Failure analysis of reinforced concrete elevated storage tanks

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Abstract
Assessing the condition of existing structures, with a particular focus on analysing the degradation level, is a complex issue for those responsible for maintenance and monitoring. Elevated storage tanks (water towers) are particularly prone to suffering obsolescence and degradation. As many of these structures are no longer in use and in a poor state of conservation, researchers and local administrators need new tools to achieve a complete overview of the tank condition on a regional scale with limited resources.
This paper presents a large-scale structural degradation analysis on the specific structural typology of storage tanks. Firstly, the tanks performances and degradation level are analysed by using a multicriteria approach useful to include both qualitative and quantitative data in the analysis. Secondly, 32 case studies in Valencia (Spain) are investigated to demonstrate the method's potential. Thirdly, the results of the degradation analysis were used to identify the most frequent damage, the related causes and the structures in the worst conditions. Finally, the best maintenance and intervention strategies to extend the tanks' remaining life and protect them from further damage are proposed.
Keywords: Damage assessment; Failure analysis; Forensic engineering; Elevated Storage Tanks.

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1. Introduction

Exposure to aggressive environmental agents, aging and extreme weather events can seriously harm Reinforced Concrete (R.C.) structures and affect their performance [1]. In the last decades, the need for a structural diagnostic system for existing structures became a huge widespread issue, as shown by some recent catastrophic events (for instance, the Morandi bridge collapse). Consequently, the management and damage analysis of existing structures is a complex issue for those responsible for the construction operability and user safety [2,3,4]. Degradation analysis and condition assessment can be helpful in planning maintenance and management on existing structures to ensure their safety and proper operability [5,6]. In the field of civil engineering, there are several applications that use synthetic indicators to quantify degradation, known as *condition ratings* [7]. Sometimes degradation analysis of existing structures is performed via pre-set compilation forms to identify every single component and types of damage. Some of these assessment methods are now statutorily prescribed, and the analysis procedure is very similar in various countries, even if there are some differences in the final goal [8]. The condition of a structure is assessed by systematically breaking down the problem into its basic components. The damage detected is classified according to predefined criteria by means of visual inspections by qualified surveyors. The severity level of the damage in the different elements is registered in a check-list and a formula generates a numerical score to quantify the overall condition of the structure. Other authors effectively apply degradation analysis on a regional scale in order to perform extensive structural diagnostics and monitoring [9,10]. These rapid approaches are typically supported by Multi-Criteria Decision-Making (MCDM) [11,12] to quantify the effect associated with each criticality and its impact on the overall structure [3,13,14].
In existing R.C. structures, elevated storage tanks are a particularly vulnerable typology since many of them are in a critical condition throughout Europe. These structures were built in the past century and have almost been completely replaced by modern water supply systems. In the last decades these structures have been neglected and disused. In addition, their poor state of conservation gets worse over the years due to lack of maintenance. In this context it is necessary develop novel approaches to determine the condition of this particular type of structure on a regional scale in order to provide a ranking of the tanks to give intervention

priority to the worst affected and avoid accidents [15]. Some authors have adopted the *Failure Modes their Effects and Criticality Analysis* (FMECA) method to identify potential damage, the causes and the failure effects on water towers [16,17,18]. It is particularly important include both the technicians' personal experience and a large amount of qualitative and quantitative data to define the criticality index. The FMECA approach is also complex to apply on a large scale due to the vast amount of data required to perform the analysis, as complex in-depth surveys are required to obtain the information and calculate the condition ratings.

The multicriteria approach named Alert-D [19,20] was recently developed for large-scale analysis of R.C. structures and works with a fast-on-site survey supported by suitable survey tabs and spreadsheets for to compute the condition ratings [21]. This multicriteria-based methodology can includes both qualitative and quantitative data in the analysis and it is customizable with some improvements to be effective in the analysis of the storage tank typology.

This paper proposes an improved version of the approach proposed by Sangiorgio et al. [19,20]; the Alert-D approach has been re-worked and adapted for the regional scale analysis of water towers. First, the classical approach is re-defined in the following phases: i) on-desk study, ii) on-site survey, iii) diagnostic approach, iv) ranking and priorities. The procedure is then applied to water towers in the Valencia Region to identify the most frequent serious damage, the related causes and the structures in the worst condition.

The novelty of this paper is threefold; for the first time a degradation analysis method is developed for these structures on a regional scale; secondly, the study analysed 32 water towers in 27 different towns in the Valencia region. Finally, the outcome of the large-scale analysis provided information on the most common damage to these structures to define intervention priority in the region.

The paper is organized as follows: Section 2 describes all the phases involved in the improved methodology. Section 3 describes 32 case studies of degradation analysis, Section 4 gives the results of the analyses and the potentiality priority ranking obtained from the condition ratings and the main conclusions drawn from this research project are given in Section 5.

2. Large-scale water tower degradation analysis

This section explains the re-working of the classical Alert-D method to obtain an improved approach suitable for the large-scale analysis of water towers, named Alert-Degradation Tank (Alert-DT).

It is worth noting that this work is focused on storage tanks associated to a inverted pendulum type structure. In addition, the investigated tanks are characterized by a similar structural scheme and a frame structure without braces. To this aim, an approximate algorithm can be applied within a homogeneous set of structures without affecting the relative value of vulnerability depending from the peculiar structural typology.

This novel approach is based on four main phases: a) *Data Collection*; b) *On-site Survey*; c) *Degradation Analysis; d) Intervention priority*. In the first phase, *Data Collection* aims at acquiring the main information on the water towers regarding: age of the structure, existing original project, location and any other useful information, such as the code in force when the structure was built. The second phase, the *On-site Survey* consists of a visual inspection. During this phase, a rapid survey is carried out to obtain geometrical data through direct measurements. In the third phase, the *Degradation Analysis* is conducted by adapting the existing *diagnostic tab, condition ratings* and multicriteria approach proposed by Sangiorgio et al. [19,20] to study the components of the storage tanks. In this phase the structure is broken down into its basic components and damage is evaluated by defining a set of criteria and alternatives. For each component the *condition ratings* are computed. The three *condition ratings* assume real values in the interval between (0 – 10) and are defined as follows: i) the *criticality condition rating* (*Cr*) is a numerical value to qualify the damage in a single component; ii) the *component condition rating* (*CCr*) is a numerical value to quantify the critical condition of a class of components (for instance beams or columns); and iii) the *structure condition rating* (*SCr*) is a numerical value that quantifies global damage in the structure. These three condition ratings synergistically provide a complete overview of the storage tank's condition.

