Multi-level approach for the assessment of bridge and viaducts within road networks

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ABSTRACT

The recent tragic events that involved bridges and viaducts, happened in the Italian road network in the last 15 years, have highlighted the high level of risk and fragility of the national infrastructural heritage, characterized by a very high number of structures, different each other structurally and geometrically, most of them built in the second post-war period with low quality materials and not enough maintained over the years. Therefore, the need to perform a structural risk assessment of bridges and viaducts is a current and urgent issue. Applying the currently existing methods, codified by Eurocodes or national standards, for the structural assessment of all bridges in the Italian territory would require temporal and economic resources not easily sustainable by the Public Administrations, especially considering that most part of the Italian road network is managed by little realities, such as Provinces and Municipalities. These considerations highlighted the need to define and develop simple and expeditious methods to evaluate the structural risk associated to all bridges in order to define an intervention priority, classifying the structures and identifying those that need more in-depth investigations and more sophisticated analysis. The goal is passing from simple and quick evaluations on a territorial macro-scale to a more punctual evaluations to apply on a case by case basis. In this paper, a method of classification of the bridges and viaducts, based on the "*warning level*" associated to each one, is proposed. The "*warning level*" is defined according the usual framework of the risk definition and taking into account all the factors that influence the structural risk, such as the structural defectiveness level, the static scheme's vulnerability, the rapidity of the evolution of deterioration and the type and amount of traffic flows. The definition of the "*warning level*" is based on the results of visual inspections of the structures, that allow to evaluate the state of conservation of the bridges and to know their main characteristics. Combining the state of conservation with the other factors, like the construction period, it is possible to make a reliable estimate of the structural risk associated with each bridge and to evaluate the necessity and the urgency of an intervention. The proposed methodology was calibrated on the basis of the study of the existing scientific literature in this field and the results of over 100 visual inspections of bridges in Province of Pisa and in Province of Caserta. This paper presents the main characteristics of the methodology and its application to a sample of bridges.

1 INTRODUCTION

Bridges are integral parts of road networks, thus they have to be safe and efficient. The lack of safety or efficiency of an infrastructure can cause events with severe social and economic consequences, producing huge direct losses, in terms of human life and structural damages, but also indirect losses, related to the downtime of the network after collapses of bridges, the losses incurred by the local productivity activities and the hardships caused to the affected communities. Therefore, it is necessary not only to ensure the structural safety and to minimize the risk of structural collapses, but also to guarantee an adequate road system resilience, in order to reduce the consequences of unexpected events on society as much as possible. For these purposes, the administrative bodies are increasingly interested in having a system of support and optimization of decisions-making process in all phases of the bridges management. Most of them, especially those that manage roads with lower importance, do not have a complete and consolidated system of management of their infrastructures yet: it is, indeed, an open problem not easy to solve. They have to deal with peculiar not trivial issues related to the high number of structures to manage, very different each other in terms of structural typologies, construction materials, constructions period, etc., the high fragmentation of administrative competences, the lack of knowledge about the structures and so on. The lack of knowledge is also consequence of a lack of inspections on the structures over the years. Many bridges were not even subject to the ordinary inspection and maintenance activities, because of the limited economic budget and a widespread common approach based on emergency and not on prevention. This caused the progressive deterioration of the conservation state of many structures that suffer from the effects of time without adequate control and maintenance. Moreover, in the last decades, there was an increase of vehicular traffic, especially of the truck traffic, so the loads to which the bridges are subjected are almost always higher than the loads considered in their project, making the structures even more vulnerable and exposed. For these reasons, it is clearly necessary a tool, such as a Bridge Management System (BMS), that first of all allows to improve the knowledge about the structural features and the current state of preservation and safety of existing bridges in a relatively simple and quick way, and that allows to optimize the allocation of economic resources for the inspection, maintenance, rehabilitation and replacement (American Association of State Highway and Transportation 2018).

One of the main focus in a BMS is the evaluation of the safety of a structure, also considering its current conditions of preservation. The methodology foreseen by the technical standards gives surely reliable information about the structural safety and, consequently, allow to perform risk analysis of the considered structures, but it is difficult to apply to all the existing bridges, considering the limited economical and human resources available and the high number of structures to be analysed.

There is a clear need to calibrate the difficulty and the accuracy of the evaluation activities and the needed resources in function of the actual necessity of interventions and in depth analysis on the structures. This necessarily translates into proceeding by subsequent levels, in order to apply quick and simple methods of evaluation on all the existing structures and more accurate and reliable ones to a limited number of selected structures, when needed. This is the logic at the basis of the application of a multilevel approach organized in different levels of analysis and assessment with different levels of difficulty and detailing.

At the basis of the multilevel approach, the creation of a database and the prioritization of bridges in need of more in depth analysis have to be, in order to optimize the decision-making processes and to understand where and how to concentrate the available resources, selecting the bridges to analyse in the subsequent levels. The classification of bridges is a problem of particular importance, on which many scientific studies were focused in order to develop expeditious methods that allow to harmonize both the necessity to have a wide and complete survey of the current structural risk associated with all bridges within the road networks and the limited temporal and economic resources to invest in it. Many methods of classification, such as the Italian method proposed by the *4Emme Service S.p.A.* (Ceccotti et al. 2011), foresee the evaluation of the Bridge Condition Index as product of factors related to the degradation phenomena recognized during visual inspections, taking into account only the state of preservation of the structural elements. They so give information about the needs of maintenance activities but they are not enough complete to perform the risk assessment of the structures and they do not always allow to identify the most critical situations. Other methods, such as the method proposed by *A. Montepara et al.* (Montepara et al.), the model *RAM (Road Asset Management)* used by the Italian corporation *ANAS* (ANAS Gruppo Ferrovie Italiane 2018) or the method proposed by *P. Franchetti et al.* (Franchetti et al. 2003), correct the Bridge Condition Index with coefficients related to the structural features, the traffic volume or factors related to seismic and hydrogeological hazards. All these factors are condensed in a single numerical value. This approach does not allow to understand the importance of every aspects influencing the evaluation of the intervention priority. It thus appears so clear the necessity to define a classification system easily applicable to a significant number of bridges, that can consider all parameters and that allows to understand how everyone influences the structural risk, both at the project level and at the network level. It has to allow to identify immediately the critical situations, when it is necessary to intervene more urgently and to give information about the ways to proceed on each classified bridge. The present paper presents a new methodology for the existing bridges classification to apply on territorial macro-scale, defined starting from the study and the application of some of the existing ones. The proposed method is focused on the structural and geotechnical risk classification, not including, at the moment, the seismic risk and the hydraulic one, in order to avoid distorting the classification. The structural and geotechnical risk is considered more relevant, being related to the effective exercise of the structure; it is characterized by a lower return period than the seismic and hydraulic actions and related effects are predominant on the typical structural schemes of the bridges.

