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A new bridge management system based on spatial database and open source GIS

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Abstract
Bridge management is a complex and challenging task at global scale. The main purpose of bridge management is to facilitate the identification of bridge deficiencies in order to carefully plan and execute maintenance operations, and ensure the continued safety of traffic. In 2020, the Italian Ministry of Infrastructure issued mandatory guidelines for risk classification and management, safety assessment and monitoring of bridges. These guidelines rely upon bridge inventory, which includes a number of heterogeneous inspection data organized in different files. This paper presents a hardware and software architecture for the automatic entry of all inspection data (e.g. spatial information, sheets and photos) in a relational spatial database and their visualization through a Desktop and Web GIS (Geographic Information System) application. The procedure is summarized in a new Bridge Management System (BMS), whose main novelty is the full control of the georeferenced infrastructures, with the opportunity of improving the status check and management of bridges and their components. The BMS has been developed using data collected during inspection surveys requested by the Consortium of Sicilian Highways on the conditions of the bridges and viaducts belonging to motorways in Sicily (Italy). The developed system overcomes most of the common limitations in existing BMSs, such as the limited capacity of visualizing geospatial data and the reduced supported data formats, providing a valid Decision Support System in evaluating and prioritizing repair and maintenance actions.

Keywords Bridge management systems · GIS · Relational database management software · Automatic data entry

1 Introduction

Bridges and viaducts are important road infrastructures with a great impact on mobility and economy, especially in Italy, where 85% of goods are shipped by road. As all infrastructures, bridges undergo variable deformations caused by several factors, including natural ground motion, temperature fluctuation, subsidence, landslides, earthquakes, water/sea level variation and subsurface resource extraction (Rainieri et al. 2020; Hadjidemetriou et al. 2021; Maroni et al. 2022).

When a bridge is no longer viable, alternative roads are offered that do not often provide the same degree of effectiveness in terms of travel time and speed. In the most serious cases, damage caused by natural hazardous events or human errors can pose a risk for human safety, such as in August 2018, when the collapse of the Morandi bridge (Liguria, Italy) killed 43 people (Calvi et al. 2019). Bridge monitoring and maintenance is thus of great importance to guarantee the continuity of the service and avoid the closure of road sections, affecting traffic and the local economy.

Maintenance intervention of bridges and viaducts includes two major challenges: (i) improving the availability and functionality (i.e. preventing the closure) of existing and ageing infrastructures, (ii) planning scheduled interventions in order to assure safety over time. However, these strategic actions are often difficult or unpractical to implement due to the lack of complete and detailed information about the status of bridges and viaducts. Indeed, the little

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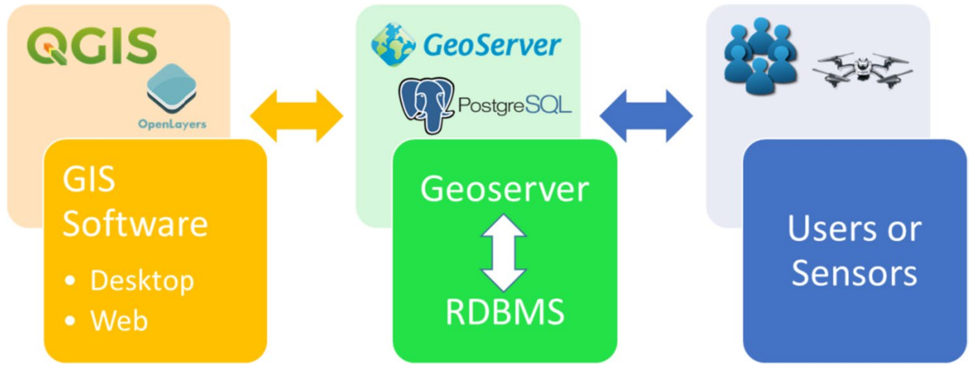


Fig. 1 Block diagram of the software architecture used in our BMS. The geoserver and the RDBMS are located at the centre, allowing the sharing and editing of the spatial data with both the GIS software and the other users or sensors, such as drones

information available is on paper or stored in digital spreadsheets that include disagreeable data (e.g. inspection reports and photos) and thus very difficult to use. This is because data collection is carried out through targeted surveys, which are constrained by financial resources and/or specialized personnel.

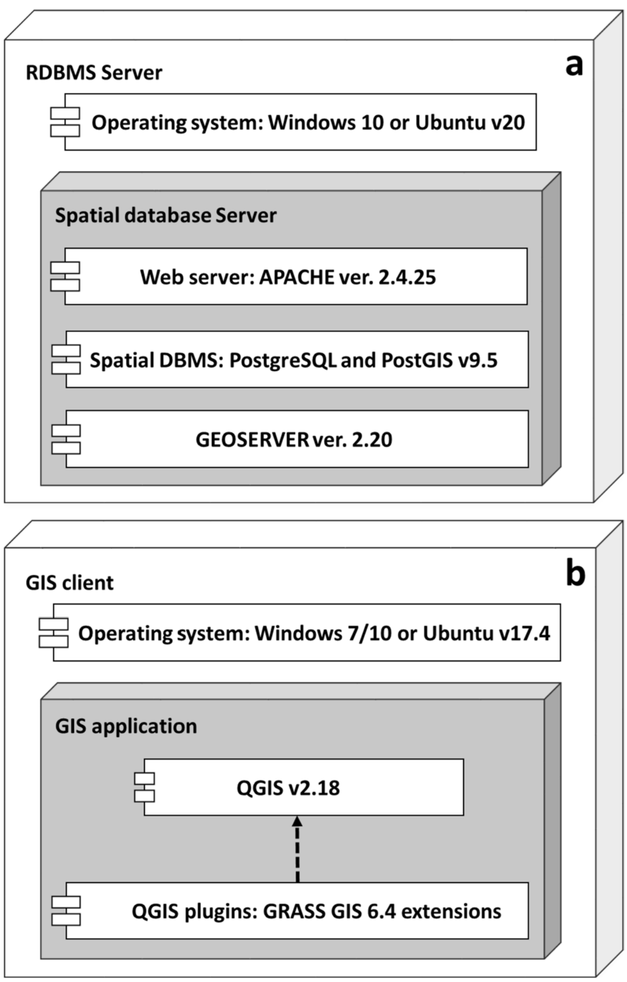


Fig. 2 UML deployment diagram of the RDBMS server (**a**) and the GIS client (**b**). The nodes, represented as cubes, are the physical entities, which can be hardware or software. Inside the cubes, the software programs used are indicated

In recent years, many efforts have been made by researchers to assess the health condition of a bridge and improve the planning of maintenance actions. This task has benefited from the ever-greater development of Information and Communication Technologies (ICTs), which allow for a better quality of inventory and inspection data, and more control over deterioration, forecasting and management models (Darbani and Hammad 2007). However, there is still a lack in literature of works using ICTs within the bridge maintenance process to enhance the efficiency of the key processes. Moreover, knowledge and information, which are redundant and fragmented, are continuously exchanged by different stakeholders with different levels of technical expertise, preventing from effective and accurate maintenance decisions (Ren et al. 2019).

