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Guidelines for the classification and management of risk, for the evaluation of safety and for the monitoring of existing bridges: differential analysis of experimental software applications for level 0,1,2 assessments

Giacomo Viti[a], Ilaria Castriota[a], Emanuele Renzi[a], Franco Ciminelli[b], Egidio Lofrano[b], Davide Bernardini[b], Achille Paolone[b], Galileo Tamasi[b]*

[a]*National Safety Agency for Safety of Railway and Road infrastructures, Viale del Policlinico,2 – 00185 Roma, Italy*
[b]*Department of Structural and Geotechnical Engineering, University "La Sapienza", Via Eudossiana 18, 00184 Rome, Italy*

Abstract

This paper investigates the application of the procedure described by the Italian Guideline for existing bridges and its related Operating Instructions for an existing bridge through three different IT (Information Technology) applications in order to evaluate its compliance with the regulation, and its effectiveness and efficiency, also in perspective of product certification. The work initially describes the result obtained applying manually the Guidelines with the aid of a non-commercial software developed at Sapienza for the definition of the level of defectiveness. Thus, the same procedure is repeated using two open-source commercial software, Inspicio and InBee which allow to operate within a Bridge Management System framework. Finally, a differential analysis among the three analyses is performed, highlighting the differences and the main characteristics of the software for the definition of the level of defectiveness, which is crucial for determining the attention class and to properly schedule the maintenance operations. Pros and cons of each individual software are detailed, followed by some suggestions for their potential improvement.

Keywords: BMS, Differential analisys, Software certification, Infrastructures supervision, Operational supervision plans, Road Network classification

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* Corresponding author. Tel.: +39(320)6197910;
E-mail address: galileo.tamasi@ansfisa.gov.it

1. Introduction

Most of the Italian heritage of bridges and viaducts is many years old. In the past, many Italian road operators planned maintenance of the bridges according to defined deadlines indicated in the ministerial circular no. 6736 / 61A1 (MLP, 1967). In Europe the first Bridge Management System (BMS) was developed in the early 2000s in the BRIME project whose goal was to create a unique standard for the European area (Woodward et al, 2001).

The regulatory evolution in the infrastructure sector, promoted by the Italian Ministry of Infrastructure, has led to the update of the "Guidelines for Risk Classification and Management of Existing Bridges" (Guidelines). This update, outlined in the CSLLPP ministerial decree no. 204/2022, refines, and surpasses the previous provisions of decree no. 578/2020, and is integrated with the operational instructions provided by ANSFISA in 2022. This regulatory revision introduces a more sophisticated risk assessment system, which unfolds through a stratified and multi-level methodology, aimed at optimizing the safety and monitoring of existing road infrastructures (bridges and viaducts).

This methodology, as outlined by Buratti et al. (2022), is based on the separate and then integrated analysis of various risk factors: structural and foundational, seismic, landslide, and hydraulic, into an Overall Attention Class. The process is structured in levels, described by Santarsiero et al. (2021) as follows: Level 0 focuses on the inventory of infrastructures; Level 1 is dedicated to visual inspections; and Level 2 culminates in the determination of the Overall Attention Class.

This multilevel approach, which differs from other previous BMSs developed by local authorities in Italy, (Bortot et al., 2006; Zonta et al., 2007; Yue, 2013; Fattorini, 2023), is similar to Hazus bridge classification method, initially developed by FEMA for seismic risk in 1997 and then extended from 2004 to a multi-hazard version (FEMA,2022).

The importance of these Guidelines is further emphasized by the research of Cutrone et al. (2023), which highlights the effectiveness of adopting innovative methods to improve the classification of landslide risk. Moreover, De Matteis et al. (2022) and Di Sano et al. (2023), demonstrate the applicability of the Guidelines through a selected cases study, underlining the need for a holistic approach in the management of infrastructural risks.

The main objective of this study is to highlight the urgent need for automated software procedures, as described by Natali et al. (2023), to effectively manage a large inventory of bridges, significantly reducing both the time required for the compilation of defect sheets and the possibility of error. This automated approach is essential for the practical long-term implementation of the levels 0, 1 and 2, thus ensuring a more efficient and reliable risk monitoring and management for existing bridges.