The proposed classification methodology is based on the evaluation of the so-called "*warning level*", taking into account all the sources of structural risk in a simple and rapid manner, through visual inspections on the structures, in order to allow that any administrative bodies, even the smaller ones, can apply it on their structures, using limited economic and temporal resources. At the end of the classification, how and when to act on each inspected bridge have to be clear. On the basis of it, the bridges will be subject to different analysis and interventions, in terms of complexity, urgency and detail, such as periodical monitoring, safety evaluation and so on, foreseen by the higher levels of the multilevel approach.

The definition, the calibration of parameters and the validation of the methods were carried out on the basis of the acquired experience by the Department of Civil and Industrial Engineering of University of Pisa and by the Department of Architecture and Industrial Design of University of Campania *Luigi Vanvitelli*, on the bridges of Province of Pisa and Province of Caserta, respectively. In the paper, an application of the method on a sample of bridges of the Province of Pisa is presented.

2 LITERATURE REVIEW: METHODS OF PRIORITIZING OF BRIDGES. APPLICATIONS AND CRITICAL ANALYSIS

In order to highlight the limits of applicability and the shortcomings of the existing methods of bridges classification, some of them were applied to a sample of bridges under the jurisdiction of Province of Pisa, for which much data are available thanks to the performing of visual inspections on the structures.

Three different methods were selected. The first one is the method proposed by the 4Emme Service S.p.A. (Ceccotti et al. 2011), the most widespread method in Italy, that takes into account only the state of preservation of the bridge. The second one is the method proposed by A. Montepara at al. (Montepara et al.). The authors of the method considered, as well as the state of preservation of the bridge, also factors related to the network level, such as the importance of the bridge within the road network and the volume of traffic, but neglects other factors of risk, such as the vulnerability associated with the static scheme, the geometrical dimensions and the aging of the bridge. The last applied method is proposed by S. Valenzuela et al. (Valenzuela et al. 2010). It condenses in a single index the damage level, the hydraulic vulnerability and the seismic risk. These three factors are related to aspects very different each other. Therefore, they result hardly comparable. Moreover, the method neglects completely other factors of structural risk, such as the vulnerability related to the structural features.

The methods are very different each other and they consider different factors to classify the bridges, but they have a common aspect: all the three methods estimate the condition rating of the bridge starting from an index related to the condition of the single structural elements, depending on the extension, the intensity and the weight of the defects, detected during visual inspections. In order to compare the three methods, 18 bridges of the Province of Pisa were classified basing only on the indices related to the state of preservation of the bridge. To make more easy the comparison, the elements condition index was evaluated with the same formula (1) provided by the method proposed by the 4Emme Service S.p.A..

$$D_r = \sum(G \cdot k_1 \cdot k_2) \qquad (1)$$

where G is the weight associated with each defect, variable between 1 and 5; k_1 is the extension coefficient, variable between 0.2, 0.5 and 1.0 and k_2 is the intensity coefficient, variable between 0.2, 0.5 and 1.0.
The methods foresee three different approaches for the evaluation of the condition rating of the whole bridge, as indicated in Table 1.

Table 1 Approaches and formulae for the evaluation of the bridge condition indices with the three considered methods

Existing methods	Used approach	Index of defectiveness
4Emme S.p.A.	Sum of the relative defectiveness indices D_r	$D_{a1} = \sum D_r$
A. Montepara at al.	Maximum of the D_r values	$D_{a\,3} = \max(D_r)$
S. Valenzuela et al.	Weighted average of the D_r basing structural element importance (w_i) and material (m_i)	$D_{a\,2} = \frac{\sum_1^n w_i \cdot m_i \cdot D_r}{\sum_1^n w_i \cdot m_i}$

The classification obtained by each method was compared with a subjective one based on the expert judgement of engineers who inspected the structures, which well reflects the actual state of damage of the bridges.

Even if the three methods foresee three different approaches for the condition rating of the structures, everyone should be sufficiently representative and give results in terms of order of priority at least comparable each other. Unfortunately, their application did not demonstrate it: depending on the used method, in fact, different orders of priority are obtained. This does not allow univocal choices for the management of a bridges stock. Moreover, the classification obtained by the three methods does not often correspond to the expert judgement. This happens especially because the evaluation of a single numerical index can make lose sight of the actual existing defects and their gravity. Therefore, bridges with many medium-severe defects could have higher indices than bridges with very severe but localized defects.

The application of the methods highlighted the need to advance the existing classification systems, improving and integrating them in order to overcome the found limits, but exploiting the past experiences anyway. First of all, it is important being able to have always a clear and immediate judgement about the structural degradation of a bridge, not always evident by the reading of a numerical index. Moreover, it is necessary to take into account other factors besides the state of preservation, in order to get as close as possible to the evaluation of the structural risk associated with a structure. These factors must be related both to the structure, considered isolated, and to the road network, in order to include first rapid and simple considerations about its resilience.

