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Index of Attention for a Simplified Condition Assessment and Classification of Bridges

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Abstract: A procedure for a simplified evaluation of bridges is proposed based on census and visual inspections. The structural–foundational, seismic, landslide, and hydraulic risks are considered, the hazard, vulnerability, and exposure factors of which are quantified with an index that can assume integer values from 1 to 5. Polynomial functions are then defined combining these indices, calculating an index for each risk and finally a multi-risk index of attention. The procedure follows a mathematical approach, less influenced by subjective choices, leading to a more gradual and efficient classification that managers can directly utilize. Specific needs and requirements result in specific configuration and calibration of the mathematical model coefficients. In this study, the authors calibrated coefficients to obtain results that were compliant with the Italian guidelines for existing bridges. The procedure, tested on a set of 86 bridges, does not replace an accurate evaluation, which is necessary in some cases and represents a higher level of knowledge, nor does it claim to provide a definitive result. It provides a more efficient classification, useful for establishing a rational decision-making process to prioritize any subsequent retrofit interventions.

Keywords: index of attention; bridge; evaluation; bridge guidelines; case studies

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1. Introduction

The recent disasters that affected bridges all over the world, which in Italy culminated in the collapse of the Polcevera Viaduct in Genoa on 14 August 2018, have highlighted a state of degradation of road infrastructures in Europe and the world, partly due to age, but sometimes to the lack of adequate maintenance [1–5]. The problem is enormous, and a serious and reliable solution is not possible in the short term. However, starting a process to resolve it shortly is essential, as has already been done in some cases [6,7].

A simplified but reliable evaluation is needed to quickly establish a priority ranking. Knowledge undoubtedly represents the first fundamental step in evaluating the condition of each bridge and establishing suitable ratings to schedule successive interventions.

Nowadays, the refinement of knowledge and the availability of powerful calculation tools allow very accurate and sophisticated assessment analyses of the condition of existing bridges. This applies both to modern bridges [8,9] and historic ones. In the first case, the knowledge of the construction details and characteristics of the materials is generally satisfactory due to the availability of the original design and/or the possibility of carrying out reliable tests on materials and structures. For the latest, instead, the geometry and properties of the materials are rarely known in depth, and sometimes simple models should be preferred [10].

Both static and dynamic monitoring and periodic experimental tests play a fundamental role in the knowledge process concerning a bridge. Numerous examples of experimental

analysis and structural health monitoring are available in the literature [11]. In several cases, the experimental analysis is used for the dynamic characterization of a bridge [12–14], considering innovative techniques [15], or as a basis for the structural assessment [16,17]. Continuous monitoring is more suitable for checking the health status of a bridge [18], identifying damages [19–22], defining maintenance planning [23,24], and checking specific issues [25]. It is also important to analyze the actual behavior of particularly significant structures [26]. The weigh-in-motion should always be considered as well [27–29]. On the other hand, thanks to the multiplication of studies on the actual behavior of bridges, it has been possible to improve knowledge in this regard and refine the analysis methods, also reducing the safety factors [30]. But there is still much to do.

The objective of these studies is twofold. On the one hand, there is the purpose of being able to evaluate the condition of individual bridges, and on the other hand, managing the entire road network of a country or region, establishing priorities for intervention or reconstruction, and optimizing the available budget. Finally, interesting proposals on information technology management platforms have been made [31].

Monitoring, experimental analysis, and structural assessment indeed represent the right path to take when evaluating the condition of a bridge. But this requires a long time, which is not compatible with the need for safety. In this regard, a reliable but expeditious evaluation methodology is necessary to draw up a scale of priorities for any in-depth subsequent investigation or intervention. This should be based on the geometrical and structural characteristics of a bridge and an accurate visual inspection, which can be sped up, for example, by using drones.

The problem has also been addressed by national codes and guidelines [32–35]. Among the most recent proposals, mention must be made of the Italian guidelines for classification and risk management, safety assessment and monitoring of existing bridges [36], issued in 2020 (LG2020 in the following) and updated in 2022. LG2020 proposes a multilevel and multi-risk approach, with the first three levels mandatory to be developed quickly to define a priority order for bridge maintenance activities. Structural–foundational, seismic, landslide, and hydraulic risks are considered, each related to the combination of the three usual factors, i.e., hazard, vulnerability, and exposure. LG2020 provides five classes for the factors and five classes for the risk evaluation. The result of the procedure is the assignment of a multi-risk class of attention (*CA*) for each bridge (i.e., a warning class; these classes will be detailed later). The use of this approach points out criticalities, which do not allow a useful classification necessary to prioritize the necessary interventions and the use of the resources.

The main issues that arise are as follows.

- In situations where many bridges fall into the highest *CA*s.
- In situations where bridges in similar condition are assigned to different *CA*s and vice versa.
- In situations where significantly different bridges fall into the same *CA*.

Therefore, a mathematical procedure is needed to define a priority order for the bridges within each class of attention.

In this paper, a mathematical procedure for a simplified assessment of bridges is proposed. Based on census and visual inspection, an index is attributed to each risk factor, which can take integer values from 1 to 5, analogous to the five discrete classes defined by LG2020. Polynomial functions are then defined, combining these indices to arrive at an index for each risk and then at a multi-risk index. The advantages are obvious. The mathematical approach is less sensitive to subjective choices, and a gradual evaluation is obtained with a more efficient classification that managers can use directly. The coefficients of the mathematical models can be calibrated according to specific needs. In this study, they were calibrated to obtain results similar to those of LG2020.

The procedure does not replace an accurate evaluation, which is necessary in some cases and represents a higher level of knowledge, nor does it claim to provide a definitive assessment of bridges. It is helpful for a simplified assessment and a more efficient

preliminary classification of bridges, which is necessary to plan subsequent actions with greater awareness. The proposed assessment applies to all types of bridges. This can be considered an improvement of the methodology proposed by present codes or guidelines, such as LG2020 for structural health monitoring and damage detection of bridges, which is probably the most advanced in the world now. Therefore, LG2020 represents a suitable reference in this study. From a methodological point of view, this study remains generic and can be used worldwide, accounting for differences in loads and codes.

