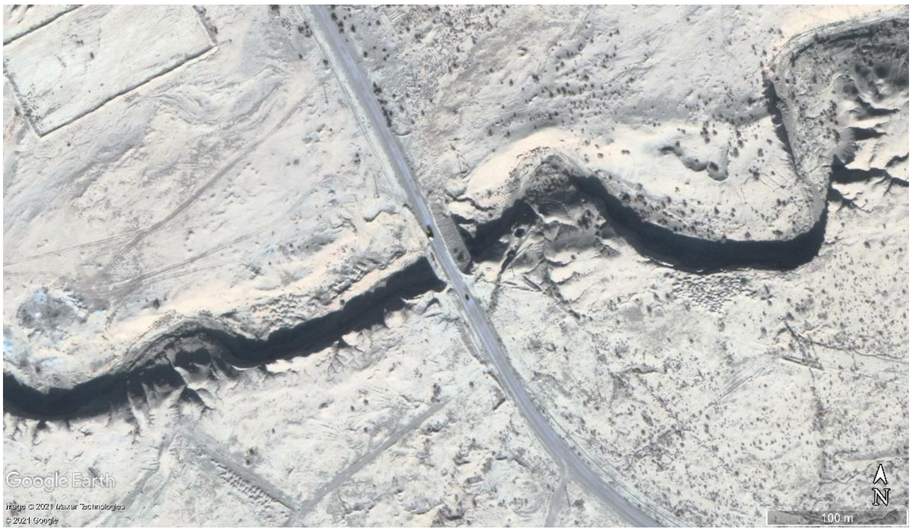

Figure 20. The bridge No. 5 on Google Earth (Latitude: 35°31′59″ N, Longitude: 53°30′46″ E).

Figure 21. Damage in the wall of the bridge No. 5.

Figure 22. Bridge scour in bridge No. 5.

Figure 23. Distresses of pavement and safety problems in bridge No. 5.

In this section, the authors aimed to check the ability of their methodology. They selected five case studies from the bridge network in Semnan province, in Iran. The authors tried to adopt the bridges that have the maximum possible difference in condition. According to Tables 18–22, the bridge of 12th km of Semnan-Jandaq road has the lowest BCI among the five studied bridges (BCI = 56.8). This bridge takes the highest priority for maintenance. The second priority is related to the bridge of 6th km of Semnan-Jandaq road with BCI = 62.2. The bridge at the beginning of Shahmirzad road, with BCI = 72.8, takes the third priority. Two other bridges with BCI = 73.2 take the lowest maintenance priority.

As mentioned in the earlier sections, a review of previous studies shows the lack of a comprehensive method for evaluating and prioritizing bridges. Each of the methods proposed by other researchers generally focuses on limited parts of the factors affecting the bridge conditions. In this study, the authors tried to develop a new methodology that includes all the factors affecting the condition of bridges. Scrutiny of the results obtained from five under-study bridges, with different characteristics, confirms that this method is feasible. On the one hand, the method is simple and can save time and money in the health monitoring process of the bridge network. On the other hand, the flexibility of the methodology is high, and therefore this methodology can be easily calibrated and implemented in any other place. It is enough to design the relevant questionnaire, gather the opinion of bridge experts, analyze the filled questionnaires, determine scores and weights, and after that, inspect and prioritize bridges. This study helps remove another gap: The lack of an efficient, comprehensive method/system for health monitoring of bridges in Iran. This gap results in wasting resources and time. Continuous, exact, complete health monitoring and correctly prioritizing are essential needs for infrastructures. The proposed methodology can simply apply in various regions of Iran. Therefore, this study helps improve the quality of BMS activities in Iran, and it can be another helpfulness of this work.

Despite the positive points mentioned in the previous paragraph, the proposed method has a limitation named the subjective influence of inspectors. Visual inspection is a measurement mechanism implemented by humans. Accordingly, variability influences the reliability of this mechanism. In fact, the visual examination gives valuable data on bridge health, but it is not always guaranteed since it depends mainly on the inspector's experience and knowledge. Of course, this issue can hardly be avoided. One solution for such an issue is to use auxiliary analyses, such as non-destructive tests (NDTs). Although this solution can confine the subjective influence of inspectors, it will confront the authors with another limitation. Most of the local organizations in Iran are deprived of NDT equipment or similar tools. Moreover, the authors intend to present an easy-to-use, applicable method for all organizations in Iran, including local organizations. Eventually, the authors decided to base their methodology according to direct inspection by inspectors. In their opinion, the advantages of being more usable of the methods conquer possible disadvantages of subjective influence of inspectors. For solving or reducing the problem of inspectors' influence, they suggest that organizations should focus on the personal selection and better training of inspectors.