Finally, the *matrix of damages* is derived by following the standard procedure and the *intervention priority* can be deduced from the condition ratings. Figure 1 shows the flow chart of the evaluation phases.

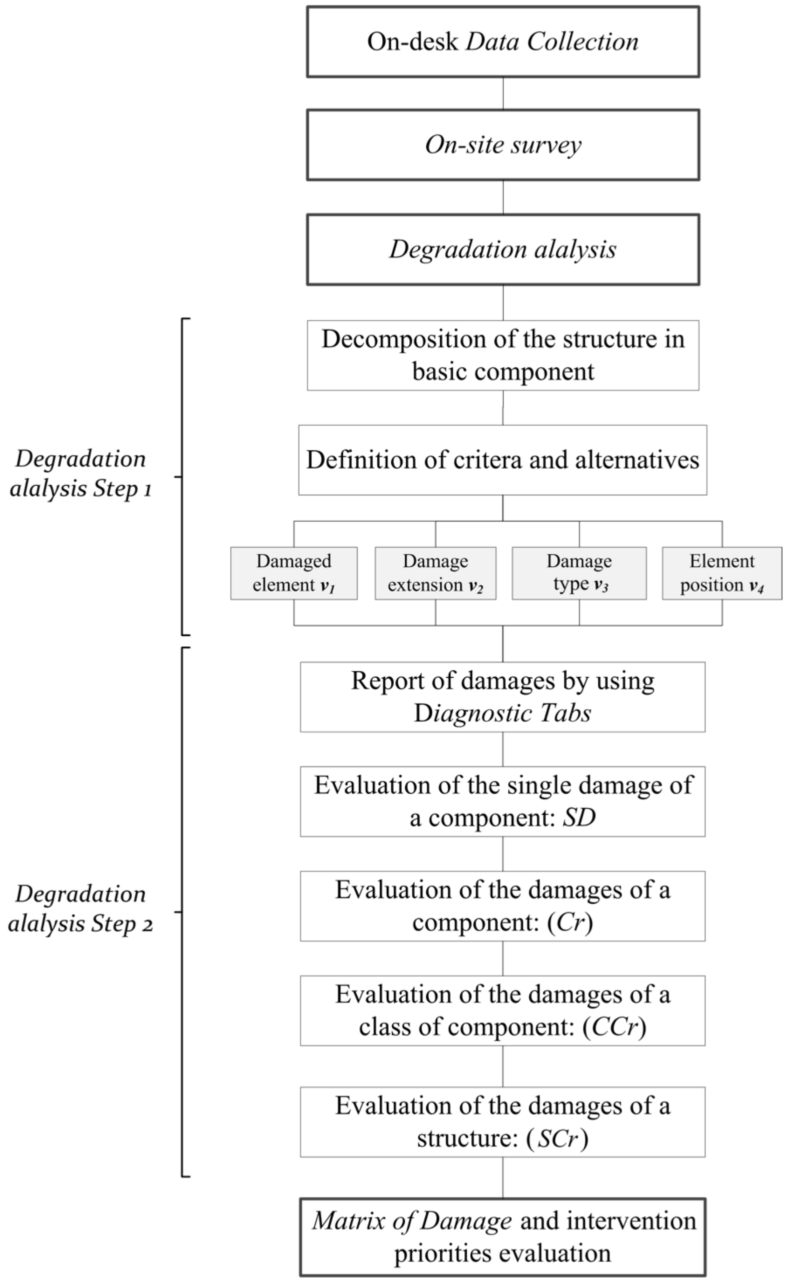


Fig. 1 Flow chart of the Alert-DT damage evaluation method.

2.1 On-desk preliminary study

Before applying an on-site survey, a preliminary on-desk study can be conducted to obtain the tanks' existing documentation and historical data. In this phase the existing information and documentation are collected in order to study the structural design, any modifications after construction and the seismic history of the tank. In large-scale analyses this is a fundamental phase in order to identify all the tanks in the region and set up the subsequent on-site investigation phase.

2.2 On-site survey

Once historical data have been acquired, the on-site survey can be performed with the support of the *Survey Tabs*. The classical *Survey Tab* proposed by Sangiorgio et al. [20] has been re-worked to acquire specific information. This tab helps to acquire technical registry data and store information regarding the geometric, morphological, and constructional features of the tank, including design prescriptions and reference building codes. The goal of this phase is to retrieve, process, and easily store all the existing information and make it available for the subsequent analyses. The *Survey Tab* (Figure 2) includes descriptive information used to geographically locate each structure, identify the urban context and characterize functional and service performance. This sheet is divided into six subsections: 1) *General Data*; 2) *Typological Data*; 3) *Geometric and Characteristic Data*; 4) *Foundations and soil type;* 5) *Seismic Data* and 6) *Environmental Data*.

General data includes registry information (country, region, etc.) and additional information regarding the status of the tank and whether or not it is still in use. This information can be important in terms of the degradation analysis, since the progress of damage and its consequences can be directly connected to the presence of water in the tank.