2. Criteria and Procedures for a Simplified Assessment of Bridges

Suitable procedures for the safety assessment of bridges and their classification according to their structural condition have been proposed in several countries [37]. Usually, these are based on census, visual inspections, a simplified assessment, and when necessary, additional inspections, monitoring, and an accurate assessment. Finally, maintenance planning or a retrofit intervention is defined to guarantee a longer life for the bridge.

Among these proposals, LG2020 provides a procedure to manage the safety of existing bridges. The aim is to classify all the infrastructures in the Italian territory, guarantee their safety, and correctly plan the maintenance works. A multilevel and multi-risk approach is proposed with growing complexity and an even more detailed study (Figure 1).

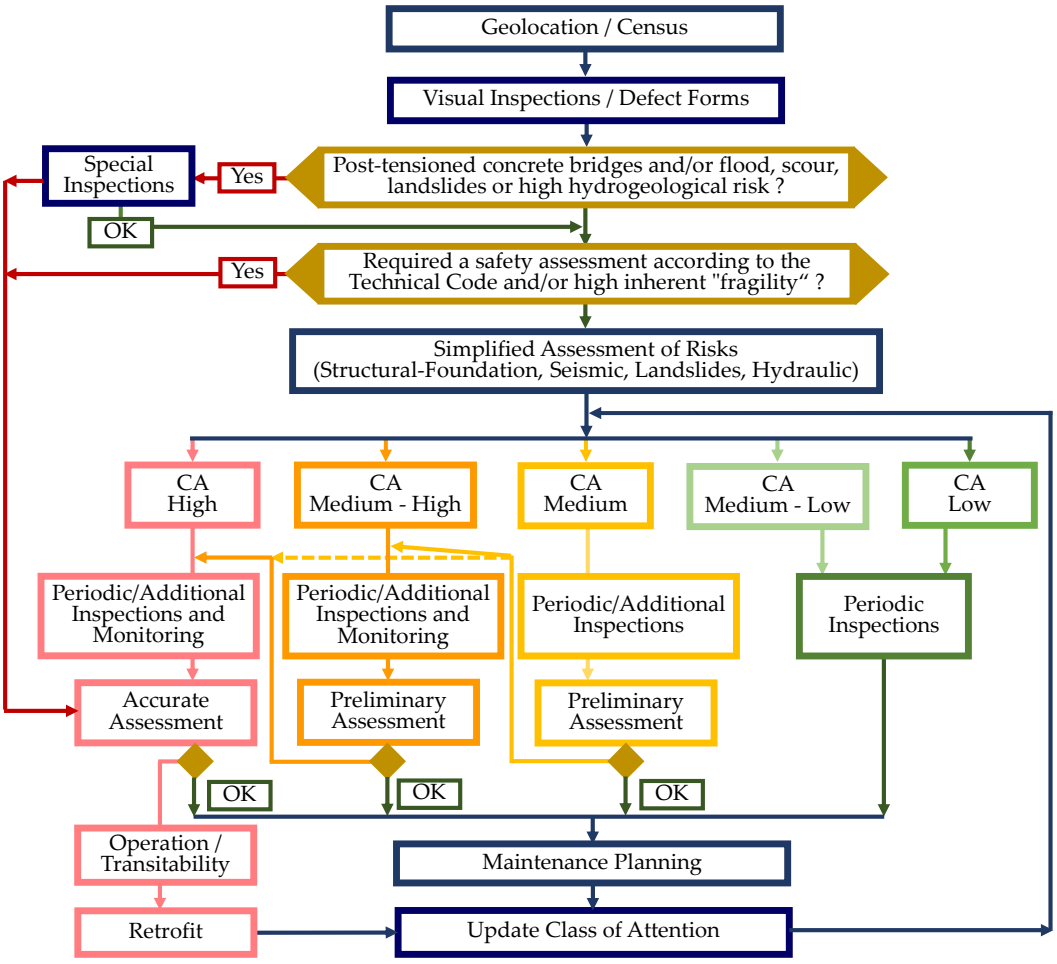


Figure 1. Flowchart of the multilevel approach of LG2020.

The first step, the census, is fundamental for the successive ones. All the existing information and documentation (e.g., original design, test certificates, etc.) should be available for each infrastructure. All the bridges must be registered:

- To create a database of all infrastructures [38].
- To know the number of infrastructures and their features.
- To choose an order of priority for the visual inspections.

Visual inspections of bridges represent the second step, the aims of which are:

- Verifying the information gained during the census.
- Evaluating the state of the infrastructure, inspecting each element of the bridge, and paying particular attention to critical elements.
- Evaluating the environmental state, establishing if there is a hydro-geological risk, and if the area is subjected to landslides, erosion, and flooding.

Bridges whose structural elements present serious apparent deficiencies deserve additional inspections and an accurate analysis. The same is true for structures in areas subject to landslides, erosion, and flooding or with high hydro-geological risk.

For all the other bridges, a simplified assessment is performed. The condition of a bridge is related to four different risks: structural–foundational, seismic, landslide, and hydraulic. Each risk is a combination of hazard, vulnerability, and exposure factors. These can be evaluated based on several parameters. The parameters to be considered are those reported in Table 1. These are divided into primary and secondary parameters. A usual procedure starts with the analysis of these parameters, which allows for a first evaluation of each risk factor. Appendix A shows how these parameters influence the indices for the different factors of the structural–foundational risk according to LG2020. Similar procedures are followed for the other risks.

Table 1. The four risks with the three factors and their primary and secondary parameters.

Risk	Factor	Primary Parameters	Secondary Parameters
Structural	Hazard	Expected loads	-
	Vulnerability	Degree of damage Static scheme, span, material	Design code Rate of degradation
	Exposure	Average daily traffic Span	Alternative road Type of bypassed obstacle Transport of dangerous goods
Seismic	Hazard	PGA Topography	Subsoil
	Vulnerability	Degree of damage Static scheme, span, material	Design criterion
	Exposure	Average daily traffic Span	Alternative road Type of bypassed obstacle Transport of dangerous goods Strategic nature
Landslide	Hazard	Slope instability	Model uncertainty Mitigation measures
	Vulnerability	Bridge typology Foundation typology	Interference extension
	Exposure	Average daily traffic Span	Alternative road Type of bypassed obstacle Strategic nature
Hydraulic	Hazard	Probability of occurrence Event consistency	Model uncertainty Mitigation measures
	Vulnerability	Resilience to natural events	Event typology Mitigation measures
	Exposure	Average daily traffic Span	Alternative road Type of bypassed obstacle Strategic nature

The evaluation for each factor is given on a scale of five classes: low (L), medium-low (ML), medium (M), medium-high (MH), and high (H). For each risk, the classes of hazard, vulnerability. and exposure are combined to obtain the class of attention of the risk (CA_r). The assessment of the risks is also organized in the same five classes (L, ML, M, MH, H). The four risks are finally combined to obtain the multi-risk *CA* of the bridge. The procedure is performed using logical operators, and the classes are combined using logical flows.