As part of future works, the authors are investigating three different research objectives. First, the authors are very interested in connecting new technologies/tools/methods with their methodology. One of these new technologies is remote sensing (RS). RS analyzes different objects on the earth's surface by data received from a device that is not in contact with those objects. Another tool is machine learning (ML). ML originated from artificial intelligence (AI) and has been used in recent years in various scientific areas. Increasing applications of RS [48–54] and ML [55–59] in structural health monitoring of infrastructures in recent years motivates the authors to conduct this idea. Second, the authors intend to extend the proposed methodology for other types of bridges, including steel and stone (old) bridges. The latter idea can help enlarge the application dominance of the methodology. Finally, by increasing the number of experts asked to fill the questionnaire, the accuracy and efficiency of the methodology will be more reliable.

5. Conclusions

This study presents a new methodology for the determination of BCI in concrete bridges. BCI constitutes eight indices and several sub-indexes. Each one of these indices and sub-indices has a specific score and importance weight. The scores and weights are assigned by experts of bridge engineering. After determining scores and weights, inspectors survey the bridge and assign the scores to all sub-index based on their condition. Then, the score of each index is obtained. Finally, by summing the weighted scores of indices, BCI will be determined. The necessity of this research could be justified in the absence of any comprehensive and effective system or index for assessing the bridge conditions, especially in Iran. Due to financial constraints and the lack of qualified specialists, it is also crucial to provide solutions to overcome these shortcomings. Therefore, in this research, attempts were made to develop a new, simple method for assessing bridge conditions in order to optimize the management activities. The novelty of this study is in the scoring system because the scoring system is constructed by native experts' views. On the other hand, because of the lack of a comprehensive, proper index in Iran, this paper is considered innovative. Simplicity is one of the characteristics of the proposed method because it does not require the application of non-destructive equipment or laboratory tests. The method allows measuring BCI and prioritizing bridges for maintenance based on the visual evaluation of the damages and general characteristics of the bridge and their performance. Therefore, time and budget can be saved in this method. On the other hand, the experts' views, scores, and coefficients of relative importance may vary in different organizations or countries. Thus, the calibration of this method is only done by designing the questionnaire and collecting experts' views. For testing the proposed method, five bridges in Semnan province were inspected, and their BCI was determined to prioritize bridges.

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Appendix A. Survey Questionnaire

This appendix presents the questionnaire used in this study.

Appendix A.1. Introduction

This survey belongs to a study that will provide a bridge condition index (BCI) for concrete bridges in Iran. BCI is an applicable tool that can be help engineers in bridge management programs. This tool provides a method for evaluating and prioritizing the existing bridges. Because this method will be implemented for bridge networks in Iran, the viewpoint of Iranian experts is crucial in this study. Therefore, this questionnaire aims to gather the opinion of bridge experts about influencing indexes on bridge conditions in Iran.

Appendix A.2. Overview

BCI involves eight indices, including Structural, Hydrology and Climate, Safety, Bridge Performance, Geotechnical and Seismic, Strategic Importance, Facilities, and Traffic and Pavement. Moreover, each index divides into several sub-indexes. Therefore, you deal with these indexes and sub-indexes.

This survey consists of several tables, which you must insert your standpoint as a number. The necessary explanations are presented in each part and help you.

Appendix A.2.1. BCI Indices

Table A1 aims to provide the relative importance of affecting indices on bridge conditions. You must assign a value between 0 and 10 based on your technical experience and expertise in each cell of the table. If the row index is more important than the column index, a value between 1 and 10 must be assigned (the more important, the bigger the number). In contrast, if the column index is more important than the row index, a value between 0 and 1 must be assigned (the more important, the smaller the number). In this pairwise comparison, the number one is related to the same relative importance.