3 PROPOSAL FOR A CLASSIFICATION METHOD

The proposed classification methodology is based on the evaluation of the so-called "*warning level*" defined by the combination of factors of hazard, vulnerability and exposition, following the typical framework of the risk definition. At the moment, only the sources of structural and geotechnical risk are considered, neglecting those related to the seismic and hydraulic ones, characterized by different return periods and different effects on the bridge structure.

The proposed method considers parameters related to the single structure and parameters related to the road network, in order to include a first and simple resilience assessment. The definition and the combinations of these parameters are carried out in a simple and quick manner and they do not require the performing of expensive and more invasive investigation than the visual ones, as well as mathematical and complex analysis. This way to proceed involves a series of simplifications and hypothesis, thus it is characterised by a limited degree of precision, but it represents a very useful tool to perform a first and rapid check of all the bridges within the road network, to select those in need of urgent interventions or more in depth analysis. The classification approach consists in two phases: the acquisition of data about the structures, their state of degradation and the road network, through in-situ visual inspections and available documentation and the elaboration of data, in order to obtain the classification of the structures.

3.1 Acquisition of data: objective parameters and state of degradation

A well-done management of structures cannot depart from an adequate knowledge of structures themselves and of the territory in which they are included. For this reason, the first step foreseen by the approach is the collection of objective parameters about all the bridges on the territory.

The objective parameters are identified as the factors that will never change their values, whose definition cannot be subject to interpretations. They are essentially associated with the localization of the bridges, their structural and geometrical characteristics and with the features of belonging road networks. The goal is the creation of a database, with all information about the structures, to update continuously in function of the increasing level of knowledge about them. The acquisition of the objective parameters is simple, quick and not expensive. It does not require to carry out inspections on the structures, but only the collection and the consultation of all the available documentation and the use of information system of geolocation and mapping. In this way, it is possible to order all the bridges of a territory and to make easier and more rational the planning of the visual inspections.

Visual inspections are necessary to know the current state of preservation of the bridges, through the identification of the present degradation phenomena on the materials and the present structural damages. In accordance with the principles common to many methods proposed in literature, the evaluation of the state of preservation is based on the survey of the extension and intensity of the existing defects, associating with them numerical coefficients. They are useful to estimate the level of defectiveness of the bridge, one of the main parameters necessary for the structural risk assessment of it.

3.2 *Elaboration of data: definition of the warning level of bridges*

All information acquired through the consultation of available technical documents and the visual inspections is used to draw up the classification of the bridges, defining a parameter, called "*warning level*" to indicate the risk associated with each bridge. The choice to use a new parameter came out by the awareness that the evaluation of the risk, as commonly defined, would require deeper and more precise analysis than those used in the proposed method. In any case, the definition framework of the warning level reminds the typical framework of the risk definition, in order to make it more familiar for the users and to allow the subsequent comparison with other kind of risk, such as the seismic risk and the hydrogeological one.

The warning level is defined as the combination of factors of hazard, vulnerability and exposition. Differently from many existing methods of prioritization, the definition of the factors includes all the aspects that can represent a source of structural risk for the bridge. Not only the state of preservation is taken into account, but also the aging of the structure, the static scheme, the design traffic loads and so on. On the basis of the scientific and practical experiences, the influencing parameters identified as more representative for each factor are shown in Table 2. Some of them are related to the single structure; other ones, such as the Average Daily Traffic, the Average Daily Truck Traffic and the presence/absence of alternative routes, are related to the belonging road network. In this way, the two levels of management – project level and network level – are linked and simple and rapid considerations about the resilience of the road networks are included in this level of assessment, too.

Table 2 Parameters influencing the definition of the warning level

Factors	Primary parameters	Secondary parameters
Hazard	Defectiveness level	Degradation evolution Design period
Vulnerability	Structural scheme, span length, construction materials	-
Exposition	Average Daily Traffic and Average Daily Truck Traffic	Presence/absence of suitable alternative routes

Each parameter and consequently each factor can be defined following an approach for classes and logical operators. According to it, each parameter is represented by classes that combined each other give as result the *warning level* of the bridge. The criteria of belonging to each class are precisely defined, in order to make the classification more objective as possible. The use of classes instead of numerical indices allow to have an immediate and not misunderstood indication about the *warning level* to which the bridge must be subjected. Classes of hazard, vulnerability and exposition are defined and determined by an algorithm that combines the *primary parameters* and the *secondary parameters*, identified in the Table 2. In function of the value of the *primary parameters*, a bridge falls into one of 5 classes identified in high, medium-high, medium, medium-low and low. The class of the bridge, defined on the basis of the primary parameters, is then corrected in function of the *secondary parameters* values, if any, in order to obtain the final classes of hazard, vulnerability and exposition associated with the bridge. Combining them, the *warning level* is obtained and classified into the usual 5 classes – high, medium-high, medium, medium-low and low. A total of 5^3 combinations are defined in order to consider all the possible cases. The number of combinations decreases considering that the three factors do not have the same weight. Much importance is given to the class of hazard of the bridge: if the class of hazard is high, the *warning level* is high regardless of other factors. In this way, a bridge that requires immediate interventions or deeper analysis because of its bad state of preservation has always a high priority than the others.

3.2.1 Classes of hazard

The definition of hazard considers all the factors not depending on the features of the single structures but depending on the presence of elements that can compromise the safety, such as the surrounding environment, and elements that cannot be modified in anyway. In order to determine the class of hazard of a bridge, it is necessary elaborating data collected during the visual inspection for the evaluation of the level of defectiveness (*primary parameter*) of the bridge. The latter is classified in function of the location, the gravity and the intensity of the detected defects, distinguishing the defects that can compromise the static of the whole structure or the defects on critical elements, such as the pre-stressing reinforcement (Figure 1) and the Gerber saddles (Figure 2). The criteria of classification of the defectiveness level were calibrated basing on the results obtained by the carrying out of visual inspections on existing bridges within the road networks managed by the Province of Pisa. They highlighted that it is important to distinguish bridges with one serious defect from bridges with more numerous but less relevant defects, in order to avoid that the latter have a higher priority than the former.