Even though the next steps for the assessment of bridges are out of the scope of this paper, it is essential to look at the actions to be taken after the simplified assessment. These can be summarized as follows:

- Bridge in low *CA*: no other actions except for periodic inspections.
- Bridge in medium-low *CA*: no other actions except frequent periodic inspections.
- Bridge in medium *CA*: preliminary assessment taking into account the information from periodic inspections and, if necessary, additional inspections. Based on this assessment, it could be decided to proceed according to the rules provided for bridges in medium-high or high *CA*.
- Bridge in medium-high *CA*: preliminary assessment taking into account the information periodic inspections and, if necessary, additional inspections and monitoring. Based on this assessment, it could be decided to proceed according to the rules of high *CA*.
- Bridge in high *CA*: accurate assessment, considering the information periodic inspections and, if necessary, additional inspections and monitoring.

The procedure proposed by LG2020 will be used in the following section, but numerical indices will be introduced instead of the five qualitative classes. The advantage is evident. When applying logical operators, the final ranking still considers only five classes. Conversely, the mathematical approach allows for an increase in the number of possible outcomes, obtaining a more detailed classification, preventing many bridges from falling into the same class, and therefore providing an efficient priority scale.

3. Index of Attention

The factors of hazard (H), vulnerability (V), and exposure (E) of each risk are first evaluated accounting for the parameters in Table 1 (see Appendix A). An index is associated with each of them: I_H, I_V and I_E, respectively. These indices can assume integer values from 1 to 5, corresponding to the L, ML, M, MH, and H classes of LG2020, respectively (Table 2). At this level, a more detailed evaluation would not be reliable, but as will be seen later, this is enough to establish a suitable ranking.

Table 2. Correspondence between LG2020 classes and the indices for the factors H, V and E.

Class	I_H, I_V, I_E
L	1
ML	2
M	3
MH	4
H	5

To understand the relationship between H, V, E, and the index of attention of any risk (IA_r), linear regression techniques are employed. The goal is to find a function that best approximates the results provided by LG2020. During the analysis, various polynomial linear, quadratic, cubic, etc. terms are examined to determine which provides the best fit for the observed data. Although exponential and trigonometric terms are considered, it is found that a combination of polynomial terms is generally sufficient to model the observed behavior for most risks accurately.

The index of attention of the risk r (IA_r) is given by the relation:

$$IA_r = \sum_i a_i I_i + \sum_{ij} a_{ij} I_i I_j + a \quad r = sf,\ s,\ l,\ h \quad i,\ j = H,\ V,\ E \tag{1}$$

The coefficient values are reported in Table 3. A unique set of coefficients is proposed for the structural–foundational risk (sf) and the seismic risks (s) and for the three components of the hydraulic risk (h), which will be introduced later. A different set is provided for the landslide risk (l). In more detail, this procedure is implemented using a combination of software tools, including Python. Libraries such as NumPy and Pandas are used for data manipulation, while scikit-learn is used for the regression models. To ensure the robustness of the proposed equations, the coefficient of determination R^2 is considered to evaluate their performance [39].

Table 3. Coefficient values for Equation (1).

Coefficient	Structural–Foundational Risk, Seismic Risks, Components of Hydraulic Risk	Landslide Risk
a_H	0.395	0.487
a_V	0.572	0.262
a_E	0.591	0.263
a_{HH}	0.136×10^{-1}	0.286×10^{-2}
a_{VV}	0.100	-0.400×10^{-2}
a_{EE}	0.138×10^{-1}	0
a_{HE}	-0.224×10^{-1}	-0.286×10^{-2}
a_{HV}	-0.558×10^{-1}	0.200×10^{-2}
a_{EV}	-0.997×10^{-1}	0
a	–1.13	0.118

The final function is chosen based on its ability to maximize the R^2 value and maintain consistency with LG2020 results. Linear terms are essential to represent the direct dependence between the quantities. Quadratic terms are included to capture any second-order nonlinear effects, such as interactions between the factors. Cubic terms are considered to further enhance the model's accuracy, especially where the relationships between the factors and the risk attention index exhibit higher-order complexity. Although exponential and trigonometric terms were tested, they did not significantly improve the model's accuracy compared to the polynomial terms. The same procedure is applied for the following index of attention.

The index of attention for the hydraulic risk (IA_h) is evaluated considering the general erosion risk, the local erosion risk, and the overcome risk. The indices of attention of these risks ($IA_{h,ge}$, $IA_{h,le}$, and $IA_{h,o}$, respectively) are determined using Equation (1), combining the indices of the H, V and E factors. The erosion risk ($IA_{h,e}$) is then evaluated using the following relation, which allows obtaining results compliant with LG2020:

$$IA_{h,e} = \frac{0.937\left(IA_{h,ge}^3 + IA_{h,le}^3\right)_l + 4.89}{0.146\left(IA_{h,ge}^3 + IA_{h,le}^3\right)_l + 6.12} \tag{2}$$

Finally, the IA_h is obtained as the maximum between $IA_{h,o}$ and $IA_{h,e}$:

$$IA_h = \max(IA_{h,o}, IA_{h,e}) \tag{3}$$

Landslide and hydraulic risks are combined, obtaining a landslide hydraulic index of attention (IA_{lh}) using the relation:

$$IA_{lh} = \frac{IA_l^{0.843} + IA_h^{0.843}}{1.44} - 0.214 \quad (4)$$

Finally, the multi-risk index of attention (IA) of a bridge is evaluated using the relation:

$$IA = \sum_i a_i IA_i + \sum_{ij} a_{ij} IA_i IA_j + \sum_{ijk} a_{ijk} IA_i IA_j IA_k + a \quad i,\ j,\ k = sf,\ s,\ lh \quad (5)$$

whose coefficients are given in Table 4. The procedure is synthesized in Figure 2.