Table A1. Relative importance of indices.

Index	**Structural**	**Hydrology and Climate**	**Safety**	**Bridge Performance (Load Impact)**	**Geotechnical and Seismic**	**Strategic Importance**	**Facilities**	**Traffic and Pavement**
Structural	1							
Hydrology and Climate		1						
Safety			1					
Bridge Performance (load impact)				1				
Geotechnical and Seismic					1			
Strategic Importance						1		
Facilities							1	
Traffic and Pavement								1

Appendix A.2.2. Structural Index

The structural index includes four sub-indexes. Table A2 aims to determine the relative importance of these sub-indexes. Please, assign a value between 0 and 10 based on your technical experience and expertise in each cell of the table. If the row index is more important than the column index, a value between 1 and 10 must be assigned (the more important, the bigger the number). In contrast, if the column index is more important than the row index, a value between 0 and 1 must be assigned (the more important, the smaller the number). In this pairwise comparison, the number one is related to the same relative importance.

Table A2. Relative Importance of Sub-Indices in Structural index.

Sub-Index	Deck	Girder	Bent-Abutment-Wall	Foundation
Deck	1			
Girder		1		
Bent-abutment-wall			1	
Foundation				1

Based on the damage intensity, score four sub-indexes of the structural index in Table A3. Your scores must be in the range of 0 to 100. Note that the score of 100 is related to the best condition and the score of 0 is related to the worst condition.

Table A3. Scores of Sub-Indexes in Structural Index.

Damage Intensity	Sub-Indexes Scores			
	Deck	Girder	Bent-Abutment-Wall	Foundation
Low				
Mediate				
High				

Appendix A.2.3. Hydrology and Climate Index

Based on the explanation of Table A4, rate river condition, river type, climatic feature, and the existence of destructive agent. Your scores must be in the range of 0 to 100. Note that the score of 100 is related to the best condition and the score of 0 is related to the worst condition. It is important to point out that all sub-indexes have the same importance. Therefore, the overall score of the index includes the sum of sub-indexes scores with equal weights.

Appendix A.2.4. Safety Index

Based on the explanation of Table A5, provide the proper score for various conditions of safety equipment. Your scores must be in the range of 0 to 100. Note that the score of 100 is related to the best condition and the score of 0 is related to the worst condition. It is important to point out that all sub-indexes have the same importance. Therefore, the overall score of the index includes the sum of sub-indexes scores with equal weights.

Table A4. Scores of sub-indexes in hydrology and climate index.

Sub-Indexes Scores			
River Condition		**River Type**	
Description	**Score**	**Type**	**Score**
There is no erosion in the riverbed or the erosion is trivial. The amount of sedimentation and debris is negligible		Area under the bridge is not a river path	
The riverbed has eroded slightly. There are signs of depositions in the upstream and downstream. Further analysis is required to detect failures		There is seasonal river flowing under the bridge.	
The erosion of the riverbed is critical and concerning. There are enormous amounts of sedimentations around the bridge. Serious measures have to be taken.		There is permanent river flowing under the bridge.	
Climatic Features		**Destructive Agents**	
Description	**Score**	**Quality of Protection against Destructive Matters**	**Score**
Mild (there are no invasive agents such as moisture, transpiration, freezing and melting cycle, corrosive substances, etc.)		Very good	
Medium (conditions that are occasionally exposed to moisture and transpiration, and elements that are permanently exposed to non-invasive soils and water, or underwater with a pH > 5)		Good	
Severe (extreme humidity or transpiration, or freezing and thawing cycle, elements immersed in water, such that one surface is exposed to air, elements in chlorine ion air, elements exposed to corrosion caused by the use of anti-freezing agents)		Medium	
Extremely severe (conditions that are exposed to gases, water and static sewage with a pH of up to 5, corrosive matters, moisture with extreme icing and melting)		Bad	
Exceptionally severe (conditions subject to extreme erosion, flowing water and sewage with a maximum pH of 5)			

Table A5. Scores of sub-indexes in Safety index.