Most works available in literature include the development of Bridge Management Systems (BMSs) based on indices, such as the Bridge Health Index (Shepard and Johnson 2001), the Integrated Bridge Index (Valenzuela et al. 2009), the Defect-based Urgency Index (Abu Dabous et al. 2016), or the Bridge Overall Priority Index (Mahdi et al. 2022), which provide a measure to rank the maintenance interventions on the basis of the bridge status. Other BMSs are based on the integration of Geographic Information Systems (GIS) and Building Information Modelling (BIM), providing a support during the entire lifecycle of a bridge, including plan, design, construction, operation and dismantling, as well as a good basis for maintenance (see, e.g. Ibrahim and Yunus 2019; Wattan and Al-Bakri 2019; Achuthan et al. 2021; Badruzzaman and Hendriana 2021; Wei et al. 2021; Zhou 2022). However, current BMSs are still time-consuming, inefficient and affected by different problems, such as the limited ability to retrieve and share the available data electronically, the limited ability to visualize geospatial data, the limited collection capability of additional information (such as survey data or photos), unintuitive graphic user interfaces, nearly no web-based applications. GIS technology has often the function of a macro layout to improve traffic jam or select the best geographic locations for new bridges (Hojune et al. 2019; Wei et al. 2021; Debnath 2022), or to maximize

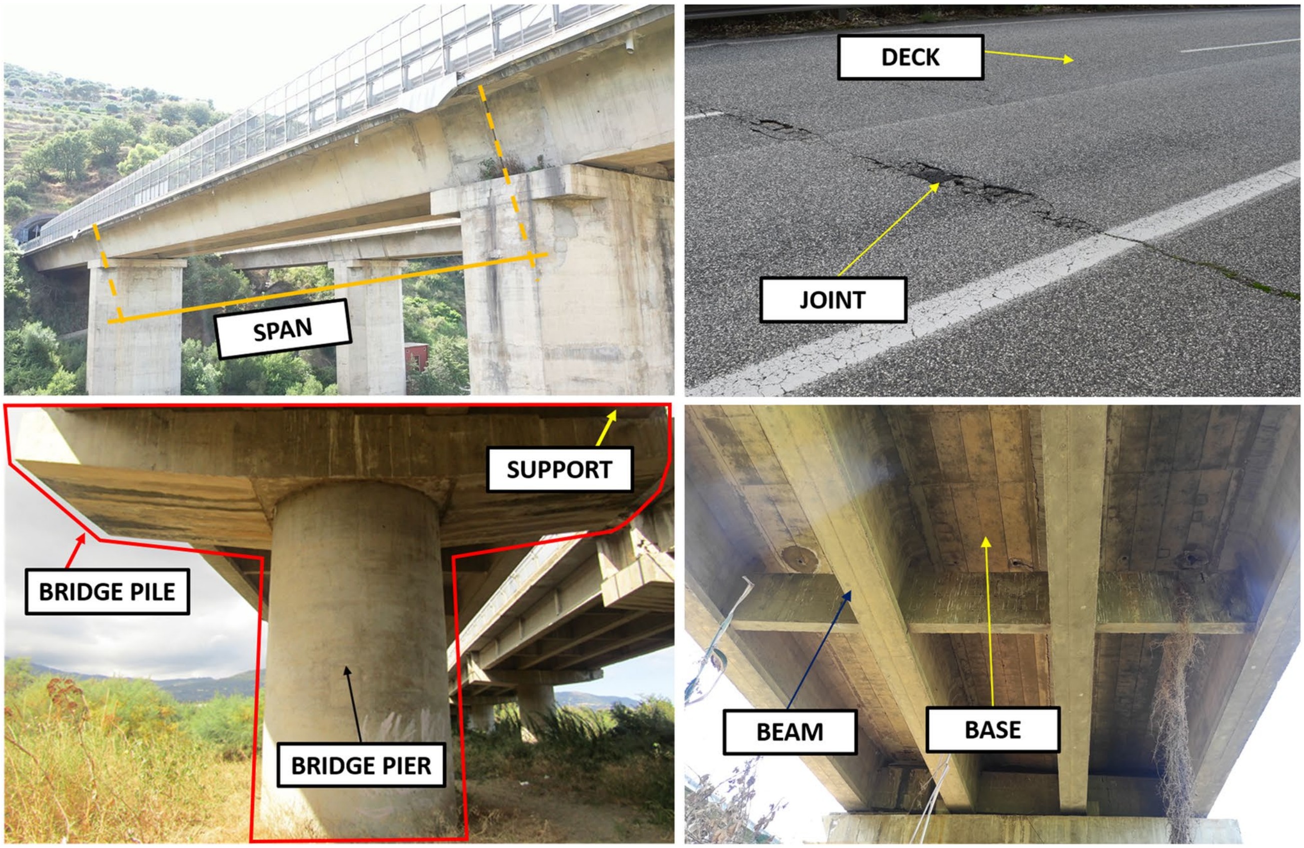


Fig. 3 Main entities of a bridge, representing the components on which the census is carried out and any defects are detected

bridge inspection activities (Badruzzaman and Hendriana 2021). There is no information on how the data is structured, stored and made available through the GIS, and the elements of the bridge do not reflect its real structure (Wattan and Al-Bakri 2019). Indeed, the most common limitation is the lack of design and description of the data structure, with the topographical references of the bridge completely neglected, and the defects wrongly related to the entire bridge, and not to the single elements that compose it (see, e.g. Ibrahim and Yunus 2019).

Another problem derives from the fragmentary management of bridges and viaducts, which are usual in charge of several infrastructure management companies. These operate in a disaggregated way, using in-house BMSs that include data collected during own field surveys.

In order to homogenize the inspection data, standardize the evaluation protocols and plan optimal intervention programs, different countries have invested great resources and efforts to develop own management systems for bridges and travel networks, including USA (Robert et al. 2003), Denmark (Lauridsen and Bjørn Lassen 2015) and Japan (Miyamoto and Motoshita 2015). Due to the differences in bridge management practices between countries, these systems are designed to suit specific needs, so they can be used only at national and/or local scale. Moreover, there are still many problems during their practical application because the information stored is fragmented and isolated, the visualization is hard to realize, and bridge engineers and managers find it difficult to collaborate with each other through the system (Wan et al. 2019). A detailed literature review of current bridge management practices and systems in operation in the world can be found in Saback de Freitas Bello et al. (2021).

In Italy, on 6 May 2020, the Superior Council of Public Works of the Ministry of Infrastructure approved the guidelines for the classification and management of risk, safety assessment and monitoring of existing bridges (available online at https://www.mit.gov.it/comunicazione/news/mit-approvate-le-linee-guida-per-la-sicurezza-dei-ponti). These guidelines outline a standardized procedure for the management of bridges in order to prevent damage, make the risk acceptable and ensure continuity of operation (Santarsiero et al. 2021). The procedure, which has a multi-level structure, guarantees a calibrated assessment to establish the actual need and urgency of bridge maintenance interventions. It is based on field inspection surveys for the acquisition of data both on the census of the infrastructures and on their condition of deterioration, which are stored in