Table 4. Coefficient values to combine structural–foundational (sf), seismic (s) and landslide hydraulic (lh) risks.

Coefficient	Value	Coefficient	Value
a_{sf}	1.06	$a_{sf,s}$	0.129×10^{-1}
a_s	0.490	$a_{sf,lh}$	0.156
a_{lh}	-0.277×10^{-1}	$a_{s,lh}$	-0.243×10^{-1}
$a_{sf,sf}$	−0.383	$a_{sf,sf,s}$	-0.171×10^{-1}
$a_{s,s}$	-0.686×10^{-1}	$a_{sf,sf,lh}$	-0.300×10^{-1}
$a_{lh,lh}$	0.243×10^{-1}	$a_{s,s,sf}$	0.100×10^{-1}
$a_{sf,sf,sf}$	0.717×10^{-1}	$a_{s,s,lh}$	0.571×10^{-2}
$a_{s,s,s}$	0.333×10^{-2}	$a_{lh,lh,sf}$	-0.143×10^{-2}
$a_{lh,lh,lh}$	0	$a_{lh,lh,s}$	0
a	−0.180	$a_{sf,s,lh}$	0.200×10^{-2}

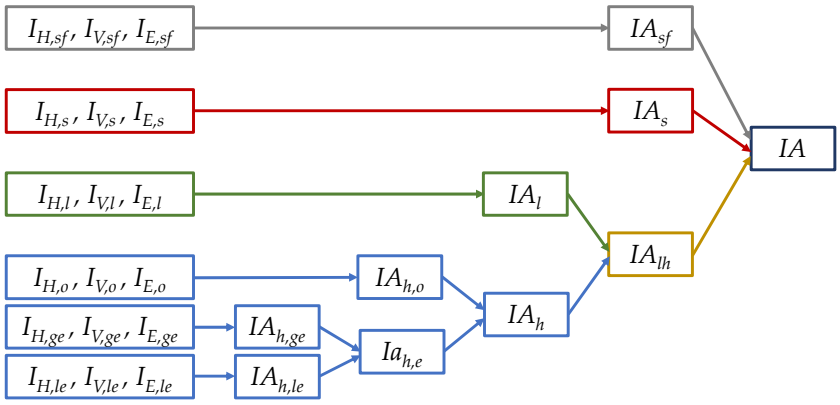


Figure 2. Flowchart for the evaluation of the multi-risk index of attention.

The selection of polynomial terms is guided by the objective of obtaining a simple yet accurate model that can be easily interpreted and applied to the different types of risks analyzed. This methodology allows for the establishment of an effective priority ranking based on the defined parameters. Moreover, while this study mainly refers to LG2020, the underlying principles and analytical framework of the methodology are designed to be adaptable. Therefore, this approach can be generalized for application in any country, where similar risk assessment guidelines are established, making it a versatile tool for global use.

4. Validation of the Procedure: Comparison with the Italian Guidelines for Bridges

The coefficients of Tables 3 and 4 have been calibrated with LG2020. Furthermore, for a comparison between the five classes of LG2020 and the values of *IA*, the range of these values has been divided into five intervals, as shown in Figure 3.

CA	*IA* Lower Limit	*IA* Upper Limit
L	-	1.62
ML	1.62	2.45
M	2.45	3.55
MH	3.55	4.40
H	4.40	-

Figure 3. Intervals of *IA*, classes of attention, and representation colors.

In Figure 4a, the indices of attention obtained for the structural–foundational and seismic risks are shown as a function of the *H*, *V* and *E* indices. The different colors defined in Figure 3 are useful for a comparison with the *CAs* of LG2020 shown in Figure 4b. Only in two cases did the *IA* (IA_{sf} or IA_s) obtained indicate a class lower by one step with respect to LG2020. In a few cases, the class is overestimated by one step. It is worth noting that in all these cases, the values of *IA* are very close to the boundary chosen between the two adjacent classes.

Hazard		1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
Exposure		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Vulnerability	1	0.38	0.89	1.43	1.99	2.58	0.74	1.22	1.74	2.28	2.85	1.12	1.59	2.08	2.60	3.15	1.53	1.98	2.45	2.94	3.47	1.97	2.39	2.84	3.32	3.82
	2	1.09	1.50	1.94	2.41	2.90	1.40	1.78	2.20	2.64	3.11	1.72	2.09	2.48	2.91	3.35	2.08	2.42	2.80	3.19	3.62	2.46	2.79	3.13	3.51	3.91
	3	2.01	2.32	2.66	3.03	3.42	2.26	2.55	2.86	3.20	3.58	2.53	2.80	3.09	3.41	3.76	2.83	3.07	3.35	3.64	3.97	3.16	3.38	3.63	3.90	4.21
	4	3.13	3.34	3.58	3.84	4.14	3.32	3.51	3.72	3.97	4.24	3.53	3.70	3.90	4.12	4.37	3.78	3.92	4.09	4.29	4.52	4.05	4.17	4.32	4.50	4.70
	5	4.44	4.56	4.69	4.86	5.06	4.58	4.67	4.78	4.93	5.10	4.74	4.81	4.90	5.02	5.17	4.93	4.97	5.04	5.14	5.27	5.14	5.17	5.22	5.29	5.40

(**a**)

Hazard		L	L	L	L	L	ML	ML	ML	ML	ML	M	M	M	M	M	MH	MH	MH	MH	MH	H	H	H	H	H
Exposure		L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H
Vulnerability	L	L	L	L	ML	ML	L	L	ML	ML	M	L	L	ML	M	M	L	ML	ML	M	M	ML	ML	M	M	MH
	ML	L	L	ML	M	M	L	ML	ML	M	M	ML	ML	M	M	M	ML	ML	M	M	M	M	M	M	M	MH
	M	L	ML	M	M	M	ML	ML	M	M	MH	M	M	M	M	MH	M	M	M	MH	MH	M	M	MH	MH	H
	MH	ML	M	M	M	MH	M	M	M	MH	MH	M	M	MH	MH	MH	M	MH	MH	MH	H	MH	MH	MH	H	H
	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H

(**b**)

Figure 4. (**a**) Indices of attention for the structural–foundational risk, IA_{sf}, and seismic risk, IA_s; (**b**) corresponding LG2020 classes of attention. Colors refer to the classes of attention in Figure 3.