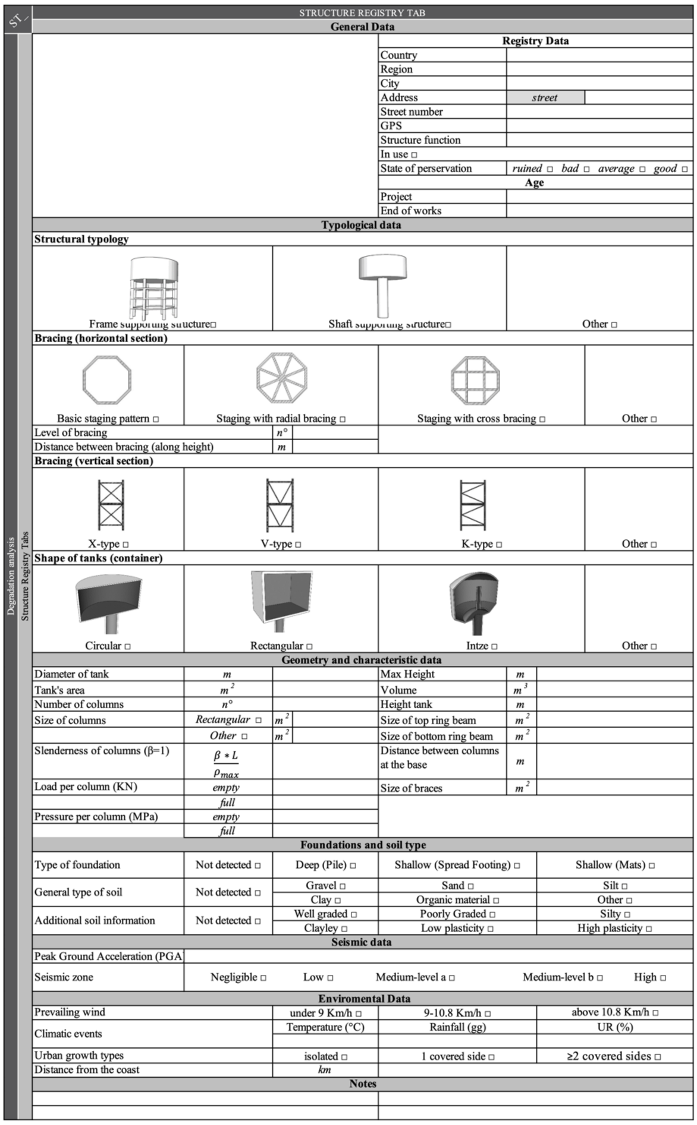
Typological data classify the typology of the storage tank. It includes the typology of the structure (frame or shaft supported), shape of horizontal and vertical bracing, and shape of the container.

Geometric and characteristic data include information on the number and dimensions of the tank's components (columns, beams, etc.) and relative loads.

Foundations and soil type include information regarding the construction typology of foundations and useful typological and qualitative data of the soil. This information can be important, during the identification of the intervention priority, to understand if a specific damage combination can be attributed to a foundation problem.

Seismic data includes information on the *Peak Ground Acceleration (PGA)* and *Seismic zone*;

Environmental data examine the external environment of structures, which can influence tank degradation. The marine atmosphere is one of the most aggressive environments for R.C. structures and has a considerable effect on service life. Exposure to this environment is considered by the parameters in Sangiorgio et al. [10].



ST-

Degradation analysis

Structure Registry Tabs

STRUCTURE REGISTRY TAB

General Data

Registry Data	
Country	
Region	
City	
Address	*street*
Street number	
GPS	
Structure function	
In use □	
State of perservation	*ruined* □ *bad* □ *average* □ *good* □
Age	
Project	
End of works	

Typological data

Structural typology

Frame supporting structure□ | Shaft supporting structure□ | Other □

Bracing (horizontal section)

Basic staging pattern □ | Staging with radial bracing □ | Staging with cross bracing □ | Other □

Level of bracing	*n°*	
Distance between bracing (along height)	*m*	

Bracing (vertical section)

X-type □ | V-type □ | K-type □ | Other □

Shape of tanks (container)

Circular □ | Rectangular □ | Intze □ | Other □

Geometry and characteristic data

Diameter of tank	*m*		Max Height	*m*	
Tank's area	m^2		Volume	m^3	
Number of columns	*n°*		Height tank	*m*	
Size of columns	*Rectangular* □ m^2		Size of top ring beam	m^2	
	Other □ m^2		Size of bottom ring beam	m^2	
Slenderness of columns (β=1)	$\frac{\beta * L}{\rho_{max}}$		Distance between columns at the base	*m*	
Load per column (KN)	*empty*		Size of braces	m^2	
	full				
Pressure per column (MPa)	*empty*				
	full				

Foundations and soil type

Type of foundation	Not detected □	Deep (Pile) □	Shallow (Spread Footing) □	Shallow (Mats) □
General type of soil	Not detected □	Gravel □	Sand □	Silt □
		Clay □	Organic material □	Other □
Additional soil information	Not detected □	Well graded □	Poorly Graded □	Silty □
		Clayley □	Low plasticity □	High plasticity □

Seismic data

Peak Ground Acceleration (PGA	
Seismic zone	Negligible □ Low □ Medium-level a □ Medium-level b □ High □

Enviromental Data

Prevailing wind	under 9 Km/h □	9-10.8 Km/h □	above 10.8 Km/h □
Climatic events	Temperature (°C)	Rainfall (gg)	UR (%)
Urban growth types	isolated □	1 covered side □	≥2 covered sides □
Distance from the coast	*km*		

Notes

Fig. 2 *Registry tab*: empty form.

2.3 Diagnostic approach and condition ratings

In this section the *condition ratings* are re-worked to be suitable for storage tank diagnostics by following the standard approach.

The first step is the decomposition of the structure into a set $F=\{f=1,\dots,N_F\}$ of component classes (shear column, beam, braced frame, water tank etc.) and a set $E=\{e=1,\dots,N_E\}$ of possible components. It should be noted that each f-th component class includes a subset of components (the column classes include the subset of column components).