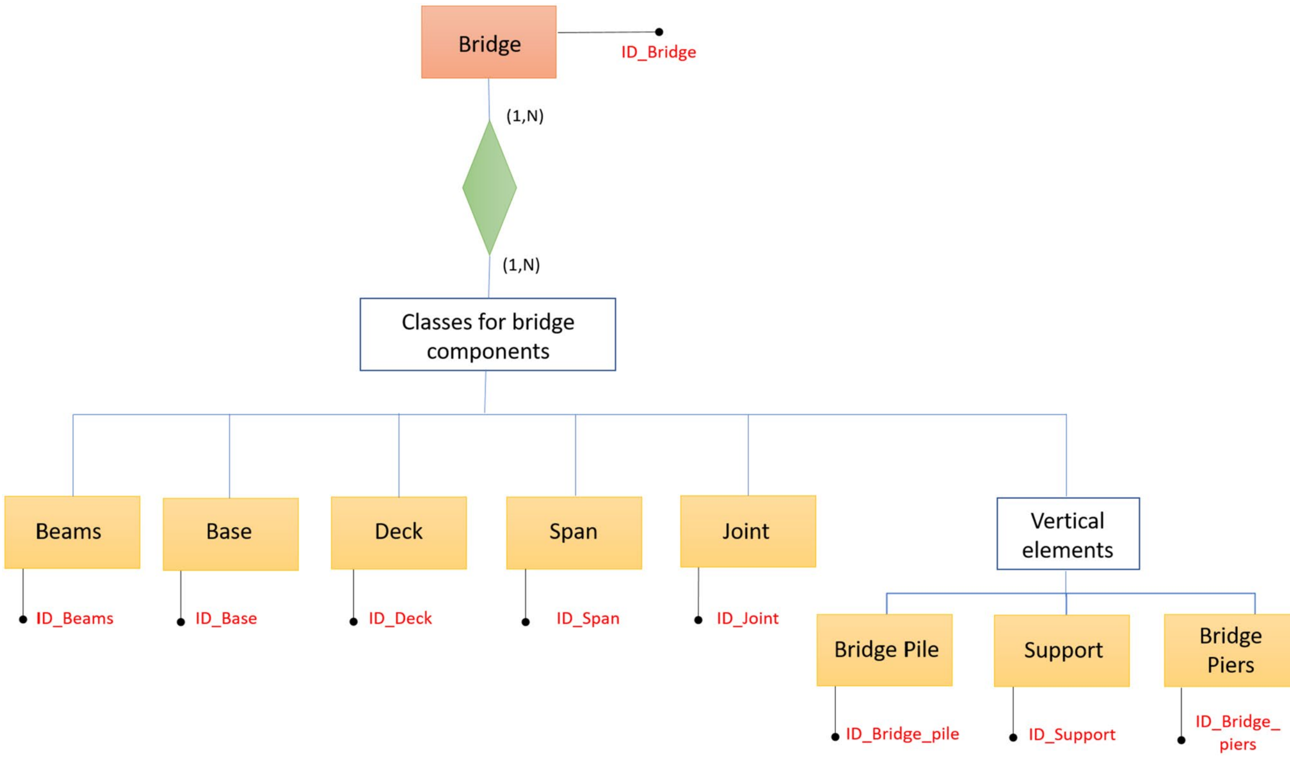


Fig. 4 Generalized Entity-Relationship (E-R) diagram related to the conceptual design of the data structure designed for our BMS, referred to a single bridge of the database. Entities are in rectangle boxes (red for the Bridge and yellow for its components), with each primary key (in red). *ID_Bridge* is the primary key of the bridge and the foreign key for the other entities. The green diamond identifies the relationship between the bridge and its classes of components. The one-to-many (1,N) relationship means that one entity has an event that occurs one time, while the other entity can have more than one repetition of the event

complex Excel files prepared by the Italian Ministry, As example, the Excel file with the census data includes the start of the first and last bridge joints, the start and length of each span, the number of lanes, deck width.

Following the 2020 Italian guidelines, we have developed a new software and defined its hardware architecture for the automatic data entry of the census data stored in the Excel files and their easy visualization. In particular, we have developed a GIS application based on QGIS to organize georeferenced data and make them available for advanced analysis and interpretation. GIS data about bridges are managed in a Relational Database Management Software (RDBMS) using PostgreSQL, which provides efficient methods for the interpretation and manipulation through queries in SQL (Structured Query Language), the standard language for accessing and manipulating databases. The data entry in the RDBMS has been completely automated thanks to the implementation of an Excel Visual Basic macro code that opens the Excel files containing the bridge information, and performs the parsing, validation and storage of the data into the database using a specific data structure.

The result is an innovative BMS that provides an effective, easy usage and fast-sharing platform that has a significant potential as a Decision Support Systems (DSS) to optimize the planning of bridge maintenance actions. The system stores all available data about bridges and viaducts, including the Excel census and defect files, photos and additional data in different formats, in a systematic and organized manner. In this way, full control over georeferenced bridges and viaducts is provided, allowing a more straightforward interpretation of the condition of a bridge.

The paper is structured as follows: Sect. 2 describes the materials used to conduct the work and the procedures that are undertaken; Sect. 3 presents the key results of our work using data about the bridges and viaducts present along the motorways in Sicily (Italy); Sect. 4 discusses the results in perspective of previous studies and suggests possible directions for future research; finally, Sect. 5 summarizes the major achievements, highlighting the overall purpose.

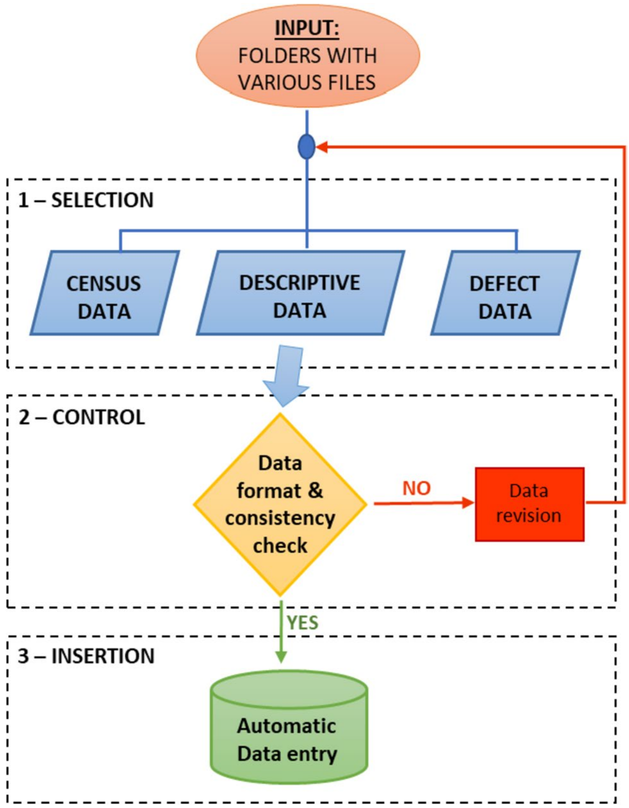


Fig. 5 Flowchart of the three main steps (e.g. selection, control and insertion) of the automatic procedure developed for the data entry in the spatial database

2 Materials and methods

We have developed a Bridge Management System (BMS) by using only free and open-source software technologies, with the aim of easily managing all the data related both to the census and to the state of health of bridges and viaducts.

The development of the BMS was preceded by a long phase of brainstorming with people who carried out the field surveys and collected the data relating to the bridges and their structural elements. In particular, we analysed all available data and outlined the requirements of the final product. This phase was followed by a scientific research (including the review of the BMSs already developed in other countries and the search for suitable software) for the correct design of the database and the automation of data entry.

In the following sections, we will describe the software and hardware architecture, the data structure implemented, the automatic procedure for the data entry, and the Desktop and Web GIS application.