Analogously, in Figure 5a, the index of attention for landslide (IA_l) obtained using the coefficients given in Table 3 is shown as a function of the *H*, *V* and *E* indices. The different colors indicate the different classes of attention defined before and are helpful for a comparison with the classification of LG2020, shown in Figure 5b. Only in one case does IA_l indicate a class lower by one step with respect to LG2020, but the value of *IA* is very close to the chosen boundary. It is worth noting that the same value is often present in more than one cell. This occurrence, which reduces the possible numerical outcomes, is related to the procedure used in LG2020, where the same weight is given to both vulnerability and exposure.

The index of attention for the hydraulic risk (IA_h) is evaluated from the overcome, the general erosion, and the local erosion risks. For each of these, the index of attention is evaluated from the *H*, *V* and *E* indices using Equation (1), and the combination values of Figure 4a are also valid. The indices $IA_{h,ge}$ and $IA_{h,le}$ are combined using Equation (2), whose coefficients were chosen in order to obtain results similar to those provided by

LG2020. As an example, the indices $IA_{h,e}$ obtained for specific values of $IA_{h,ge}$ and $IA_{h,le}$ are reported in Figure 6a. The corresponding classes of attention obtained according to LG2020 are in Figure 6b.

Hazard		1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
Exposure		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Vulnerability	1	1.13	1.39	1.65	1.91	2.17	1.62	1.88	2.14	2.39	2.65	2.12	2.38	2.63	2.89	3.14	2.63	2.88	3.13	3.38	3.64	3.14	3.39	3.64	3.89	4.14
	2	1.38	1.64	1.90	2.16	2.42	1.88	2.13	2.39	2.65	2.91	2.38	2.63	2.89	3.14	3.40	2.89	3.14	3.39	3.64	3.89	3.40	3.65	3.90	4.15	4.40
	3	1.62	1.88	2.14	2.40	2.66	2.12	2.38	2.64	2.89	3.15	2.63	2.88	3.14	3.39	3.64	3.14	3.39	3.64	3.89	4.14	3.65	3.90	4.15	4.40	4.65
	4	1.86	2.12	2.38	2.64	2.90	2.36	2.62	2.88	3.13	3.39	2.87	3.12	3.38	3.63	3.88	3.38	3.63	3.88	4.13	4.39	3.90	4.15	4.39	4.64	4.89
	5	2.09	2.35	2.61	2.87	3.13	2.59	2.85	3.11	3.36	3.62	3.10	3.35	3.61	3.86	4.12	3.61	3.86	4.12	4.37	4.62	4.13	4.38	4.63	4.88	5.13

(**a**)

Hazard		L	L	L	L	L	ML	ML	ML	ML	ML	M	M	M	M	M	MH	MH	MH	MH	MH	H	H	H	H	H
Exposure		L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H
Vulnerability	L	L	L	ML	ML	ML	ML	ML	ML	ML	M	ML	ML	M	M	M	M	M	M	MH	MH	M	M	MH	MH	MH
	ML	L	ML	ML	ML	ML	ML	ML	ML	M	M	ML	M	M	M	M	M	M	M	MH	MH	M	MH	MH	MH	MH
	M	ML	ML	ML	ML	M	ML	ML	M	M	M	M	M	M	M	MH	M	M	MH	MH	MH	MH	MH	MH	MH	H
	MH	ML	ML	M	M	M	ML	M	M	M	M	M	M	M	MH	MH	M	MH	MH	MH	MH	MH	MH	MH	H	H
	H	ML	ML	M	M	M	M	M	M	M	MH	M	M	MH	MH	MH	MH	MH	MH	MH	H	MH	MH	H	H	H

(**b**)

Figure 5. (**a**) Indices of attention for the landslide risk, IA_l; (**b**) corresponding LG2020 classes of attention.

$IA_{h,e}$		$IA_{h,ge}$				
		1	2	3	4	5
$IA_{h,le}$	1	1.05	1.79	3.05	4.21	5.02
	2	1.79	2.35	3.36	4.35	5.07
	3	3.05	3.36	3.96	4.65	5.20
	4	4.21	4.35	4.65	5.03	5.40
	5	5.02	5.07	5.20	5.40	5.61

(**a**)

$CA_{h,e}$		$CA_{h,ge}$				
		L	ML	M	MH	H
$CA_{h,le}$	L	L	ML	M	MH	H
	ML	ML	ML	M	MH	H
	M	M	M	MH	H	H
	MH	MH	MH	H	H	H
	H	H	H	H	H	H

(**b**)

Figure 6. (**a**) Indices of attention for the erosion of the hydraulic risk obtained combining the indices of general erosion and local erosion for particular values of $IA_{h,ge}$ and $IA_{h,le}$; (**b**) corresponding LG2020 classes of attention.

The hydraulic risk index is obtained from Equation (3) and then combined with the landslide risk using Equation (4). As an example, the values of IA_{lh}, obtained for specific values of the IA_l and IA_h, are reported in Figure 7a. For comparison, the corresponding classes of attention of LG2020 are in Figure 7b.

IA_{lh}		IA_l				
		1	2	3	4	5
IA_h	1	1.17	1.73	2.23	2.71	3.18
	2	1.73	2.28	2.78	3.27	3.73
	3	2.23	2.78	3.29	3.77	4.24
	4	2.71	3.27	3.77	4.25	4.72
	5	3.18	3.73	4.24	4.72	5.18

(**a**)

CA_{lh}		CA_l				
		L	ML	M	MH	H
CA_h	L	L	ML	ML	M	M
	ML	ML	ML	M	M	MH
	M	ML	M	M	MH	MH
	MH	M	M	MH	MH	H
	H	M	MH	MH	H	H

(**b**)

Figure 7. (**a**) Indices of attention IA_{lh} for the landslide-plus-hydraulic risk; (**b**) corresponding LG2020 classes of attention.

Finally, the multi-risk indices of attention are obtained from Equation (5). As an example, the values of IA, obtained for specific values of the indices IA_{st}, IA_s and IA_{lh}, are reported in Figure 8a. The comparison with the corresponding classes of attention of LG2020 (Figure 8b) is excellent. In more detail, in two cases, the IA provides a class lower

by one step with respect to the corresponding class of attention of LG2020, whereas in another two cases, the *IA* is overestimated by one step.