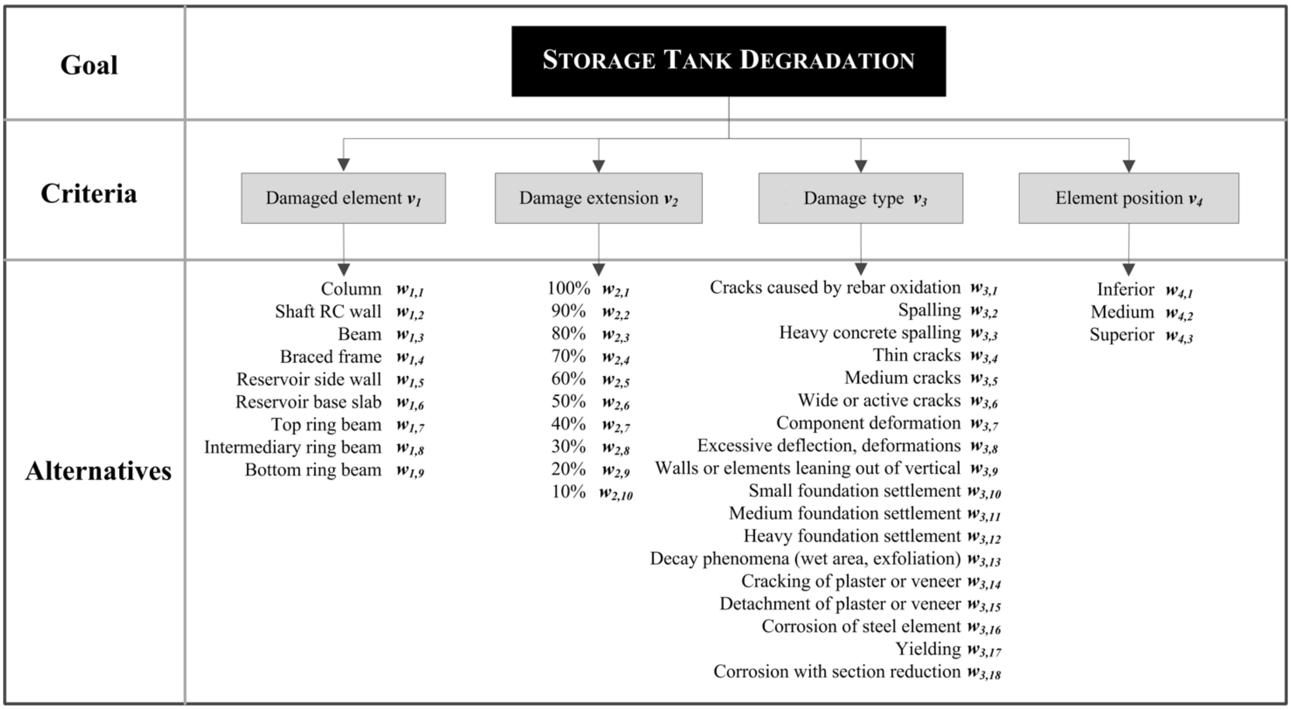


Fig. 3 Storage tank damage evaluation: alternative criteria and associated weight.

In addition to performing diagnostics, suitable criteria and alternatives are defined and selected by the standard approach (Sangiorgio et al 2019). The original method considers many component and damage types, since it was designed for a generic structure. In this work, only components and damage compatible with water towers are considered. Figure 3 shows the selected criteria, alternatives and associated weights.

The problem is structured into m=4 criteria: *damage type*, *damage extension*, *damaged element* and *element position*. The weights are defined as follows:

- v_i is the weight associated with each criterion;
- w_{ij} is the weight associated with each alternative criterion.

In the second step, a report is generated on the basis of the visual analysis for individual tank damage: every report is composed of a photographic survey and additional structured information, organized in the set of *alternatives*.

For each report, 4 tabulated weights evaluated are then assigned to each j alternative. Table 1 reports the tabulated weights extracted on the basis of Sangiorgio et al. [19,20] for the case of the storage tanks degradation analysis. It is worth noting that these weights have been firstly defined by interviewing multiple experts and calibrated through an optimization-based procedure, secondly the procedure has been validated by a comparison with similar approaches and finally a sensitivity analysis, in particular a numerical incremental analysis, has been performed to verify the robustness of the approach.

Table 1 Tabulated weights of elevated storage tanks [19,20].

Alternatives	Weight	Value
Damaged element	v_1	0.10
Damage extension	v_2	0.43
Damage type	v_3	0.44
Element position	v_4	0.03
Column	$w_{1,1}$	10.0
Shaft RC wall	$w_{1,2}$	10.0
Beam	$w_{1,3}$	3.4
Braced frame	$w_{1,4}$	4.1
Tank side wall	$w_{1,5}$	5.3
Tank base slab	$w_{1,6}$	6.1
Top ring beam	$w_{1,7}$	4.1
Intermediary ring beam	$w_{1,8}$	7.1
Bottom ring beam	$w_{1,9}$	7.1
100%	$w_{2,1}$	10.0
90%	$w_{2,2}$	9.0
80%	$w_{2,3}$	8.0
70%	$w_{2,4}$	7.0
60%	$w_{2,5}$	6.0
50%	$w_{2,6}$	5.0
40%	$w_{2,7}$	4.0
30%	$w_{2,8}$	3.0
20%	$w_{2,9}$	2.0
10%	$w_{2,10}$	1.0
Cracks caused by rebar oxidation	$w_{3,1}$	2.1
Spalling	$w_{3,2}$	3.9
Heavy concrete spalling	$w_{3,3}$	8.8
Thin cracks	$w_{3,4}$	2.1
Medium cracks	$w_{3,5}$	4.4
Wide or active cracks	$w_{3,6}$	9.1
Component deformation	$w_{3,7}$	2.4
Excessive deflection, deformation	$w_{3,8}$	8.3
Walls or elements leaning out of vertical	$w_{3,9}$	9.1
Small foundation settlement	$w_{3,10}$	5.1
Medium foundation settlement	$w_{3,11}$	2.1
Heavy foundation settlement	$w_{3,12}$	10.0
Decay phenomena (wet area, exfoliation)	$w_{3,13}$	1.4
Cracking of plaster or coating	$w_{3,14}$	2.1
Detachment of plaster or coating	$w_{3,15}$	3.9
Corrosion of steel element	$w_{3,16}$	0.7
Yielding	$w_{3,17}$	3.5
Corrosion with section reduction	$w_{3,18}$	3.5
Inferior	$w_{4,1}$	10.0
Medium	$w_{4,2}$	6.4
Superior	$w_{4,3}$	3.3

In addition, each weight is associated with only one criterion or alternative. Consequently, the weights can be automatically assigned once the set of alternatives is known.