The class of level of defectiveness is then corrected basing on the construction period, following the logical path represented in Figure 4. The construction period influences both the *secondary parameters* considered, namely the rapidity of the degradation evolution over the years and the hazard due to the different methods of design and traffic loads evaluation foreseen by the standards in force at the construction time and the standards currently in force. For both the aspects, the bridges are subdivided into two macro-classes – Ante 1980 and Post 1980.

Figure 1 Breaking and leakage of pre-stressing reinforcement bars

Figure 2 Degradation, spalling and corrosion in correspondence of a Gerber saddle

The year 1980 was identified as the year separating recently built structures (Post 1980) from less recently ones (Ante 1980), in order to consider the different rapidity of degradation of two bridges with the same current level of defectiveness but built in different time. In fact, at the same level of defectiveness, a bridge “younger” worries more than another built less recently, for which the existence of a certain level of degradation can be considered physiological. As represented in Figure 3, assuming, for example, that the original degradation of bridges, at the construction year, was nil and the degradation increases in time linearly (uniform probability density function of degradation), the expected defectiveness level in 50 years of a bridge built in 1980 is higher than that of a bridge built in 1950 with the same current level of defectiveness. Therefore, the level of defectiveness increases of a class for bridges built Post 1980.

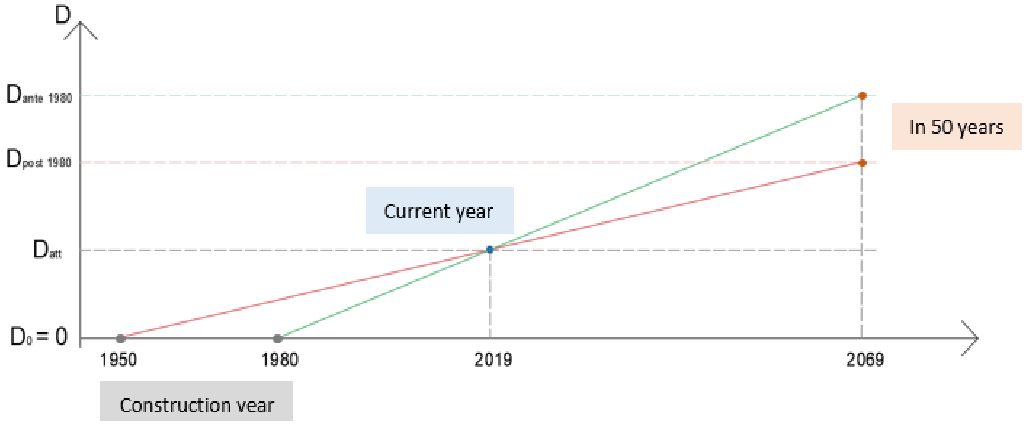

Figure 3 Degradation evolution: examples for bridges built in 1950 and 1980. In the figure: D_0 = original degradation; D_{att} = current level of defectiveness; $D_{post\ 1980}$ = degradation in 2069 for bridges built in 1980 characterized by a level of defectiveness D_{att}; $D_{ante\ 1980}$ = degradation in 2069 for bridges built in 1950 characterized by a level of defectiveness D_{att}.

Moreover, the study about the Italian standards in force over the years demonstrated that in 1980 there was a change in the definition of the traffic loads. The standards in force before 1980 foresaw load schemes that reproduced the real means of transportation used at the time. On the contrary, the traffic loads foreseen by the standards in force after 1980 and also by the current ones are conventional loads, without an exact correspondence with the real transportation means and much higher than the previously.

These differences have been demonstrated by a parallel study carried out by the Department of Civil and Industrial Engineering of University of Pisa and the Department of Architecture and Industrial Design of University of Campania *Luigi Vanvitelli*. The study, regarding the methods and the traffic loads values used in Italy for the bridges design over the years, highlighted that bridges designed Ante 1980 and verified as existing structures with the current national code (Ministero Delle Infrastrutture e dei Trasporti 2018) do not have enough structural resources to cope with loads currently foreseen. Instead, bridges “Post 1980” were designed with traffic loads values more similar to the current ones. The details, the assumptions and the results of the study are reported in (Salvatore et al. 2019). To take into account these differences, the expected level of defectiveness increases of a class if the bridge was built Ante 1980, because it most probably has fewer reserves against the current traffic loads than those built Post 1980, when the values of the design traffic loads and the design methods were more similar to the current ones.