2.1 The software and hardware architecture

A significant part of our work is the software and hardware architecture, which was designed and developed thanks to our experience in different research fields of the civil engineering, such as transportation, management of hydrological emergencies and navigation of autonomous robots (see, e.g. Mangiameli et al. 2013; Mangiameli and Mussumeci 2013a; 2013b; 2015). The software architecture is characterized by a Relational Database Management Software (RDBMS) that is centrally located, a GIS software and a Geoserver (Fig. 1), which allows the use of the data structure implemented by multiple application interfaces (WebGis, remote access to the GIS browser, etc.). In particular, the relational database was developed using the PostGIS spatial extension of PostgrSQL ver.9.5; QGIS ver.2.18 was used as GIS software; GeoServer vers. 2.20 was exploited as open-source server for sharing the geospatial data. The software architecture developed is synthetized in the block diagram shown in Fig. 1.

From the hardware point of view, we have chosen to dedicate a server for the RDBMS, while the Desktop and Web GIS and the possible future applications (GIS application on tablet, PC and smartphone, etc.) are in external devices. In this way, it is possible to exploit all the characteristics of the RDBMS, improving the speed of querying, updating and displaying the spatial data stored in the database.

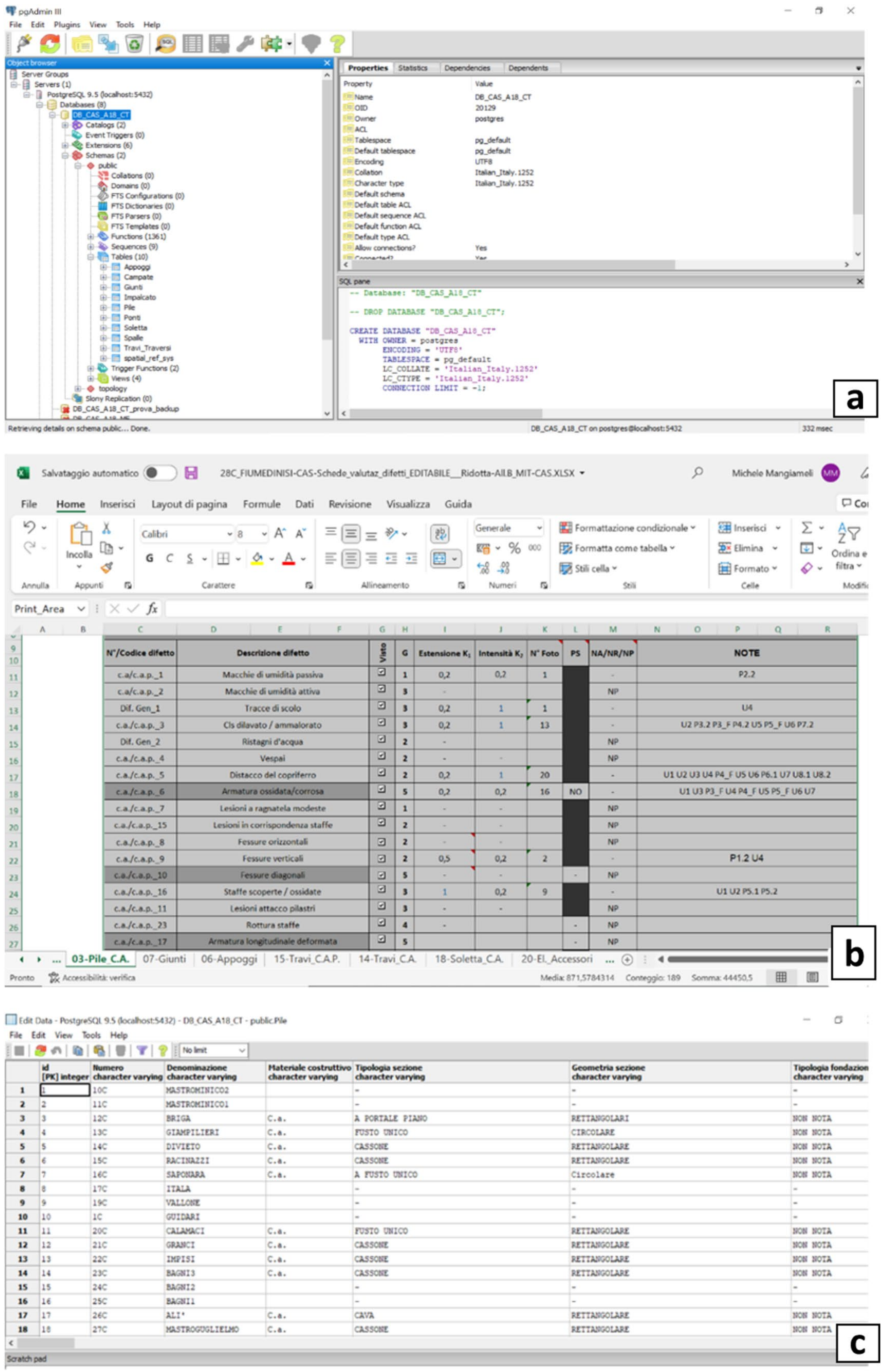
Figure 2 shows the deployment diagrams for the RDBMS server and the GIS client. A deployment diagram is a Unified Modeling Language (UML) diagram type that displays the architecture of a system, including nodes such as hardware or software environments, and the middleware connecting them. The nodes reflect all hardware devices and the software platform, while the relationships reveal the physical implementation of components.

2.2 The data structure

The design of the data structure implemented within the RDBMS has followed four main phases:

1. Identification of the entities involved in the bridge management;
2. Definition of the relationships between the entities previously identified;
3. Conceptual design of the data structure using the entity relationship diagram;
4. Physical implementation of the data structure within the spatial RDBMS.

According to the 2020 guidelines issued by the Italian Ministry of Infrastructure and Transport, the following nine


pgAdmin III
File Edit Plugins View Tools Help
Object browser
Server Groups
Servers (1)
PostgreSQL 9.5 (localhost:5432)
Databases (8)
DB_CAS_A18_CT
Properties Statistics Dependencies Dependents
SQL pane
-- Database: "DB_CAS_A18_CT"
-- DROP DATABASE "DB_CAS_A18_CT";
CREATE DATABASE "DB_CAS_A18_CT"
WITH OWNER = postgres
ENCODING = 'UTF8'
TABLESPACE = pg_default
LC_COLLATE = 'Italian_Italy.1252'
LC_CTYPE = 'Italian_Italy.1252'
CONNECTION LIMIT = -1;
a
Salvataggio automatico
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Michele Mangiameli
File Home Inserisci Layout di pagina Formule Dati Revisione Visualizza Guida
N°/Codice difetto
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c.a/c.a.p._2 Macchie di umidità attiva
Dif. Gen_1 Tracce di scolo
c.a./c.a.p._3 Cls dilavato / ammalorato
Dif. Gen_2 Ristagni d'acqua
c.a./c.a.p._4 Vespai
c.a./c.a.p._5 Distacco del copriferro
c.a./c.a.p._6 Armatura ossidata/corrosa
c.a./c.a.p._7 Lesioni a ragnatela modeste
c.a./c.a.p._15 Lesioni in corrispondenza staffe
c.a./c.a.p._8 Fessure orizzontali
c.a./c.a.p._9 Fessure verticali
c.a./c.a.p._10 Fessure diagonali
c.a./c.a.p._16 Staffe scoperte / ossidate
c.a./c.a.p._11 Lesioni attacco pilastri
c.a./c.a.p._23 Rottura staffe
c.a./c.a.p._17 Armatura longitudinale deformata
03-Pile_C.A. 07-Giunti 06-Appoggi 15-Travi_C.A.P. 14-Travi_C.A. 18-Soletta_C.A. 20-El_Accessori
b
Edit Data - PostgreSQL 9.5 (localhost:5432) - DB_CAS_A18_CT - public.Pile
id [PK] integer
Numero character varying
Denominazione character varying
Materiale costruttivo character varying
Tipologia sezione character varying
Geometria sezione character varying
Tipologia fondazion character varying
MASTROMINICO2
MASTROMINICO1
BRIGA
GIAMPILIERI
DIVIETO
RACINAZZI
SAPONARA
ITALA
VALLONE
GUIDARI
CALAMACI
GRANCI
IMPISI
BAGNI3
BAGNI2
BAGNI1
ALI'
MASTROGUGLIELMO
A PORTALE PIANO
FUSTO UNICO
CASSONE
CAVA
RETTANGOLARE
CIRCOLARE
NON NOTA
Scratch pad
c