2. Depiction of the software

Inspicio and InBee are two commercial software (SW) used for the implementation of the procedure defined by the Guidelines. The adopted revisions are the ones released on May 30, 2023. Additionally, an *in-house* software, developed within a Python environment by the University of Rome La Sapienza (version 1.0), was used to help the manual procedure; details are in section 4.

Both commercial software can be accessed through a web app, which is accessible from any location with an internet connection. Therefore, it is also possible to enable the 'multiple user profiles' to facilitate multidisciplinary activities and coordinate contributions by different technicians.

The SW Inspicio (https://vger-1.unipi.it/login) divides the information required by the Guidelines and the related parameters into a level 0 card and three level 1 cards (descriptive, landslide risk, and hydraulic risk, respectively) with their relevant subsections (structural data, location, etc.). Element sheets are added for defining the level of structural and seismic degradation, along with a level 2 card for the automatic generation of attention classes.

On the other hand, SW InBee (https://inbee.it/) has two cards (level 0 and level 1) divided into further sections (context, structure, accessory elements, services), and an overview card with a graphical representation of the results of the automated calculation of the attention class. There is also a panel for viewing geolocated bridges with an indication of their respective attention class, allowing filtering based on representative parameters.

Both applications offer the automatic generation of level 0 and 1 report, the ability to attach documentation related to the studied project, and the option to link inspection documentation (including photographs) via a mobile application.

3. Description of the case-study

As a demonstrative case, the procedures outlined by the Guidelines ha been implemented on a viaduct located in the metropolitan area of Rome, an urban context situated within the hydrographic basin of the Tiber River. The original project dates to the late ‘80s, whereas the construction occurred between 1990 and 2000. The bridge, designed with a statically determined scheme, has a total length of approximately 1559 m, and consists of 47 spans of approximately 32 meters each. The overall width of the deck is about 18 meters, consisting for many spans (38 of 47, the others non-typical ones have 7, 8 or 9 beams) of 6 prestressed reinforced concrete beams with I-shaped section (Fig. 1-a): the beams are simply supported on a single pier (Fig. 1-b), for some spans, and on two independent, uncoupled, piers (Fig. 1-c), for others. All the piers have a rectangular cross-section, varying in elevation. The deck and the piers are connected by 623 supports of various types. The bridge is supported by a total of 45 piles and includes 4 abutments, two of which are positioned intermediately along the structure. To sum up, the total number of elements into which the viaduct has been divided for the visual inspections of level 1 is 1392. In this context, the use of dedicated software becomes an indispensable tool. Its utility is crucial for thoroughly analyzing the broad spectrum of risk factors and for facilitating the effective determination of attention classes starting from this large amount of data.

For the purposes of the Guidelines the following additional information are needed: the structure spans over a region designated as parking area and railway station; in case of service interruption, road alternatives are available and are not subject to mass and size limitations; the viaduct is not designed for frequent pedestrian passage; there is an additional seismic vulnerability element due to the bridge curvilinear path (Fig. 1-d).

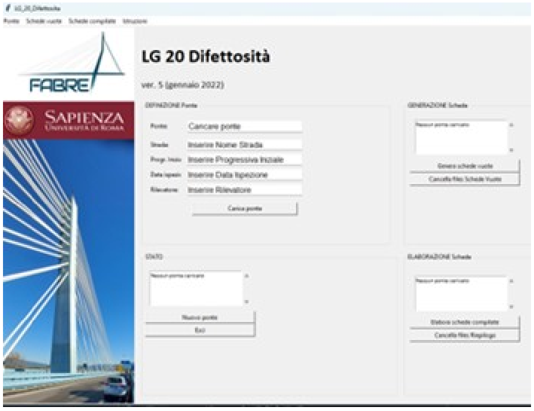
Fig. 1 Case-study: (a) typical cross-section of the deck; panoramic view of a span supported by (b) single piers and (c) pairs of piers; (d) partial longitudinal view of the viaduct.

The complexity of the case study is heightened not only by the presence of a landslide characterized by collapse and overturning phenomena, but also by the hydraulic risk. Indeed, the structure crosses two secondary rivers with two different spans and is almost entirely bordered by a main river. Both issues have been investigated at a limited degree, namely through the processing of cartographic information combined with data obtained during visual inspections (carried out without specific supplementary measurements and surveys).