IA_{sf}		1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
IA_{lh}		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
IA_s	1	1.10	1.25	1.45	1.69	1.98	1.55	1.77	2.03	2.33	2.67	2.01	2.22	2.48	2.78	3.12	2.89	3.05	3.25	3.48	3.76	4.63	4.68	4.75	4.87	5.02
	2	1.43	1.58	1.77	2.00	2.29	1.88	2.09	2.34	2.64	2.98	2.29	2.50	2.76	3.06	3.39	3.09	3.26	3.46	3.69	3.97	4.73	4.78	4.86	4.97	5.13
	3	1.69	1.85	2.04	2.29	2.57	2.15	2.37	2.63	2.94	3.29	2.54	2.77	3.04	3.34	3.69	3.29	3.47	3.68	3.93	4.22	4.84	4.90	5.00	5.13	5.29
	4	1.91	2.08	2.29	2.56	2.86	2.40	2.64	2.92	3.25	3.62	2.79	3.04	3.33	3.66	4.03	3.51	3.71	3.94	4.22	4.53	4.98	5.07	5.19	5.35	5.54
	5	2.10	2.30	2.54	2.83	3.17	2.65	2.92	3.23	3.59	3.98	3.06	3.34	3.66	4.02	4.42	3.76	3.99	4.26	4.57	4.91	5.18	5.31	5.47	5.66	5.89

(**a**)

CA_{sf}		L	L	L	L	L	ML	ML	ML	ML	ML	M	M	M	M	M	MH	MH	MH	MH	MH	H	H	H	H	H
CA_{lh}		L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H	L	ML	M	MH	H
CA_s	L	L	L	L	ML	ML	ML	ML	ML	ML	M	ML	ML	M	M	M	M	M	M	M	MH	H	H	H	H	H
	ML	L	ML	ML	ML	ML	ML	ML	ML	M	M	ML	M	M	M	M	M	M	M	MH	MH	H	H	H	H	H
	M	ML	ML	ML	ML	M	ML	ML	M	M	M	M	M	M	M	MH	M	M	MH	MH	MH	H	H	H	H	H
	MH	ML	ML	ML	M	M	ML	M	M	M	M	M	M	M	MH	MH	M	MH	MH	MH	H	H	H	H	H	H
	H	ML	ML	M	M	M	M	M	M	M	MH	M	M	MH	MH	H	MH	MH	MH	H	H	H	H	H	H	H

(**b**)

Figure 8. (**a**) Multi-risk indices of attention obtained for average values of the indices IA_{st}, IA_s and IA_{lh}; (**b**) corresponding LG2020 multi-risk classes of attention.

5. Application of the Procedure to a Significant Set of Bridges

The proposed mathematical procedure was applied to 86 bridges in Italy of different structural types and materials. In more detail, reinforced concrete, post-tensioned reinforced concrete, steel, and masonry bridges were considered. Most of the concrete and steel bridges have simply supported girders, even if some of them have continuous girders. As for the geometry, the span length varies from 6 m to 100 m, while the depth of the deck varies from 8 m to about 12 m.

For all bridges, census and visual inspection were carried out, and then the *CAs* relative to the four different risks and the multi-risk *CA* were evaluated according to LG2020. The following results were obtained: 40 bridges were in high *CA*, 24 in medium-high *CA*, 22 in medium *CA*, 0 in medium-low *CA* and 0 in low CA. It is worth noting that none of these bridges has low or medium-low CA. All the bridges fall back into the highest classes. Defining a priority scale and planning the needed maintenance or retrofit interventions is quite difficult in such a context.

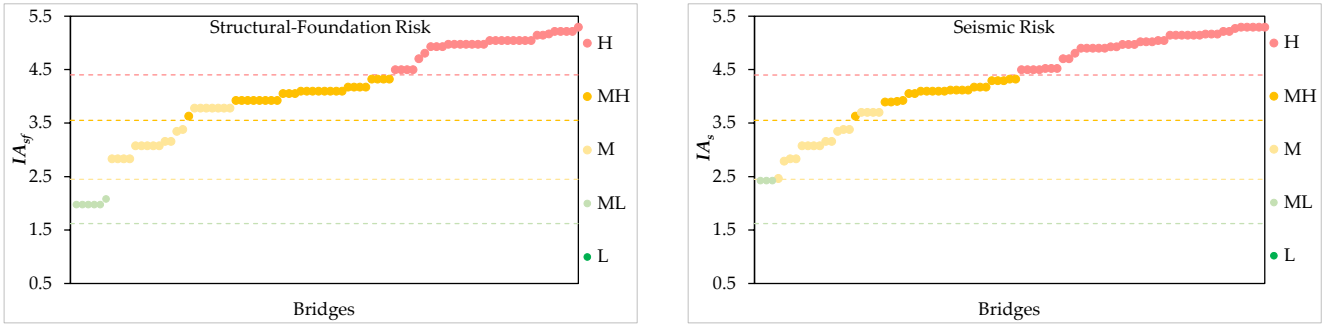
The mathematical procedure was then applied to the same set of bridges. First, the hazard, vulnerability, and exposure indices were assigned for each risk, then the indices of attention for the various risks were evaluated, following the schemes illustrated in Figure 2. Finally, the multi-risk index of attention was evaluated.

Figure 9a shows the IA_{sf} values for all bridges sorted by increasing values of IA_{sf} and the corresponding CA_{sf}, highlighted with the colors defined in Figure 3. As one can see, the same value of IA_{sf} was obtained for more bridges. This happens because some of them have the same structural type, the same geometric and material properties, and were built almost contemporarily, so their degradation is also very similar. It is worth noting that in a few cases, bridges with a medium CA_{sf} have values of IA_{sf} that fall within the range corresponding to a medium-high CA_{sf} in Figure 3.

Analogously, Figure 9b shows the IA_s values for all bridges sorted by increasing values and the corresponding CA_s. Also in this case, a few bridges with a medium CA_{sf} have values of IA_{sf} that fall within the range corresponding to a medium-high CA_{sf} in Figure 3.