◂**Fig. 6** **a** View of the spatial database implemented in the PostgreSQL software: the Browser tree control (on the left), the properties of the spatial database (top right) and the Query Tool (bottom right) to write and execute SQL commands; **b** The Excel defect sheet of the bridge pile structured and compiled according to the 2020 ministerial guides; **c** The corresponding pile table within the RDBMS, containing the information extracted from the Excel sheet

entities have been identified: *Bridge, Support*, *Span*, *Joint*, *Deck*, *Bridge Pile*, *Base*, *Bridge Piers* and *Beams* (Fig. 3). These entities constitute the subject of the census performed during the field surveys.

Following the 2020 ministerial guidelines in which the Excel files include aggregated data by entity class, we have developed the Entity-Relationship (E-R) of Fig. 4. An E-R diagram is a type of flowchart commonly used to design relational databases in the field of the software engineering, which uses a defined set of symbols such as rectangles (for entities), diamonds and connecting lines to depict the interconnectedness of entities, relationships and their attributes. In our system, the relationships were set up within the database by choosing a numeric attribute as the primary key, representing a unique identifier for the bridge table. For the other entities, the primary key of the bridge was set as foreign key and an *ID* attribute as the primary key (Fig. 4).

Using the data structure designed, we have physically implemented the spatial database within the PostgreSQL DBMS. In particular, we have developed two databases to manage the data in the two directions of the road travel in an independent way. Inside each database, we have created nine tables corresponding to the nine entities relating to the bridge and all structural elements. The cardinality constraints and the relationships between the different tables respect the ones indicated in the E-R diagram of Fig. 4.

2.3 The data entry

The census and defect bridge data are acquired during field surveys and stored in different Excel files that respect the ministerial directives. In particular, data are stored in three different Excel files, two related to the census of the bridge and its elements, and one related to the collection of defects found in each element of the bridge. Therefore, the data collected in these three independent files describe both the topographical aspect of each single bridge and its state of decay.

The disaggregated form in which all data are stored prevents a quick consultation and the implementation in a relational data structure, which is indispensable for the retrieval, manipulation and control of information. To collect and organize data in a logical way, we implemented an automatic procedure that selects the most relevant information from the Excel files and performs the insertion in the spatial database following our data structure.

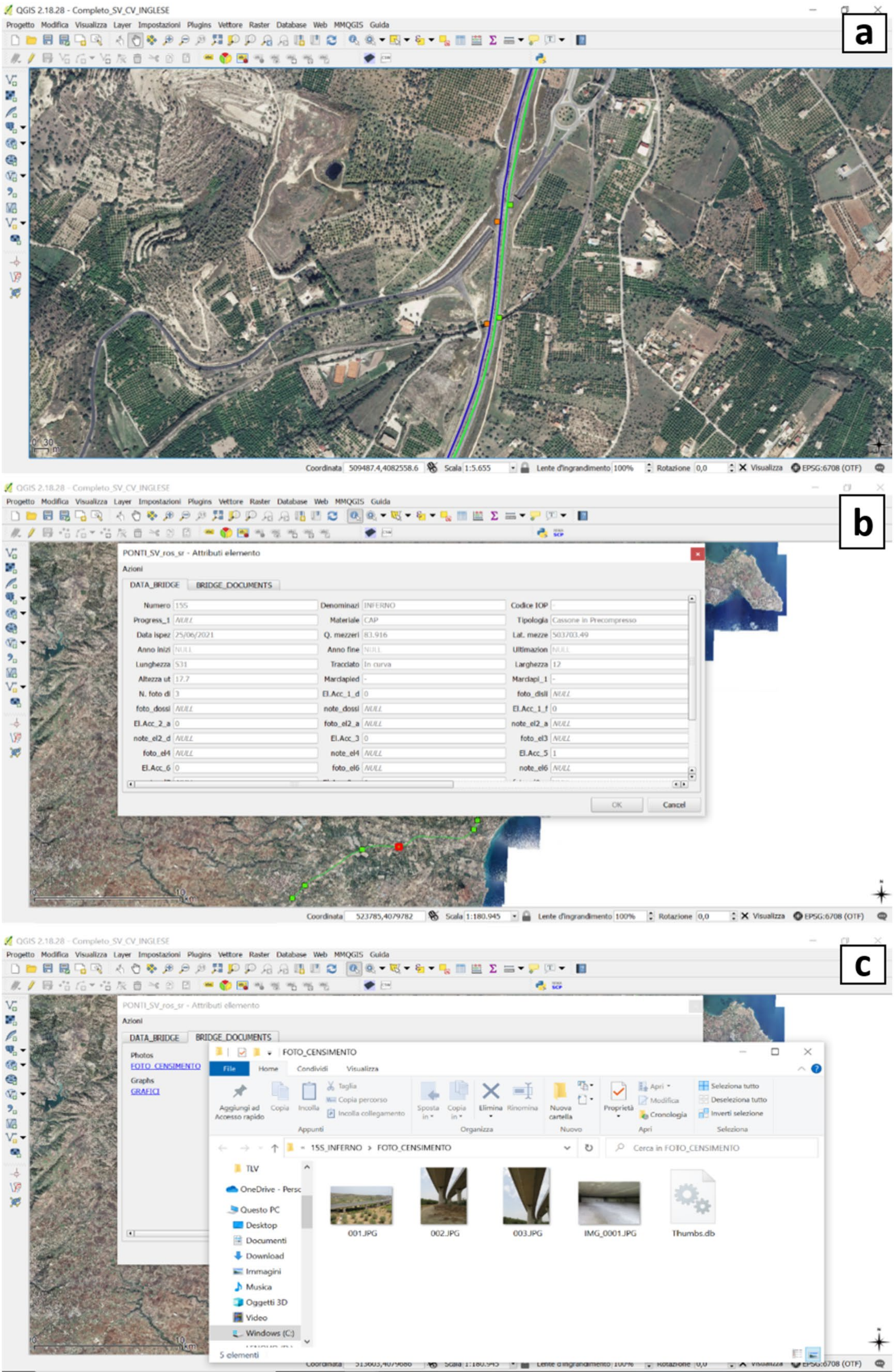
The main phases of the automatic procedure for the data entry (Fig. 5) are described in the following:

1. *Selection.* All data of each bridge are included in different directories and files. Therefore, the first step of the procedure has the main objective to scan all files to localize the three different Excel files including the census data, the descriptive data and the defects concerning the bridge and its elements.
2. *Control.* After opening the three Excel files, an automatic check is performed to verify if the information that must be selected for the spatial database have been correctly stored. In particular, the data type is checked in order to be consistent with the structure set up in the database and to avoid null or incorrect information. For example, it is verified the absence of mandatory data, such as the geographic coordinates of the bridge, or of cells including inadmissible characters. If any error is found, the software automatically produce a report including the filename and the exact field where the missing or incorrectly entered information is contained, in order to be immediately identified and fixed. Therefore, this step of the procedure guarantees the integrity of the database.
3. *Insertion.* All data already checked are automatically selected from the three Excel files and inserted in the spatial database, respecting the data structure of the RDBMS. A preview of the final structure that will be loaded into the database is automatically generated to give the user immediate feedback.