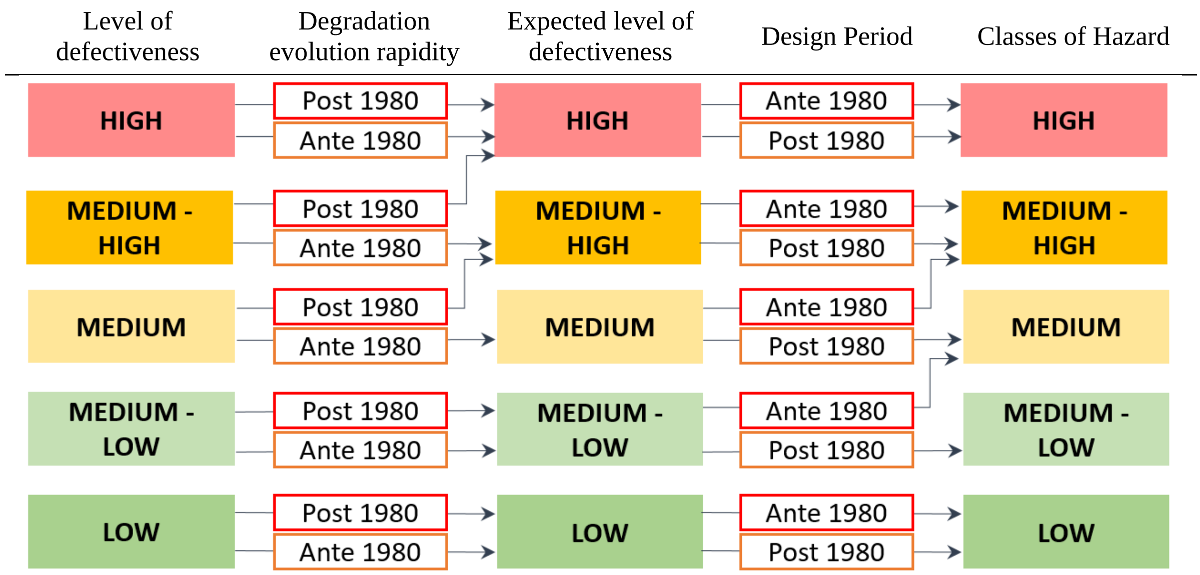

Figure 4 Logical path to obtain the class of hazard of a bridge, combining level of defectiveness and construction period

3.2.2 *Classes of vulnerability*

Vulnerability is a structural behaviour, related to the failure susceptibility of the bridge (Berdica 2002). It depends mainly on the structural features of the bridges, such as the static scheme, the span length and the construction materials. With the aim of finding the class of vulnerability of each bridge, the parameters - redundancy, sensitivity to fragile crisis, sensitivity to degradation - whose presence can aggravate the vulnerability of the bridges, are selected. On the basis of the combination between the vulnerability parameters, the bridge is classified into one of 5 classes of vulnerability – high, medium – high, medium, medium – low and low. According to the identified vulnerability parameters, more redundant static schemes, such as the massive masonry vaults (Figure 5), are considered less vulnerable than others with less reserves in case of failure, such as the supported beams bridges and so they fall into a lower class.

Figure 5 Masonry vault bridge

A high vulnerability is associated with static schemes that can be more easily subjected to fragile crisis, such as the Gerber beams (Figure 6), falling in the highest class. Similarly, construction materials, characterized by a high sensitivity to the deterioration (e.g. reinforced concrete) implies a higher vulnerability than other materials, such as the steel, more resistant to external agents, if well protected.

Figure 6 Gerber beams bridge

Basing on the vulnerability parameters, the classes of vulnerability were individuated for each combination of static scheme, span and construction materials.

3.2.3 *Classes of exposition*

The exposition takes into account the typology and the amount of traffic flows over the bridges, in terms of Average Daily Traffic (ADT) and the Average Daily Truck Traffic (ADTT), and the presence or absence of alternative routes. The presence or absence of alternative routes influences the strategic importance assumed by a bridge within the road network, in case the bridge is not passable by users. If an adequate and suitable alternative route is not available, the bridge acquires a high importance for the proper functioning of the ways of transport. Therefore, it is necessary to preserve its efficiency and to avoid possible failures or decrease of functionality as much as possible. The identification of alternative routes is a primary and quick way to quantify the resilience of the road networks. On the basis of the ADT and ADTT, 5 classes of road system were defined. The definition of the criteria of belonging to the different classes was based on the results of the traffic measures performed by Province of Pisa on the roads in its territory. Therefore, they are related to provincial roads and they well represent the actual traffic flows on them, but they can be extended to other typologies of roads, including data referred to them. Obviously, the bridges included in more trafficked roads belong to higher classes than bridges in roads where pass less vehicles, because they are more exposed and more important for the ways of communication.. The class identified basing on the ADT and the ADTT increases if alternative routes are not present or not adequate, following the logical path in Figure 7.

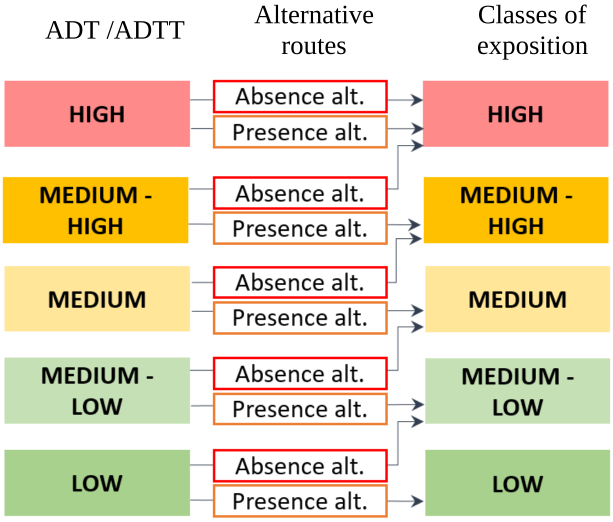

Figure 7 Logical path to determine the classes of exposition

4 APPLICATION OF THE PROPOSED CLASSIFICATION METHOD: CASE STUDY OF PROVINCE OF PISA

The proposed method of classification was applied to a sample of about 120 bridges of the Province of Pisa. To make a comparison of the new methodology of classification with the existing ones, its application on the same sample of 18 bridges, on which existing methods were applied and analysed in the Chapter 2, is presented. The obtained results in terms of classes and *warning level* are shown in Table 3. The order of bridges, with which are reported in the table, reflects the classification obtained according to the expert judgement. It is important to remind that the expert judgement was based only on the state of degradation, not taking into account other parameters. Therefore, in most case the classification provided by the experts corresponds well to the classification of the level of defectiveness identified according to the new approach. The results change considering also the other parameters, whose influence cannot be neglected.

The bridge with the code ID 2 (see Table 3) is taken as example. It is a masonry vault of small dimensions (Figure 8), built probably in the 1920's.

Figure 8 Bridge ID 2

During the visual inspection of the bridge, a worrying system of cracks was recognized, affecting both the vault and the abutments of the bridge. These cracks were considered signs of a kinematic motion, which could prejudice the static of the bridge. For this reason, the identified level of defectiveness is medium-high. Combining it with the construction period of the bridge, the class of hazard is found (Figure 11).