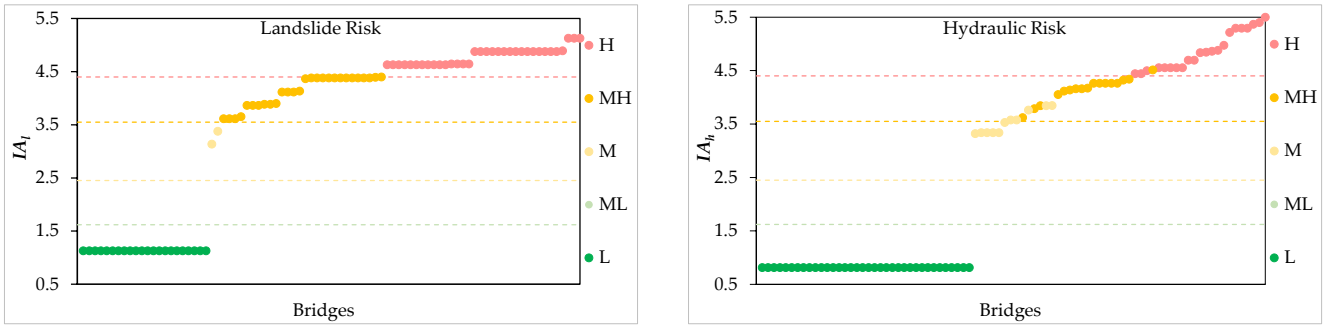
Figure 10a shows the IA_l values for all bridges sorted by increasing values and the corresponding CA_l. In this case, the correspondence with the classes of attention defined in Figure 3 is excellent. It is worth noting that the CA_l is low in a few cases. These correspond to the absence of landslide risk, for which the value "0" should be considered. Furthermore, there is a stepped trend with different bridges having the same IA_l value.

This occurrence relates to the procedure used in LG2020, where the same weight is given to both vulnerability and exposure.



(**a**) (**b**)

Figure 9. (**a**) IA_{sf} and CA_{sf} relation; (**b**) IA_s and CA_s relation (horizontal dashed lines separate the range of IA values into the five intervals defined in Figure 3).

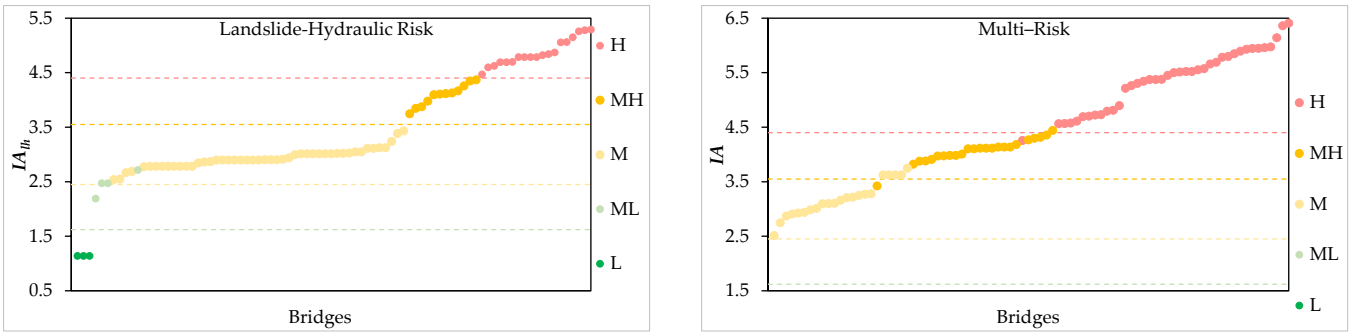


(**a**) (**b**)

Figure 10. (**a**) IA_l and CA_l relation; (**b**) IA_{lh} and CA_{lh} relation.

Figure 10b shows the IA_h values for all bridges sorted by increasing values and the corresponding CA_h of LG2020. Only in five cases do bridges with a medium CA_h have a value of IA_h that falls within the range corresponding to a medium-high CA_h in Figure 3, and only one bridge with medium-high CA_h falls within the range associated with a high CA_h. Also, for this risk, there are many cases of low CA_h. These correspond to the absence of hydraulic risk, for which the value "0" should be considered.

Landslide and hydraulic risks have been combined. Figure 11a shows the IA_{lh} values for all bridges sorted by increasing values and the corresponding CA_{lh} of LG2020. Only in three cases did bridges with a medium-low CA_{lh} have a value of IA_{lh} that falls within the range corresponding to a medium CA_{lh} (Figure 3).



(**a**) (**b**)

Figure 11. (**a**) IA_{lh} and CA_{lh} relation; (**b**) multi-risk IA and CA relation.

Finally, Figure 11b shows the multi-risk *IA* values for all bridges sorted by increasing values of *IA* and the corresponding *CA* of LG2020. Only one bridge with high *CA* had a value of *IA* that falls within the range corresponding to a medium-high *CA* in Figure 3, and one bridge with medium-high *CA* has a value of *IA* that falls within the range corresponding to a medium CA. On the contrary, five bridges with medium-low *CA* fall within the range corresponding to a medium *CA*, and one bridge with a medium-high *CA* falls within that corresponding to a high *CA*.

Cohen's kappa factor was used to validate the correlation between the *IA* and LG2020 classification. The statistic index was calculated by comparing the *CA* associated with the *IA* following Figure 3 and the *CA* obtained following LG2020. For the structural–foundational risk, seismic risk, hydraulic risk, and landslide risk, Cohen's kappa is equal to 0.88, 0.93, 0.90, and 1.00, respectively. For the combination of landslide and hydraulic risks, Cohen's kappa is equal to 0.94, while the value associated with the multi-risk analysis is equal to 0.85. Following the ranges characterized in [40], the obtained values may be considered to represent an excellent degree of agreement.

6. Conclusions

Starting from the consolidated criteria for a simplified assessment of existing bridges, a procedure based on the definition of an index of attention has been proposed. Four different risks, i.e., structural–foundational, seismic, landslide, and hydraulic, are considered, and the hazard, vulnerability, and exposure factors that influence each risk are quantified with an index varying from 1 to 5. Polynomial functions are then defined combining these indices, calculating an index for each risk and finally a multi-risk index of attention.

Using an index instead of a set of discrete classes, like the five ones proposed in LG2020, avoids unsuitable situations in which many bridges fall into the same class of attention or bridges in very similar condition fall into different classes. Instead, it will allow a useful classification for planning interventions and use of resources by defining a priority scale.