Let us consider a generic component $e \in E$ and the Δ detected damages related to e. The index associated to the *single damage* SD_d with d=1,…, Δ is obtained by the following formula [19,20]:

$$SD_d = \sum_{i=1}^{m} v_i \times w_{ij} \qquad with\ j \in \{1, \dots, al_i\} \tag{1}$$

where for each i only one j is associated.

Once the *single damage* SD_d has been obtained, the *criticality condition rating* (Cr_e), which quantifies the deterioration of a component, is defined as a function of the values of SD_d as follows [12]:

$$Cr_e = SD_{max}\left(1 + \frac{\sum_{d=1}^{\Delta} SD_d - SD_{max}}{2 * \sum_{d=1}^{\Delta} SD_d}\right) \tag{2}$$

where SD_{max} is the maximum value obtained for SD_d, with d=1,…, Δ.

The synthetic index that quantifies the deterioration of the *f-th* class of components, named *component condition rating* of class *f* (CCr_f), is calculated by aggregating the values of Cr_e representing the *criticality* *condition rating* of component *e* belonging to the same *f-th* class (obtained by eq. (2)). The value of CCr_f is computed as follows:

$$CCr_f = \frac{\sum_e Cr_e}{n_e} \ , \tag{3}$$

where n_e is the number of the component *e* belonging to the same *f-th* class. It is worth noting that in the standard approach a qualitative evaluation of the number of components of the structure was carried out. In this work it is possible to know the exact number of components n_e of the elevated storage tanks through the *on-site survey*.

Finally, the degree of deterioration of the whole structure (*SCr*) is calculated by totalling the values of Cr_e associated with all the elements belonging to the same structure through the following expression:

$$SCr = \frac{\sum_{e=1}^{N_E} Cr_e}{N_E} \tag{4}$$

where N_E is the total number of storage tank components.

2.4 Condition ratings overview through the Matrix of Damage

All the information acquired in the previous phases can be stored in the *Matrix of Damage* (Figure 4). This matrix provides an overview of the structural condition by displaying the number of damaged components and the relative condition ratings.

The classification of the matrix is structured according to the type of damaged element (reported in the matrix rows) and the types of criticality (reported in the matrix columns). The matrix cell indicates the number of detected cases of damage.

In addition, the upper left section of figure 4 contains a synthesis of the general data and rows in the lower left contain *Component Condition Ratings*.

SC1	STRUCTURES		MATRIX OF DAMAGE
	ADDRESS		Registry data
Decision Support System	Survey output		Diameter of tank: m
			Volume: m^3
			Number of columns: n°
			Construction typology:
			Max height: m
			Average Knowledge degree
			-
			Max Cr
			Structure Condition Rating:

Tech. Unit		Element			Sub-element	
Code	Type	Code	Typology	*Ccr*	Code	Component
		S1	Structural element		S1.1	Column
					S1.2	Shaft RC wall
					S1.3	Beam between columns
					S1.4	Braced frame
					S1.5	Reservoir RC side wall
					S1.6	Reservoir RC base slab
					S1.7	Top ring beam
					S1.8	Intermediary ring beam
					S1.9	Bottom ring beam

Structure Damage	Ox			Rx			Cr			Df			De			Se			Gi			Co		
Macro Type	Concrete Corrosion			Reinforcement Corrosion			Cracking pattern			Component deformation			Plaster or finiscing decay			Settlement			Defect in junction and detachment			Corrosion of external elements		
Cod	Ox1	Ox2	Ox3	Rx1	Rx2	Rx3	Cr1	Cr2	Cr3	Df1	Df2	Df3	De1	De2	De3	Se1	Se2	Se3	Gi1	Gi2	Gi3	Cs1	Cs2	Cs3
Criticality	Cracks caused by rebar corrosion	Spalling	Heavy concrete spalling	Light corrosion	Medium corrosion	Heavy corrosion (section reduction)	Thin cracks	Medium cracks	Wide or active cracks	Component deformation	Excessive deflection or deformation	Walls or elements leaning out of vertical	Decay pheneomena (wet area. exfoliation)	Cracking of plaster or veneer	Detachment of plaster or veneer	Small foundation settlement	Medium foundation settlement	Heavy foundation settlement	Defects at junction	Detachment of elements	Brick blocks falling down	Corrosion of steel element	Yielding	Corrosion with section reduction
Column																								
Shaft RC wall																								
Beam between columns																								
Braced frame																								
Reservoir RC side wall																								
Reservoir RC base slab																								
Top ring beam																								
Intermediary ring beam																								
Bottom ring beam																								

Fig. 4 *Matrix of Damage*: example of an empty matrix.

A set of threshold values are defined in order to provide an alert for certain components (class of component or structure) at high risk of collapse (Figure 5) [20].

Cr	*Local slight damage*	*Local medium damage*	*Local serious damage*
	Cr < 4	4< *Cr* <6	6< *Cr* <10
CCr	*Few damages* and limited to a class of components	*Medium damages* on a class of components	*Serious and extended damage*
	CCr < 2	2< *CCr* <6	6< *CCr* <10
SCr	*Structure in good condition*	*Medium widespread damages*	*Serious and extended danger* compromising whole structure
	SCr < 3	3 < *SCr* < 5	5< *SCr*

Fig. 5 Limit values and the corresponding qualitative expression and associate colour

The threshold values are of basic importance, indeed if one component (or class of component) of the structure is highly damaged, and this element is fundamental for the structural stability, the practitioner can understand the danger by displaying one or more *Condition Ratings* that exceed the higher threshold values in the *Matrix of Damage* (indicated with red colour).