4. Manual procedure (with the aid of Sapienza *in-house* software)

To evaluate the overall attention class of bridge, it is crucial to gather and/or estimate 57 distinct parameters, as outlined by the Guidelines. Initially, during the census phase (Level 0), some of these parameters were derived by examining existing documentation and cartographic resources (such as project documents, regional catalogs, and so on). Subsequently, the remaining parameters were assessed through visual inspections (Level 1), which also included a check on the accuracy of the information previously collected.

The most challenging parameter to be assessed is undoubtedly the **Bridge** (Structural and Seismic) **Defectiveness Level**. As previously mentioned, to determine this, it is necessary to create and process a defect sheet for each structural element, following the instructions provided by the Guidelines and relevant Annexes and operational instructions. With a total of 1932 sheets to be compiled, the operation for the given case study proves to be brutally onerous. To simplify this process, two of the coauthors (D.B and F.C.) have developed an *in-house* software dedicated to the generation, compilation, and processing of these defect sheets (Fig. 2). The software, based on a Python routine, has been developed for research (non-commercial) purposes; interested readers can ask more information to the Authors.



LG 20 Difettosità

ver. 5 (gennaio 2022)

Ponte: Caricare ponte
Strada: Inserire Nome Strada
Progr. Inizio: Inserire Progressiva Iniziale
Data ispez.: Inserire Data Ispezione
Rilevatore: Inserire Rilevatore

Nessun ponte caricato

Fig. 2 Main user interface of the Sapienza Python routine.

4.1. Evaluation of the defectiveness level

The in-house software operates through a methodical sequence of steps that are described in the following workflow:

1. Definition of the bridge and its components (beams, transverse beams, deck slabs, expansion joints, pier caps, pier columns, abutment walls, supports/bearings, etc.);
2. Automatic generation of individual element-related sheets by the software as .xls files;
3. Manual input of inspection data into the .xls sheets to assess the health condition of each element;
4. Processing of the completed sheets with the code to determine the **Bridge Defectiveness Level**.

Concerning the first three steps, once the defect sheets have been generated for each element, every revealed defect is associated with the parameters provided by the Guidelines: a weight coefficient G, that varies in ascending order of importance from 1 to 5, a coefficient K1 measuring the extent of the defect, and another coefficient K2 measuring the intensity. Additionally, for defects with a G value of 4 or 5, a PS checkbox can be marked to indicate that the defect may compromise the structure stability. Other two checkboxes are considered in the .xls file provided by the Sapienza routine. These concern two further information required by the Guidelines: E_CR indicates that the defect may involve a critical element (such as Gerber beams, prestressing cables, etc.) and is assigned ‘a priori’ by the code; if the detected defect results in a critical condition that poses immediate danger, the C_CR checkbox can be marked, thus indicating that a critical condition has been inspected.

It is clear how the availability of .xls files is crucial to reduce the time of compilation, especially in the case of elements that have the same defects (where a ‘copy and past’ process can be easily applied). Moreover, at the fourth step, the software also determines the intermediate parameters for assessing the bridge defectiveness level through a methodical sequence of steps, as illustrated in Fig. 3. More in detail, the software provides the defect levels for each group (superstructure and substructure) based on the defect levels of the individual elements that constitute them. Thus, the evaluation of the structural/foundational defect levels and of the seismic defect level are automatically obtained.