The procedure for data entry is extremely flexible, with the spatial database that can be populated also by an operator during the field inspection of the bridge or by new electronic technologies for the continuous monitoring of large infrastructures (see, e.g. Zhang et al. 2016; Lee et al. 2018). These new technologies include sensors directly installed on the bridge, Unmanned Aircraft Systems and Vehicles (UASs and UAVs) or Internet of Things (see, e.g. Achuthan et al. 2021; Bono et al. 2022; Scianna and Gaglio 2022). Once the data entry has been completed, all data are accessible through the QGIS software by specifying the physical address of the database along with the login credentials, or by the GIS application made available on the web.

2.4 The desktop and web GIS application

The Desktop GIS application has been developed using QGIS, which is a powerful, cross-platform and user friendly Open Source Geographic Information System for the analysis of geospatial data and the production of maps. The application includes georeferenced cartographic raster data, linear vector themes related to road infrastructures (comprising the bridges) and a further punctual vector theme related to


a
QGIS 2.18.28 - Completo_SV_CV_INGLESE
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b
PONTI_SV_ros_sr - Attributi elemento
Azioni
DATA_BRIDGE
BRIDGE_DOCUMENTS
Numero 155
Denominazi INFERNO
Materiale CAP
Tipologia Cassone in Precompresso
Data ispez 25/06/2021
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Lunghezza 531
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155_INFERNO › FOTO_CENSIMENTO
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Immagini
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Windows (C:)
001.JPG
002.JPG
003.JPG
IMG_0001.JPG
Thumbs.db
5 elementi

◂**Fig. 7** **a** Screenshot of the GIS application developed in QGIS. The cartographic basis is an orthophoto updated to 2013. The green and blue linear vector themes are the two driving lanes of a road infrastructure, while the punctual vector themes highlight different bridges and viaducts along the road; **b** Bridge data stored in the database and visualized inside the GIS application as a table of attributes; **c** Dedicated GIS interface to visualize the documents and multimedia files associated to the queried bridge

bridges and viaducts obtained from the automatic procedure described in Sect. 2.3. Particular attention has been paid to the road infrastructures containing the bridges, digitized in the GIS environment as linear vector themes, over which the bridges and viaducts of interest have been superimposed and displayed as punctual vector themes.

The Desktop GIS application has been published as a web map using OpenLayers and so it is also accessible by Internet. For the exportation, we have used the QGIS2Web plugin available in QGIS.

3 Results

The BMS has been developed and tested using the data available for the motorways present in Sicily (Italy). Data were requested by CAS, the Consortium for the Sicilian Highways, which is a public economic body of the Sicilian Region, concessionaire for the management of the A20 Messina-Palermo, A18 Messina-Catania and for the Syracuse-Gela. The bridges and viaducts present in these motorways and used for the purposes of our work have been surveyed from 2020 to 2022.

Each Excel file with the bridge defects includes a sheet for each structural element, according to the 2020 Italian ministerial guides. The spatial database implemented in the PostgreSQL software, along with an example of the defect sheet for the pile of a bridge along the A18 Messina-Catania and the relative table within the RDBMS, are shown in Fig. 6.

The GIS application allows viewing each bridge on a georeferenced cartography and querying it in order to visualize all the related data stored in the database through a table (Fig. 7a, b). This includes also information about the road lines (e.g. number of lanes, width and material). Moreover, the user can access and download all the multimedia information relating to the queried bridge, including photos, technical sheets, CAD and the Excel defect sheet through a customized graphic interface (Fig. 7c).

The GIS also allows visualizing all information related to the different structural elements of the bridge, such as the joints, deck, piles. An example of the table including the joints of all bridges is shown in Fig. 8. Finally, the GIS application provides a query builder to perform advanced queries and filter the tables included in the database. For example, it is possible to search for all bridges characterized

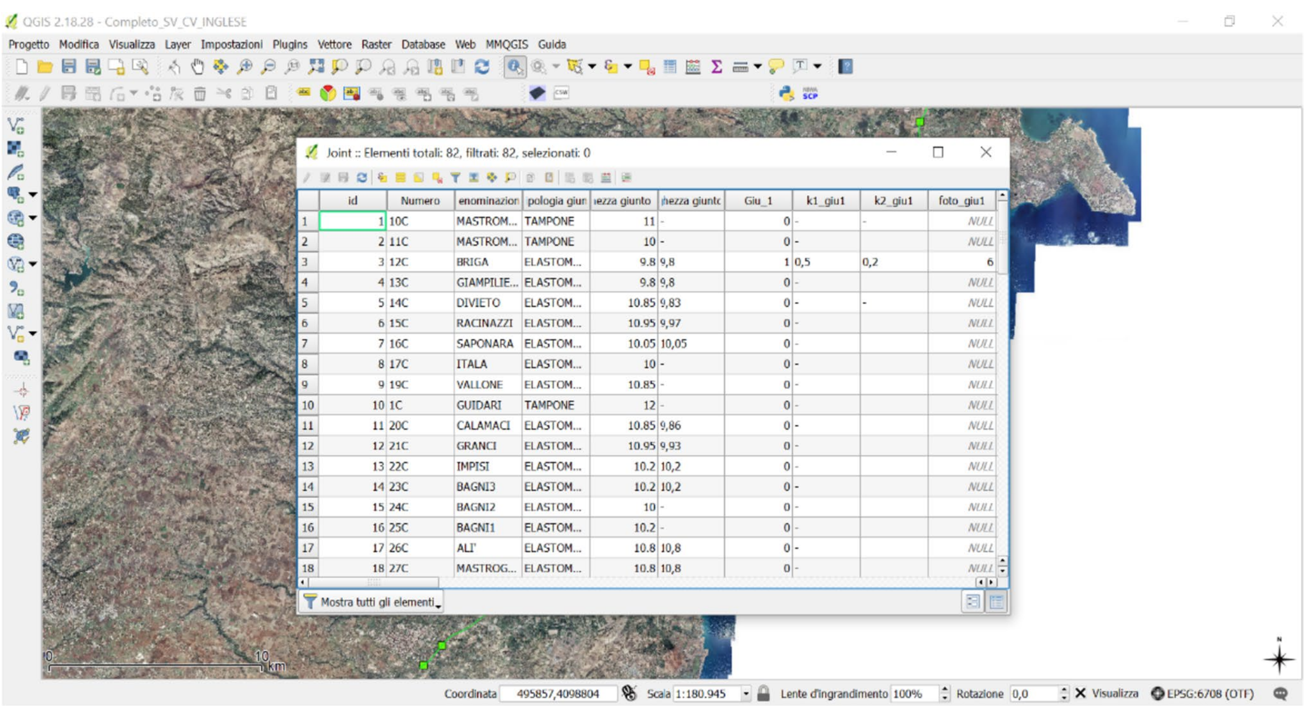

Fig. 8 Example of the table of joints. The table includes the different features of the joints (typology, length, height, etc.) for all bridges

by a prestressed caisson structure that fall into a geomorphological area of steep slope (Fig. 9).