The first index relative to the risk factors, to be assigned on the basis of the defined parameters of Table 1, can assume integer values from 1 to 5 only. This is consistent with the need not to provide illusory precise data, which could suggest an already accurate evaluation.

In this paper, the mathematical relationships have been calibrated in order to obtain the best correspondence with the Italian classification. However, this requirement can be overcome, and simpler values of both the coefficients of the various formulas and the limit values for the classes can be defined. These could also be differentiated for different applications, i.e., for different typologies or different regions.

The only limitation of the proposed method could arise from the choice of the equation coefficients. These coefficients, as well as the limits of the ranges, can be adjusted in the future and adopted for different applications in different countries.

Finally, the introduction of the zero value for single risks, especially for the landslide and hydraulic ones, should be considered if the corresponding hazard is not present.

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Appendix A

The assessment criteria of the indices of hazard, vulnerability, and exposure relative to the structural–foundational risk are shown as an example.

As in Table 1, the hazard index depends on the values of expected heavy loads, divided into five classes according to the Italian guidelines, and their frequencies (HV/D = number of heavy vehicles/day) are usually divided into three classes (high, medium, and low frequency). The resultant index values are shown in Table A1.

The evaluation of the index of vulnerability I_V is more articulated (Figure A1). A class of degree of damage is first evaluated based on gravity, intensity, and extension of damage. Particular attention is given to critical elements, crises of which could be very dangerous for the whole structure. If the damage class is high, I_V will be equal to 5, independently of the other parameters. In the other cases, the class for the degree of damage is modified, accounting for the following.

- The year of construction or of the last retrofit, which is a measure of the speed of degradation. Three periods are considered in LG2020: before 1945, between 1945 and 1980, and after 1980. Obviously, these periods depend on the evolution of the technical code in each country. Here, they are denoted as very old (V), old (O), and recent (R), respectively.
- The design code used at the time of construction. Three periods are considered in LG2020: before 1952, between 1952 and 2005 (1990 for spans < 10 m), and after 2005 (1990 for spans < 10 m). These also depend on the evolution of the technical code in each country and are here denoted as very old (V), old (O), and recent (R), respectively.

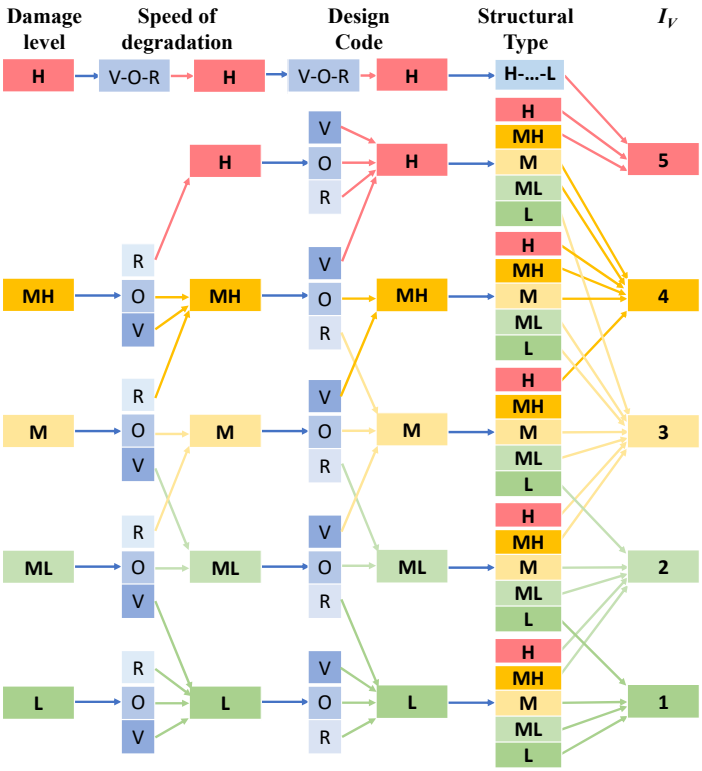

Figure A1. Evaluation of the index of vulnerability I_V.

Finally, the obtained class is combined with that evaluated based on the structural type, material, and span length, reported in Table A2 for reinforced concrete bridges. Similar tables are available for other materials. The indices given in Table A2 are first increased by 1 (but $\leq$5) if the number of spans involved in a collapse could be greater than 3.

Finally, the index of exposure is evaluated based on the daily medium traffic (V/D) and the average span length (Table A3). The value obtained is increased by one in the absence of alternative roads. It is further increased by one, kept constant, or reduced by one on the basis of the importance of the bypassed obstacle.

The presence of dangerous goods transportation will translate into a priority in cases of intervention.

Similar procedures are proposed for the factors of the other risks. The indices I_H, I_V and I_E are then combined to obtain the index of the various risks using Equation (1).

Table A1. Evaluation of I_H for the structural–foundational risk.

Load Limitations	**High Frequency HV/D $\geq$ 700**	**Medium Frequency 300 < HV/D $\leq$ 300**	**Low Frequency HV/D $\leq$ 300**
No limitations	5	5	4
$\leq$440 kN	5	4	3
$\leq$260 kN	4	3	2
$\leq$8 kN	3	2	1
$\leq$3.5 kN	1	1	1

Table A2. Evaluation of *CA* for the structural–foundational risk of reinforced concrete bridges.

Type	**$L \leq$ 5 m**	**5 $\leq L <$ 15 m**	**15 $\leq L <$ 25 m**	**$L \geq$ 25 m**
Simply supported beams	ML	M	MH	H
Continuous beams	L	ML	M	MH
Solid-spandrel arch	L	ML	M	M
Open-spandrel arch	ML	M	M	MH
Gerber type	MH	H	H	H
Simply supported slab	ML	M	MH	H
Fixed-end slab	L	ML	M	MH

Table A3. Evaluation of I_E as a function of the daily medium traffic (number of vehicles per day, V/D) and of the average span length *L*.

Daily Medium Traffic	**V/D $\geq$ 25,000**	**10,000 $\leq$ V/D < 25,000**	**V/D < 10,000**
$L >$ 50 m	5	4	3
20 $< L \leq$ 50 m	4	3	2
$L \leq$ 20 m	3	2	1

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