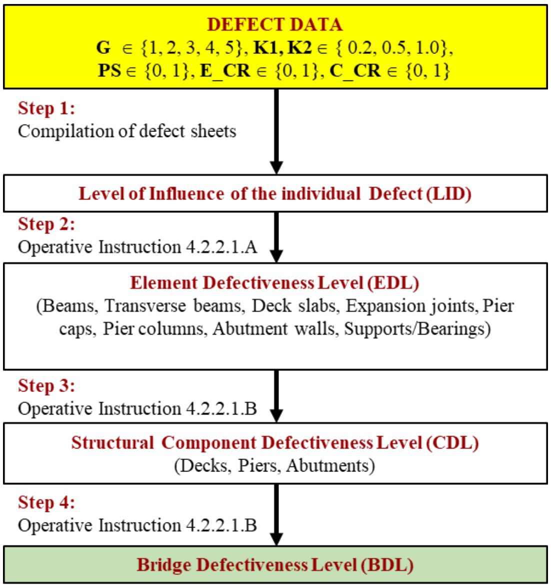
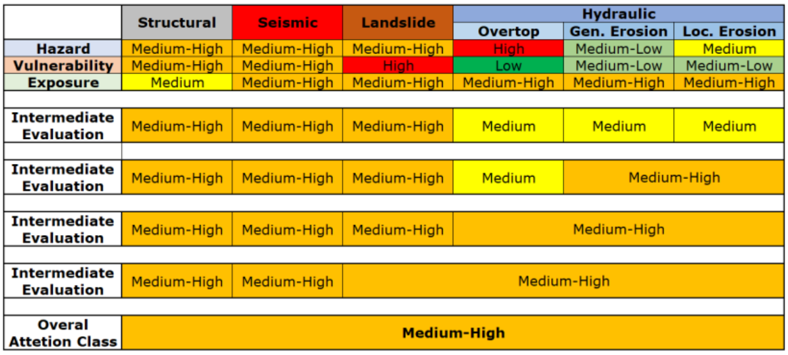


Fig. 3. Flowchart for the evaluation of Bridge Defectiveness Level (BDL).

For the given case study, the manual procedure aided by the *in-house* code provided a **medium-low** defectiveness level for both groups (superstructure and substructure) and for both types of risks (structural/foundational and seismic), resulting in an overall **medium-low** level for both structural/foundational and seismic defect levels.

4.2. Overall Attention Class assessment

The attention classes have been manually determined for each type of risk, along with the overall attention class, as shown in the Fig. 4. The overall **medium-high** attention class is primarily caused by the exposure of the structure and its structural and seismic vulnerability, which is influenced by parameters related to the static scheme, material, and span. Therefore, despite the structural/seismic defect level being medium-low, the vulnerability classes related to structural/foundational and seismic risks are anyway medium-high.



	Structural	Seismic	Landslide	Hydraulic		
				Overtop	Gen. Erosion	Loc. Erosion
Hazard	Medium-High	Medium-High	Medium-High	High	Medium-Low	Medium
Vulnerability	Medium-High	Medium-High	High	Low	Medium-Low	Medium-Low
Exposure	Medium	Medium-High	Medium-High	Medium-High	Medium-High	Medium-High
Intermediate Evaluation	Medium-High	Medium-High	Medium-High	Medium	Medium	Medium
Intermediate Evaluation	Medium-High	Medium-High	Medium-High	Medium	Medium-High	
Intermediate Evaluation	Medium-High	Medium-High	Medium-High	Medium-High		
Intermediate Evaluation	Medium-High	Medium-High	Medium-High			
Overal Attetion Class	**Medium-High**					

Fig. 4 Manual evaluation of the attention classes.

5. Evaluation using software Inspicio and InBee

The procedure proposed by the two commercial software Inspicio and InBee were implemented by inputting the same parameter values used during the manual evaluation.

At first Level 0 and Level 1 card were filled out. At his stage, the two software behave similarly, although the InBee application proved to be highly useful in populating the Level 0 structure card, leading to a detailed definition of the bridge structure in all its constituent elements. Furthermore, once this card is filled out, the software allows for the automatic generation of Level 1 element sheets.

5.1. Evaluation of defectiveness level

The evaluation of the bridge defectiveness level takes place after generating and completing the individual sheets related to the constituent structural elements of the viaduct.

The Inspicio software, which has a maximum capacity of 100 sheets, including those of levels 0, 1, and 2, does not have the capability for automated sheet creation based on census data and level 1 data. Therefore, it is necessary to manually input all the element sheets 'one-by-one', resulting in a significant data entry burden. There is no automated procedure and no duplication function between different sheets, and it is necessary to manually identify the analyzed element and the relevant macro group (superstructure/substructure) in the header of each sheet.