4 Discussion

Bridges are a critical component of road infrastructure, playing an important role in the transportation system by supporting economic and social development. In Italy, there are about 120,000 road bridges, which give severe pressure to their maintenance. However, few maintenance strategies have been implemented, due both to the high number of stakeholders involved and to the scarce investments, and this has caused local and global failures of different Italian bridges of varying typologies, dimensions and relevance (Scattarreggia et al. 2022).

The definition of effective strategies for the evaluation of priorities in terms of assessment and need for maintenance works represents a key issue for risk management and the socio-economic development of Italy. Periodic maintenance interventions on bridges and viaducts guarantee their efficient functioning during the entire life cycle, possibly avoiding invasive restoration interventions that have a strong impact on traffic management and safety.

With our work, we have proposed a new system that offers new opportunities and challenges to decision makers to define these strategies. The main novelty of the BMS developed is undoubtedly the data structure: thanks to the hardware and software architecture proposed, which is database-centric and flexible (Fig. 10), we have implemented a specialized format for storing, organizing and processing data so that they can be easily retrieved and efficiently utilized by any stakeholder. This data structure reflects the real topological dependencies of the various entities, ensuring data integrity and data sharing, and avoiding data redundancies.

In the BMSs analysed (e.g. Ibrahim and Yunus 2019; Wattan and Al-Bakri 2019; Badruzzaman and Hendriana 2021), little importance has been given to the engineering process in terms of conceptual, logical and physical design. In fact, the design of the data is fundamental for the optimal operation of the GIS application, especially if the database is developed on a RDBMS external to the GIS software.

In Italy, a national BMS is currently missing. In addition, until a few years ago, no national guidelines were available for the census and control of the defectiveness of the elements of bridges and viaducts, as well as their digital storage. After the 2020 guidelines approved by the Ministry of Infrastructure, three kinds of Excel files have been made available (one for the census, one descriptive and one for the defects), which still have a disaggregated structure, preventing an orderly consultation and to be used in any DSS. With our system, we have proposed the first ad-hoc automatic data entry for the census and defect Excel sheets into a spatial data structure for a dedicated GIS application, which offers a front-end user interface (also available on web) and a very useful cognitive aid for the processing and evaluation of the different and heterogeneous information contained in the database. Indeed, the storage of additional data in different formats, such as technical sheets and photos, further improves efficiency of the system, facilitating both relative and absolute assessments of the condition of the bridges and their components. All these features make the system a valid DSS to assist bridge managers in cost-effectively addressing the bridge needs (e.g. maintenance works).

We decided to use GIS for our BMS because it is a specialized, intuitive and effective DSS designed specifically to analyse spatial data and take decisions involving spatial data (Gennaro et al. 2019a; 2019b; Mangiameli et al. 2019a; 2019b, 2021). GIS provide the user with different tools for the management and visualization of high volume of spatial information stored as vector or raster, allowing for problem solutions, the evaluation of solution alternatives and the assessment of their trade-offs (Jankowski 2008). Nevertheless, GIS is still mainly used to digitize road networks aimed at assessing the network resilience (e.g. Twumasi-Boakye and Sobanjo 2018), at evaluating the potential impact due bridge collapses or natural disasters (e.g. Aydin et al. 2012; Kappos et al. 2014), at determining optimal set of work zones on large infrastructure networks (e.g. Lethanh et al. 2018), but especially at traffic tracking and finding shortest paths between points of interest (e.g. Hojune et al. 2019; Debnath 2022).

In summary, our BMS has two main core components:

- A relational spatial database at the centre of the software/hardware architecture, in which all the information about the bridge and its elements are stored through an automatic data entry.
- A free and open source GIS application that facilitates systematic searches for relationships and patterns among bridges, supporting the planning of maintenance strategies.

The development of the system began in 2021, but it is still undergoing optimization and advancement also in relation to the availability of the funds necessary to activate gradually the inspection of about 500 bridges, including viaducts and minor bridges at the interference with secondary roads and waterways. Currently the system does not allow archiving intervention history and handling information from inspections with respect to safety and risk. Other limitations include the lack of cost information (such as traffic delay, accident and environment costs) and predictive models to assess deterioration or improvement due to future