3. Case studies

In order to test the proposed method, 32 case studies were carried out in 27 towns and cities in the Valencia Region, an autonomous community in Spain. It is the fourth most populous region and its capital, Valencia, is the third largest city and metropolitan area in the country. The coastline is 440 km long and contains 65 townships. The Valencia region has undergone a profound metamorphosis in the last 50 years, form the 1960 the population has nearly doubled [22] and today has become an area of almost 5 million inhabitants. For this reason, it has experienced a continual growth residential building and the number of constructions in the area has greatly multiplied. This effect has reached its peak during the periods of building expansion between 1968 and 1973 [23,24]. The development was massive, multiplying the number of buildings and the population [25]. The demand for water increased in the cities, leading to the extensive construction of water towers at the end of the 1960s. In recent years modern water supply networks have been built, making the old water towers obsolete. Currently, many of these tanks are out of use and present many criticalities, becoming a problem for those responsible for their upkeep. These structures are of different types of construction and exposed to different weather conditions, including marine environments. The R.C water towers are widespread all over the region and a comprehensive knowledge of their conservation status is not available. All these conditions make the Valencia region an excellent test site for the proposed method.

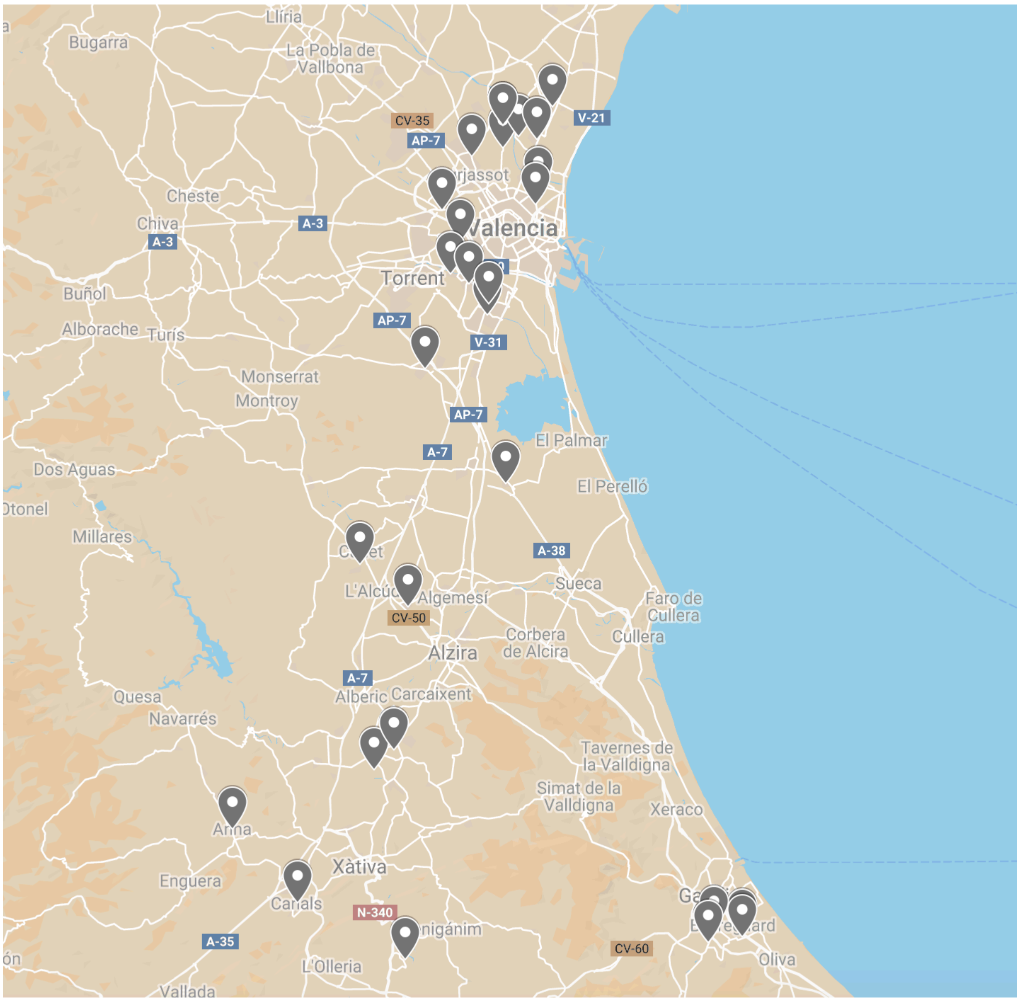


Fig. 6 Tanks location in Valencia region.

3.1 On-desk analysis of the case study

The first step of the method involves an *on-desk study* of the elevated storage tanks. The 32 examples were correctly identified by aerial photogrammetric and georeferenced maps. In this phase very few existing documents and historical data were found. On the other hand, it was possible to carry out a more detailed analysis focused on the environmental context. Twenty are close to the coast and are potentially more exposed to the aggressive marine atmosphere, while the rest are located in the hinterland. Figure 6 shows the location of the tanks. The final part of the on-desk study was scheduling the on-site inspections. Six-day surveys were planned: 3 days to inspect those close to the city of Valencia (15 storage tanks in 13 municipalities at less than 10 km from the city); and 3 days to survey the other 17 storage tanks in the south of the region.

Figures 7 show the investigated water tanks and the two principal surveyed damages for every structure.