The InBee software streamlines the evaluation process by allowing for the automatic generation of the defect sheets and their partial duplication (among the same group, such as beam n.1 belonging to span n.1 to beam n.2 belonging to the same span n.1), thereby reducing the data entry effort. Additionally, it allows for the categorization of elements by automatically dividing them into subgroups such as substructure, which includes abutments, piers, and associated connections, and superstructure, which encompasses spans and related beams and decks. This categorization facilitates the calculation of their respective levels of defectiveness regarding structural and seismic risks. Moreover, InBee includes a condition index (not listed in the Guidelines) on the header of each card, aiding in the assessment of the defectiveness status of the element under investigation.

Both software requires the parameters G, K1 and K2 in each inspection card, in accordance with the Guidelines; also the PS box is contained (in the case of defects with a magnitude G of 4 or 5). However, they differ in the interpretation of the critical element the critical condition parameters, as better described later.

For both applications, the bridge defectiveness level is determined to be **medium-low** in accordance with the manual procedure.

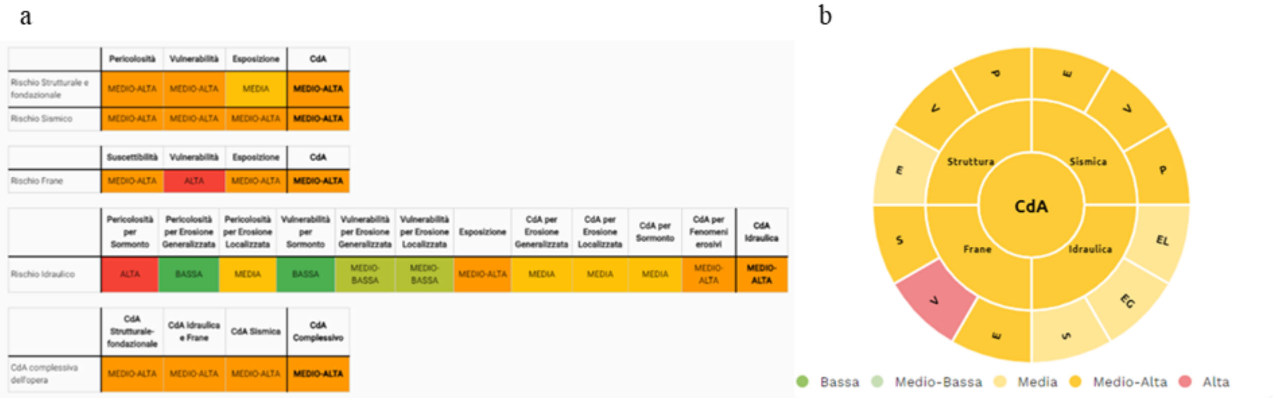
5.2. Overall Attention Class assessment

The Inspicio software, utilizing the data inputted into Level 1 sheets, automatically assigns an overall **medium-high** attention class, consistent with the manual procedure, as depicted in Fig. 5-a. In the previous versions of Inspicio, the code indicated a high attention class due to discrepancy in determining the hydraulic attention class for overtopping phenomena (assessed as medium in the manual procedure). However, this discrepancy disappears in the actual version of the software (accessed November 8, 2023).

Also, the InBee software, starting from the parameters defined at Level 0 and Level 1, automatically determines an overall **medium-high** attention level, in accordance with the manual procedure. The display of partial and overall attention classes is presented graphically in an intuitive manner to immediately identify the ruling factors (hazard ‘P’, vulnerability ‘V’, exposure ‘E’) and parameters that have contributed to the specific attention class, as shown in the Fig. 5-b.

6. Differences and main features of the software for the evaluation of defectiveness level

As already discussed, the defectiveness level has a significant impact on the evaluation of the structural/foundational, as well as seismic, attention class. These two classes have on turn a dominant influence in determining the overall attention class. Following the experience described in this paper, some pros and cons can be outlined on this standpoint, see Table 1.