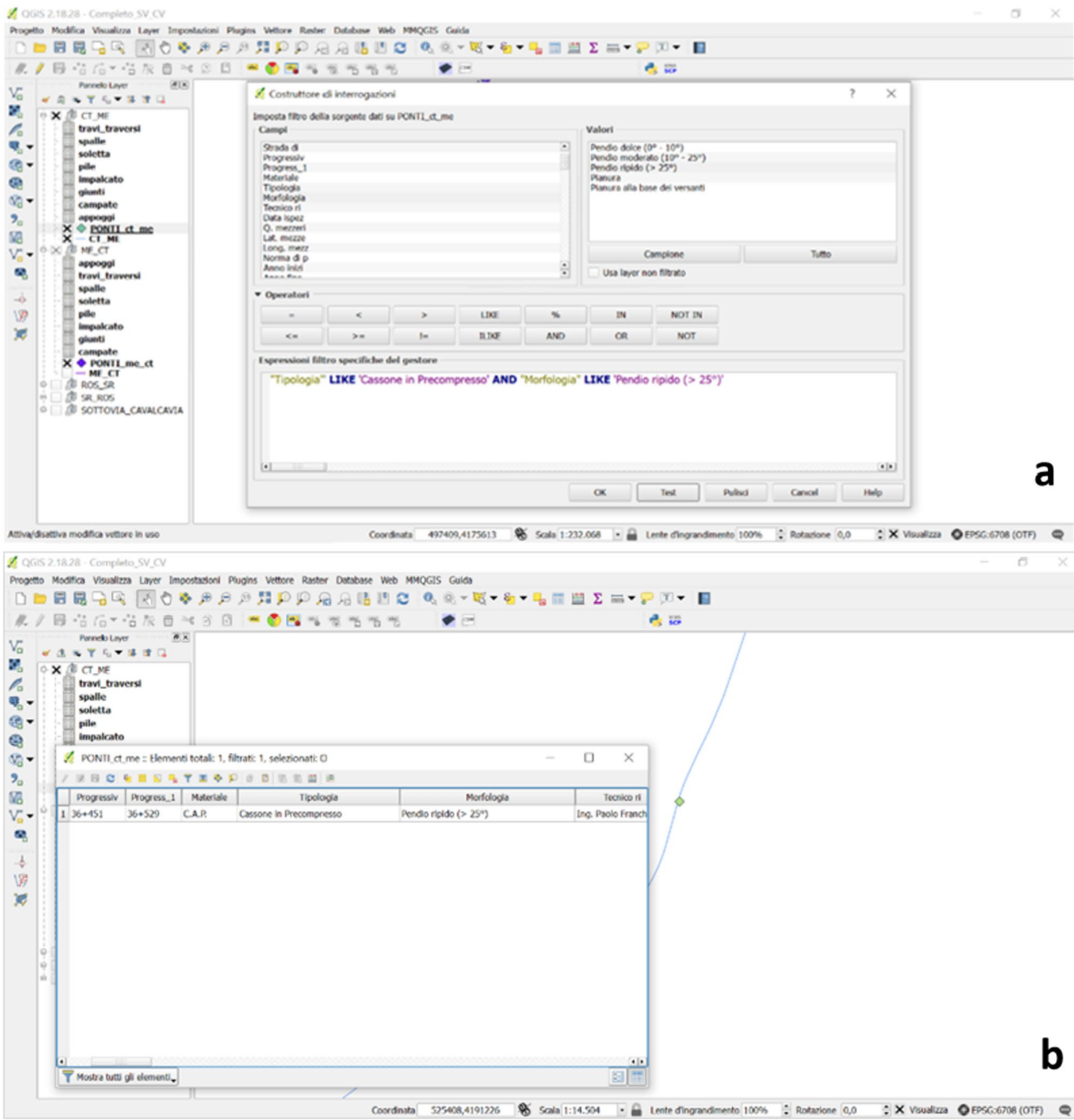

Fig. 9 **a** Example of filtered search (bridges that have a prestressed caisson structure and a slope greater than 25°) using the query builder available inside the GIS application. **b** Table of results that appears after query submission

interventions of bridges. Moreover, the automatic data entry works only with the Excel files established by the 2020 Italian ministerial guidelines. This is at the same time the biggest advantage and disadvantage, in the sense that it allows the real-time reading of all the census and defect sheets, but changes to the structure of the Excel files require modifications to the source code. However, the flexible hardware and software architecture of the system allows for quick reconfiguration and upgrades as applications change, making it

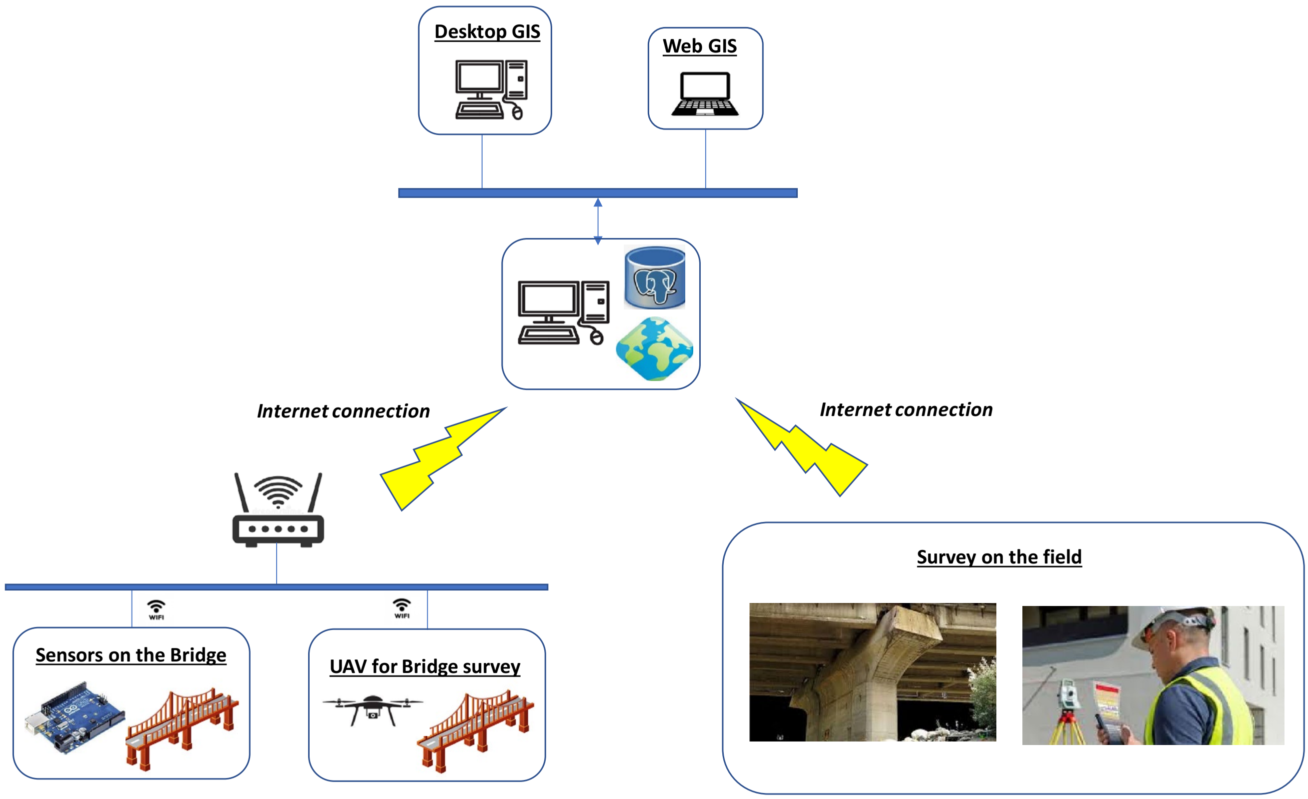

Fig. 10 Operation scheme of the BMS presented in this work

easily extendable with new functionalities and/or features, and to other regions or countries.

Future works will involve the integration of the geoserver with innovative technologies, such as Unmanned Aircraft Systems and Vehicles (UASs and UAVs) or Internet of Things (Achuthan et al. 2021; Bono et al. 2022; Scianna and Gaglio 2022) to populate or update the database with the data acquired in the field in real time and make them immediately available to be processed and used by the GIS application. This will give the opportunity to manage all the essential phases of the life cycle of a bridge, from the field survey on the state of the structural elements to the real-time use of the GIS application. We will also explore the possibility of using other emerging technologies, such as the Business Intelligence and Analytics, to improve Decision-Making performance (Peters et al. 2016; Yoshikuni et al. 2023). We will also implement new tools, such as the network analyst, to find alternate optimal routes when a particular bridge is under maintenance. Future work will include the extension of the system to implement the “Level Two” of attention defined by the 2020 Italian ministerial guidelines (Santarsiero et al. 2021), i.e. to determine the risk class to which each bridge or viaduct belongs. Finally, we will improve the relational data structure by solving the generalizations of the E-R diagram shown in Fig. 4, including new bridge components, such as the foundation and bearing elements. The data structure would thus be optimized both for data entry and for the analysis of defects on the elements. However, this change is currently not feasible without structural changes to the Excel sheets prepared by the Ministry.

5 Conclusions

We have presented a new bridge management system based on a spatial database and GIS technologies for the treatment of information relating to bridges and viaducts. The data collected concern both the census of bridges and viaducts, and their status of health. These data are stored in the spatial database that represents the heart of the system and form the basis of all decisions considered by the BMS. Access is provided through a dedicated graphic interface implemented in QGIS that includes also dynamic links to all multimedia data, such as images, technical data sheets, CAD, associated to each bridge. In this way, the various individuals and teams involved in the decision-making process can easily share data and information with the aim of enhancing collaboration and cutting costs.

The system developed can be used to evaluate the deformations and damages of bridges caused by both natural factors (e.g. landslides and earthquakes) and human errors in the design, construction and operation procedures. Moreover, it can be used to assess the vulnerability and resilience of bridges and transport networks in risk analysis studies (Zanini et al. 2017; Argyroudis et al. 2020), helping ease traffic and safety issues.

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Data availability Data subject to third party restrictions.

Declarations

Conflict of interest We declare no conflict of interest.

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