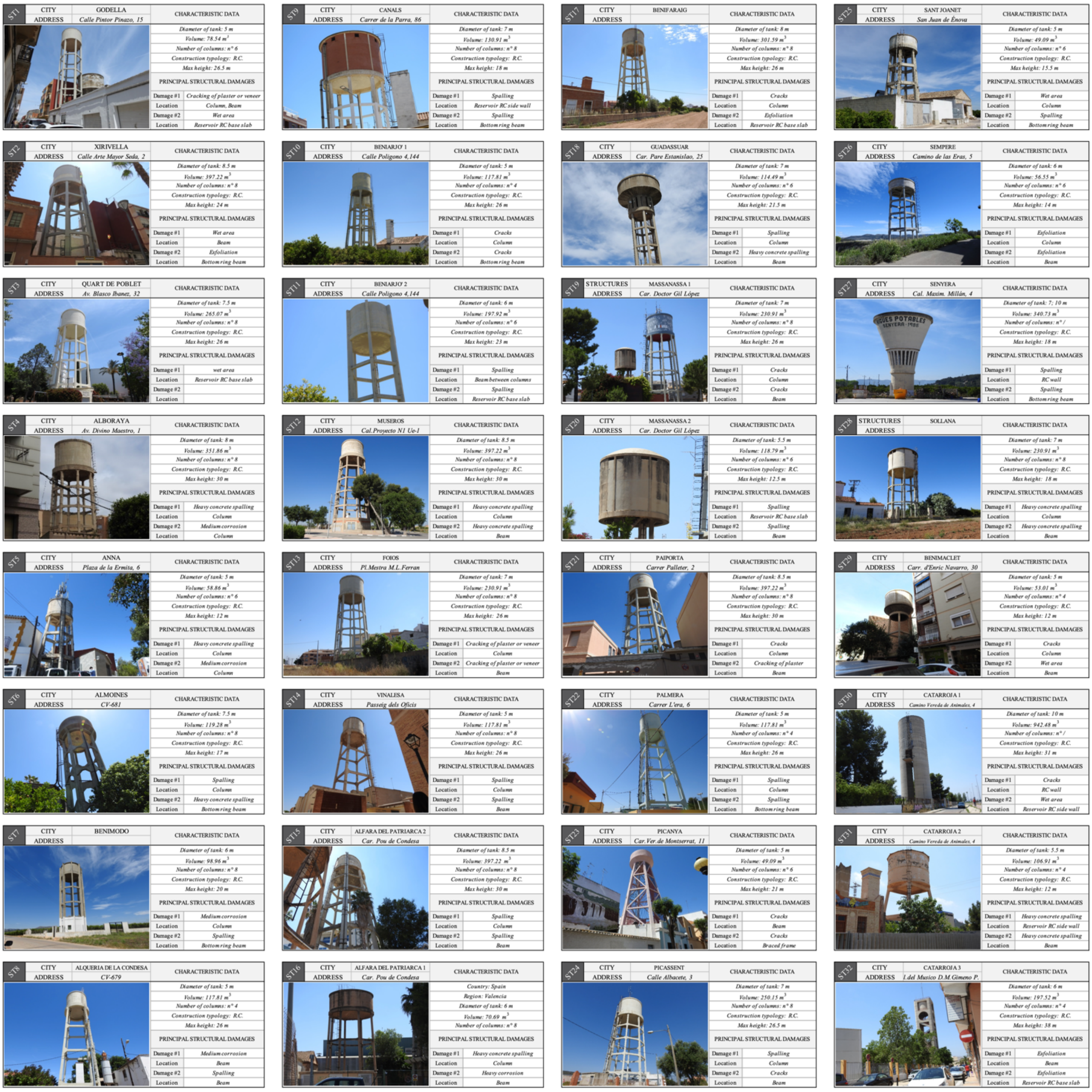


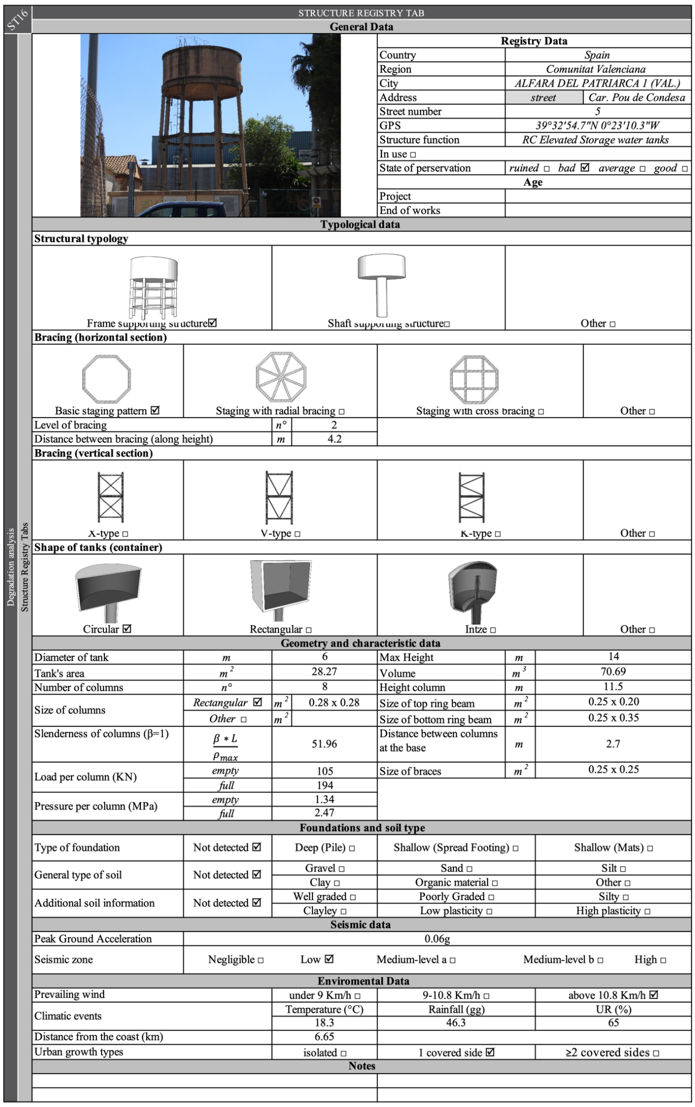
Fig. 7 Investigated water tanks and the two principal surveyed damages for every structure.

3.2 On-site storage tanks investigation

An exhaustive photographic inspection was performed on all the case studies, and the *survey tabs* were used to store all the acquired information.