	Pericolosità	Vulnerabilità	Esposizione	CdA
Rischio Strutturale e fondazionale	MEDIO-ALTA	MEDIO-ALTA	MEDIA	**MEDIO-ALTA**
Rischio Sismico	MEDIO-ALTA	MEDIO-ALTA	MEDIO-ALTA	**MEDIO-ALTA**

	Suscettibilità	Vulnerabilità	Esposizione	CdA
Rischio Frane	MEDIO-ALTA	ALTA	MEDIO-ALTA	**MEDIO-ALTA**

	Pericolosità per Sormonto	Pericolosità per Erosione Generalizzata	Pericolosità per Erosione Localizzata	Vulnerabilità per Sormonto	Vulnerabilità per Erosione Generalizzata	Vulnerabilità per Erosione Localizzata	Esposizione	CdA per Erosione Generalizzata	CdA per Erosione Localizzata	CdA per Sormonto	CdA per Fenomeni erosivi	CdA Idraulica
Rischio Idraulico	ALTA	BASSA	MEDIA	BASSA	MEDIO-BASSA	MEDIO-BASSA	MEDIO-ALTA	MEDIA	MEDIA	MEDIA	MEDIO-ALTA	**MEDIO-ALTA**

	CdA Strutturale-fondazionale	CdA Idraulica e Frane	CdA Sismica	CdA Complessivo
CdA complessiva dell'opera	MEDIO-ALTA	MEDIO-ALTA	MEDIO-ALTA	**MEDIO-ALTA**

Fig. 5 Evaluation of Attention Classes: (a) Inspicio, and (b) InBee. Data in Italian (chromatic maps as in Fig. 4).

Table 1. Comparative analysis of the main software features for the evaluation of defectiveness level.

Feature	Software		
	Manual/Sapienza	Inspicio	InBee
Automatic generation of defect sheets	Yes	No	Yes
Ability to attach defect pictures	No	Yes	Yes
Limitations in the number of defect sheets that can be generated	No	Yes	No
Defect sheets for accessory elements/services	No	Yes	Yes
Possibility to duplicate defect sheets	Yes	No	Partial
Structural/seismic critical elements	Defect level	Element sheet level	Element sheet level
Critical structural/seismic condition	Defect level	Defect level	Element sheet level
Condition index for each element	No	No	Yes

Feature	Software		
	Manual/Sapienza	Inspicio	InBee
Completion index of the defect sheet	No	No	Yes
Indication at the bridge level of defects not detected	No	No	Yes
Indication at the bridge level of the number of defects that may compromise the structure stability and the number of defects with the highest level of importance (G=5)	Yes	No	Yes

Among the others listed in the table, two main findings may be commented in detail. From one hand, it seems crucial to highlight the importance of being able to duplicate sheets among elements to reduce the compiling effort. Estimating a minimum of one minute to fill out the sheet, plus additional 10 seconds for each attached photo, the total time amounts to approximately 3.5 minutes for a sheet with 15 defects. For the given viaduct, this leads to an estimated total of 4’872 minutes, or **81 hours**, to complete all the sheets, which equates to more than 10 working days (for one person). Moreover, it is important to note that this is not a ‘one-time’ requirement since the same process must be repeated at each inspection to monitor damage progression. What is more, the high number of repeated commands increases the risk of human error in sheet completion.

On the other hand, a discrepancy exists among the software in the interpretation of the parameters related to the **critical element** and the **critical condition** settings, where further considerations seem advisable to avoid a discretionary definition by software houses or inspectors.

7. Conclusions and future developments

The findings of this study underline the need of employing software system to implement the Guidelines and to calculate the level of defectiveness, which represents the most computationally intensive parameter to be determined. Moreover, there is an increasing need to validate the software already developed by some software houses to ensure that the logical algorithms implemented by the code are consistent whit those prescribed by the Guidelines and their application instructions, thereby preventing the development of automated schemes that could yield discordant outcomes.

The comparative analysis detailed in this paper yielding consistent results among the three analyzed procedures. Certainly, this result is limited to the considered case-study. Conducting this comparison across a broader range of bridges would be beneficial to confirm the reliability of the software and to build up a benchmark database. The comparative analysis also highlights the main pros and cons of each software, where some specific features turned out to be very useful for reducing times and giving robustness to simulations.

Future developments could include the integration of Guidelines into AINOP (National Inventory of Public Structures and Infrastructures) or in to interoperable platforms and architectures based on Web Open Gis already successful tested (Dayan, 2022, Santarsiero, 2021, Pessina, 2009) allowing transfer of data and information from the proprietary applications of infrastructure managers for large scale territorial classifications of the existing infrastructure heritage.

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