Figure 9 Diagonal crack on an abutment of the bridge

Figure 10 Longitudinal crack on the vault of the bridge

Being a masonry vault of little span, the structure of the bridge is redundant and robust and the construction material is not particularly subject to degradation, so its vulnerability class is low.

The traffic measures provided by the Province of Pisa highlighted that both the ADT and the ADTT are low and alternative routes sustainable in terms of length and timing of deviation exist in case of bridge closure. Therefore, also the class of exposition of the bridge is low.

Combining the classes of hazard, vulnerability and exposition, a medium-low warning level is obtained (Figure 12). This demonstrates that every factors influence the result. Despite the class of hazard is medium-high, the combination with low classes of vulnerability and exposition decreases the level of attention associated with the bridge. A medium-low warning level implies that the bridge requires a more frequent monitoring plan to check the currently existing cracks system, but it does not require urgent and deep interventions.

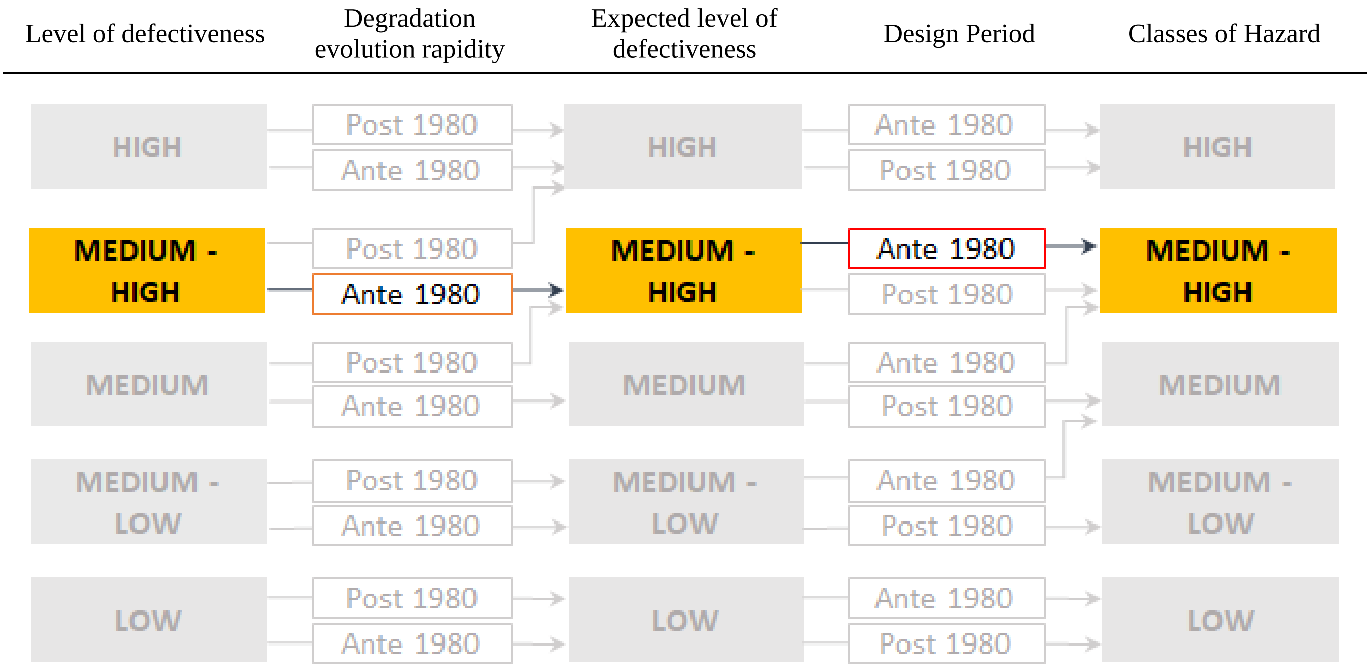

Figure 11 Logical path to determine the class of hazard of the bridge ID 2

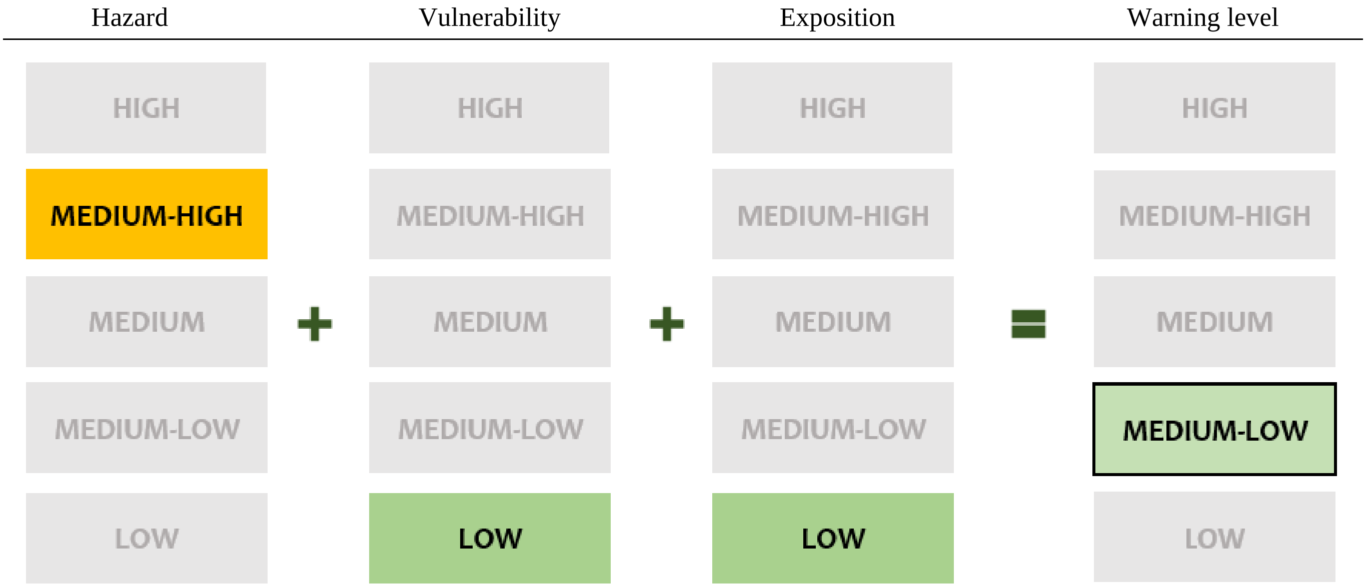

Figure 12 Logical path to determine the warning level of the bridge ID 2

Table 3 Application of the proposed classification method and determination of the warning level of a sample of bridges of the Province of Pisa

	Structural features									
	Structural typology	**Material deck**	**Total length**	**N° spans**	**Level of defectiveness**	**Construction period**	**Class of hazard**	**Class of vulnerability**	**Class of exposition**	***Warning level***
ID 1	Vault	Masonry	6,8 m	1	Medium-High	Ante 1980	Medium- High	Low	Medium - High	Medium - High
ID 2	Vault	Masonry	1,2 m	1	Medium-High	Ante 1980	Medium- High	Low	Low	Medium-Low
ID 3	Supported beams	R / C	9,5 m	1	Medium - High	Ante 1980	Medium - High	Medium	Medium-Low	Medium
ID 4	Supported beams	R / C	9,5 m	1	Medium - High	Ante 1980	Medium - High	Medium	Medium-Low	Medium
ID 5	Supported beams	P / C	510,0 m	18	Medium	Post 1980	Medium - High	Medium-Low	Medium - High	Medium - High
ID 6	Supported beams	R / C	8,0 m	1	Medium	Ante 1980	Medium - High	Medium	Low	Medium
ID 7	Fixed slab	R / C	2,5 m	1	Medium-Low	Ante 1980	Medium	Medium-Low	Medium-Low	Medium-Low
ID 8	Fixed slab	R / C	6,0 m	1	Medium-Low	Ante 1980	Medium	Medium-Low	Medium-High	Medium
ID 9	Supported beams	R / C	8,0 m	1	Medium-Low	Ante 1980	Medium	Medium	Medium	Medium
ID 10	Supported slab	R / C	2,0 m	1	Medium-Low	Ante 1980	Medium	Medium	Medium-Low	Medium-Low
ID 11	Vault	Masonry	8,5 m	1	Medium-Low	Ante 1980	Medium	Low	Medium-Low	Medium-Low
ID 12	Vault	Masonry	6,6 m	2	Medium	Ante 1980	Medium - High	Low	Medium - High	Medium - High
ID 13	Supported beams	R / C	6,0 m	1	Medium-Low	Ante 1980	Medium	Medium	Medium-Low	Medium-Low