Sub-Indexes Scores					
Curbs, Guardrails and Fences		**Lighting and Brightness**		**Drainage of Surface Water**	
Description of Defects	**Score**	**Conditions**	**Score**	**Drainage Condition**	**Score**
No repair is needed		Trivial dazzling, excellent color rendering, broad sight		Perfect drainage, adequate friction coefficient	
Partial repair is needed		Slight dazzling, color rendering and sight are relatively desirable		Drainage for securing desirable friction	
Major repair is required		Extreme dazzling, low color rendering and limited sight		Improper drainage, undesirable friction coefficient	

Appendix A.2.5. Load Impact Index

Based on the class and the type of transport (road or rail), provide the proper score for Table A6. Your scores must be in the range of 0 to 100.

Table A6. Load impact score.

Class	Transport Type	
	Road	Rail
Freeway		
Highway and major road		
Minor road		
Rural road		
Metro and monorail		

Appendix A.2.6. Geotechnical and Seismic Index

Based on the earth type and the seismic area type, give the appropriate score for Table A7. Your scores must be in the range of 0 to 100. Note that the score of 100 is related to the best and the safest situation, and the score of 0 is related to the worst and most risky one. It is important to point out that both sub-indexes have the same importance. Therefore, the overall score of the index includes the sum of sub-indexes scores with equal weights.

Table A7. Scores of Sub-Indexes in Geotechnical and Seismic Index.

Sub-Indexes Scores			
Geotechnical		Seismic	
Earth Type	Score	Seismic Area Type	Score
I		Low relative risk	
II		Medium relative risk	
III		High relative risk	
IV		Very high relative risk	

Appendix A.2.7. Strategic Importance Index

Table A8 evaluates the strategic importance of bridges. Write the appropriate scores. Your scores must be in the range of 0 to 100.

Table A8. Scores of the strategic importance index.

The Strategic Importance of Bridge	Score
High importance (links two strategic areas)	
Medium importance (links streets and non-strategic arterial)	
Low importance (other bridges)	

Appendix A.2.8. Facilities Index

Considering conditions of mechanical and electrical facilities can be conducted in Table A9. Please, write the appropriate scores in the range of 0 to 100. Note that the score of 100 is related to the best condition, and the score of 0 is related to the worst condition. It is important to point out that both sub-indexes of Table A9 have the same importance. Therefore, the overall score of the facilities index concludes from averaging of sub-indexes scores with equal weights.

Table A9. Scores of sub-indexes in facilities index.

Sub-Indexes Scores			
Mechanical Facilities		**Electrical Facilities**	
Drainage System	**Score**	**Lighting Condition**	**Score**
Fair		Good	
Critical		Medium	
Inappropriate		Unfair	

Appendix A.2.9. Traffic and Pavement Index

This index is related to traffic and pavement conditions in bridges. It has three sub-indexes, including traffic condition, traffic volume, and the pavement condition index. Fill appropriate scores in the blank cells of Table A10. This table represents the traffic condition and volume of a bridge. Your scores must be in the range of 0 to 100. Whatever the traffic condition is better and traffic volume is lower, your score must be higher because the bridge is in a more reliable situation. Furthermore, for considering the pavement condition, we use the pavement condition index (PCI). PCI is an index that ranges from 0 to 100. It is important to point out that all sub-indexes (traffic condition, traffic volume, and pavement condition index) have the same importance. Therefore, the overall score of the index includes the sum of sub-indexes scores with equal weights.

Table A10. Scores of traffic sub-index.

Traffic Sub-Indexes Scores			
Traffic Conditions	**Score**	**Traffic Volume**	**Score**
Very good (traffic facilities are perfectly working, full sight distance and the number of lanes is standard)		Low	
Good (traffic facilities are in relatively good condition, sight distance is desirable in most areas and the number of lanes is appropriate)		medium	
Moderate (Some of traffic facilities are in bad conditions and the bridge has an undesirable curve)		Heavy	
Bad (lanes are not enough, traffic facilities are not working, the bridge has a horizontal and vertical curve together, the sight distance is not appropriate).		Very heavy	

Appendix A.3. Responding Information

Here is some information that can help us. Please, provide them:
Your name (optional):
Agency/University/Company :
Current position :
Address (optional):
Date :
E-mail :
Please, submit your completed questionnaire to: N.Karballaeezadeh@shahroodut.ac.ir or N.karballaeezadeh@gmail.com
Thank you in advance for your support and cooperation with our study.

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