ID 14	Supported beams	P / C	64,0 m	3	Medium-Low	Post 1980	Medium-Low	Medium-Low	Medium	Medium-Low
ID 15	Culvert	Steel	3,5 m	1	/	/	/	/	/	Low
ID 16	Vault	Masonry	4,0 m	1	Low	Ante 1980	Low	Low	Low	Low
ID 17	Supported beams	Steel	34,0 m	1	Low	Post 1980	Low	Medium-Low	Low	Low
ID 18	Supported beams	Steel	240,0 m	8	Low	Post 1980	Low	Medium-Low	Medium-Low	Low

5 OUTCOMING WORKS

A parallel work finalized to improve the method of classification presented in this paper is currently in progress,. The goal is the definition and the development of a numerical approach that allows to identify the different classes of hazard, vulnerability and exposition and the consequent warning level through numerical indices.

The approach for classes and logical operators, described in the present paper, and the numerical approach will not travel on two parallel tracks, but they will be strictly connected each other: the latter foresees the use of the same classes definition and the same classification logic used in the former, but converting the parameters and the classes identified for each bridge in numerical indices that allow to represent the result of the classification graphically, making more easy and immediate the comparison between the bridges.

The idea is to assign numerical coefficients to the primary parameters, which will be corrected by other numerical coefficients assigned to the secondary parameters. The influencing parameters will be the same used in the approach for classes and logical operators, identified in Table 2. The numerical coefficients to assign to them will be properly determined on the basis of the available studies in this field and they will have a clear scientific meaning.

In this way, a numerical index to represent the hazard (H), one to represent the vulnerability (V) and one to represent the exposition (E) associated with each bridge will be determined. The warning level (WL) will be evaluated through the product of the indices associated with the class of hazard, vulnerability and exposition of the bridge, as foreseen by the traditional framework of risk definition (2).

$$WL = H \cdot V \cdot E \tag{1}$$

This way to proceed will allow to represent the *warning level* associated with each bridge on a three-dimensional graph, in which each bridge is represented by a point identified through three coordinates (Figure 13). In function of the position of the point in the graph, the *warning level* associated with the structure will be defined.

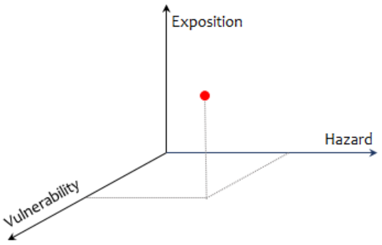

Figure 13 Point representing the bridge in a three dimensional space

The parameterization of the classes of hazard, vulnerability and exposition can allow to represent the *warning levels* through a discrete number of points (Figure 14), that reflects the result obtained by the approach for class and logical operators. The Figure 14 shows all the possible states of the bridges, according to the combinations of the classes of hazard, vulnerability and exposition.

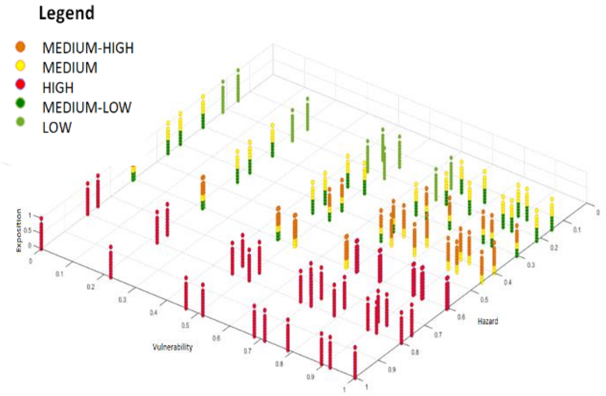

Figure 14 Points representing the possible states of the bridge according to the classes of hazard, vulnerability and exposition. The different colours correspond to the different classes of warning level, as indicated in the legend.

Identifying the point representing the bridge, it will be possible to identify immediately its *warning level*, through the reading of the colours.

The calibration and validation of the coefficients to use in this approach are currently being completed.

6 CONCLUSIONS

The present paper proposes a new method of classification of the structural and geotechnical risk associated with existing bridges. It was developed thanks to the study and the analysis of existing methods in the scientific literature and the actually applied ones, but especially thanks to the experience acquired by the Department of Civil and Industrial Engineering of the University of Pisa and the Department of Architecture and Industrial Design of University of Campania *Luigi*

Vanvitelli, in the monitoring activity currently in progress on the bridges, respectively under the Province of Pisa and the Province of Caserta administration. For this reason, the hypothesis and the criteria at the basis of the method are well applicable to bridges within provincial roads, but they can be extended to other typologies of roads, including data referred to them.

The proposed classification is based on the rapid and simple evaluation of the *warning level* of the bridges. The *warning level* condenses all factors influencing the risk in a single indicator, defined by the combination of three factors – hazard, vulnerability and exposition – according to the typical framework of the risk definition. Simple visual inspections allow to identify the factors at play and not sophisticated and expansive surveys or analysis are required. In this way, the method is easily applicable by the smaller management reality too on a large number of structures. Therefore, it works on territorial macro-scale and allows the classification of all the structures in a territory.

The definition of the factors and the *warning level* can be performed according an approach for classes and logical operator. It does not foresee the evaluation of an index of risk, but it is based on the subdivision of the bridges in classes of hazard, vulnerability and exposition, whose definition is well-established, in order to give a classification as objective and clear as possible. The approach provides immediate information about the *warning level* to be reserved to a bridge. depending on the state of degradation, the aging, the vulnerability associated with the static scheme, the exposition level and all the other parameters that influence the risk of the bridge. Respecting to the methods of classification existing in literature, the proposed one takes into account all the possible sources of structural and geotechnical risk, neglecting the seismic and hydraulic ones to not distort the result. The latter two will be analysed separately and their influence on the structural risk classification will be estimated.

The evaluation of the classes of hazard, vulnerability and exposition allows to identify how and how much each factor is involved. In this way, the management body is helped in the decision-making process, also to decide the best way to proceed on each bridge in order to reduce its *warning level* (reinforcing the structural elements, limiting the traffic loads, and so on).

The classification based on the *warning level* can be a useful tool to draw up an order of priority of intervention optimizing the allocation of the human and economic resources, starting from the most critical situations.

According to the *warning level*,, it is possible to calibrate the ways to proceed on each bridge, foreseeing different level of deepening and detail as needed. For example, it could be thought to apply more complete and accurate safety evaluation on the structures with highest *warning level* and ordinary monitoring activity on the structures with lower ones. A fundamental role can be assumed by the monitoring activities, both continuous and discrete, in order to increase the knowledge about the structures and improve the structural check condition. A better knowledge about the structures or about the traffic loads, for example, would allow to reduce the uncertainties related to the loads values, the materials characteristics and so on. This would allow to reduce the safety factors used in the verifications.

In this way, the management bodies know where and how concentrate their resources, having clear indication about the ways to proceed on all bridges. More complex, time-consuming and expensive investigations and evaluations, such as the safety evaluation or the resilience one, will be applied only on a limited number of more in need structures, selected through the proposed system of classification, passing, thus, from a macroscale assessment to a small-scale one.

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8 REFERENCES

American Association of State Highway and Transportation, 2018. The manual for bridge evaluation.

ANAS Gruppo Ferrovie Italiane, 2018. Relazione di sintesi sulle attività di vigilanza di ponti e viadotti.

Berdica, K., 2002. An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy* 9:117–127.

Ceccotti, A., Giangreco, E., Jurina, L., et al., 2011. Manuale valutazione dello stato dei ponti, 2011th edn. Centro Internazionale di Aggiornamento Sperimentale-Scientifico.

Franchetti, P., Pellegrino, C., Soffiato, A., Modena, C., 2003. La manutenzione programmata di ponti e viadotti: criteri per la valutazione dell'efficienza in servizio. *XII Convegno nazionale S.I.I.V.* Padova

Ministero Delle Infrastrutture e dei Trasporti, 2018. Decreto Ministeriale 17/01/2018. Nuove Norme Tecniche per le Costruzioni "NTC 2018".

Montepara, A., Merusi, F., Giuliani, F. Sviluppo di una nuova metodologia per la valutazione delle priorita' di intervento di manutenzione di ponti e viadotti. *17° Convegno Nazionale della Società Italiana Infrastrutture Viarie*

Salvatore, W., Buratti, G., Cosentino, A., Morelli, F., 2019. Alcune considerazioni sull'evoluzione normativa dei carichi da traffico nella progettazione dei ponti stradali in Italia.

Valenzuela, S., Solminihac, H. De., Echaveguren, T., 2010. Proposal of an Integrated Index for Prioritization of Bridge Maintenance. 15:337–343