The example of storage tank 16 (named “ST16”) is shown in the *survey tabs* in Figure 8. ST26 is in the small town of Alfara del Patriarca, 10 km from Valencia.

This tank is supported on a frame structure with basic staging patterns. It is circular in shape and there is no vertical bracing. As it is 11 km from the coast it is potentially less exposed to the marine environment.


ST16 | Degradation analysis | Structure Registry Tabs

STRUCTURE REGISTRY TAB

General Data

Registry Data		
Country	Spain	
Region	Comunitat Valenciana	
City	ALFARA DEL PATRIARCA 1 (VAL.)	
Address	street	Car. Pou de Condesa
Street number	5	
GPS	39°32'54.7"N 0°23'10.3"W	
Structure function	RC Elevated Storage water tanks	
In use ☐		
State of perservation	ruined ☐ bad ☑ average ☐ good ☐	
Age		
Project		
End of works		

Typological data

Structural typology			
Frame supporting structure☑	Shaft supporting structure☐	Other ☐	
Bracing (horizontal section)			
Basic staging pattern ☑	Staging with radial bracing ☐	Staging with cross bracing ☐	Other ☐
Level of bracing	n°	2	
Distance between bracing (along height)	m	4.2	
Bracing (vertical section)			
X-type ☐	V-type ☐	K-type ☐	Other ☐
Shape of tanks (container)			
Circular ☑	Rectangular ☐	Intze ☐	Other ☐

Geometry and characteristic data

Diameter of tank	m		6	Max Height	m	14
Tank's area	m^2		28.27	Volume	m^3	70.69
Number of columns	n°		8	Height column	m	11.5
Size of columns	Rectangular ☑	m^2	0.28 x 0.28	Size of top ring beam	m^2	0.25 x 0.20
	Other ☐	m^2		Size of bottom ring beam	m^2	0.25 x 0.35
Slenderness of columns (β=1)	$\frac{\beta * L}{\rho_{max}}$		51.96	Distance between columns at the base	m	2.7
Load per column (KN)	empty		105	Size of braces	m^2	0.25 x 0.25
	full		194			
Pressure per column (MPa)	empty		1.34			
	full		2.47			

Foundations and soil type

Type of foundation	Not detected ☑	Deep (Pile) ☐	Shallow (Spread Footing) ☐	Shallow (Mats) ☐
General type of soil	Not detected ☑	Gravel ☐	Sand ☐	Silt ☐
		Clay ☐	Organic material ☐	Other ☐
Additional soil information	Not detected ☑	Well graded ☐	Poorly Graded ☐	Silty ☐
		Clayley ☐	Low plasticity ☐	High plasticity ☐

Seismic data

Peak Ground Acceleration	0.06g
Seismic zone	Negligible ☐ Low ☑ Medium-level a ☐ Medium-level b ☐ High ☐

Enviromental Data

Prevailing wind	under 9 Km/h ☐	9-10.8 Km/h ☐	above 10.8 Km/h ☑
Climatic events	Temperature (°C)	Rainfall (gg)	UR (%)
	18.3	46.3	65
Distance from the coast (km)	6.65		
Urban growth types	isolated ☐	1 covered side ☑	≥2 covered sides ☐

Notes

Fig. 8 *Survey tab* of tank ST16.

After surveying all the case studies, the first classification of the different typologies was carried out. The case studies present different geometric and structural characteristics, for example: i) maximum tank height ranges between 12 m and 38 m; ii) tank diameters are between 5m and 10m; and iii) number of columns is between 4 and 8. The most common tank typology is circular with a *frame supported structure*. Only 4 tanks are of the “Intze shape of tank” type.

3.3 Diagnostics

The diagnostic phase exploits the photographic inspection and other important information regarding the surveyed criticalities. These tabs are used to store the information and evaluate the *condition ratings*.

Figure 9 shows the classification of a single element of tank ST16, with important damage information. The *condition rating* is evaluated by exploiting Eqs.(1) and (2) and the tabulated weights shown in Table 1. The *diagnostic tabs* contain the photographic inspections and check the information used to evaluate the *Cr* (in the lower part of the tab). In this case, the *damaged element* is the column, *damage extension* is 60%, *damage type* is heavy concrete spalling and *damage position* is in the lower column. As the result of this analysis, *Cr* value is equal to 7.8, which exceeds threshold values defined in Sangiorgio [20] and is therefore classified as serious.

ST16	CITY	ALFARA DEL PATRIARCA				
	ADDRESS	Carrer Pou De Condesa,5				
Diagnostic Tab / Elevated storage tank	id_element	date-photo	date-creation	Surveyor	id_structure	name
	12	20/06/19	20/06/19	-	16	Water tank
			Criticality			
			Damaged element	*Column*		10
			Damage extension	*60%*		6.0
			Damage type	*Heavy concrete spalling*		8.8
			Damage position	*Inferior*		10
			Cr^{12}	*Local serious damage*		*7.8*

Fig. 9 *Diagnostic tab* of tank ST16.

Once all the damage in a single structure has been evaluated by the diagnostic tabs, the *Matrix of Damage* can be filled in.

CCr and *SCr* are calculated by Eqs.(3) and (4). In this matrix the number of reports for each damage (matrix columns) and for component (matrix rows) are shown. The right-hand part of the matrix indicates the maximum value of *Cr* detected in the structure (maximum criticality condition rating), the component condition ratings (*CCr*) and the structure condition rating (*SCr*).

ST16	STRUCTURES	ALFARA DEL PATRIARCA 1	MATRIX OF DAMAGE
	ADDRESS	Car. Pou de Condesa	Registry data
Decision Support System / Diagnostic output			Country: Spain
			Region: Valencia
			Diameter of tank: 6 m
			Volume: 70.69 m^3
			Number of columns: n° 8
			Construction typology: R.C.
			Max height: 14 m
			Max Cr
			7.7
			SCr
			5.3

Macro-Element Code	Code	*Ccr*	Code	Element	Ox1 Cracks caused by rebar corrosion	Ox2 Spalling	Ox3 Heavy concrete spalling	Rx1 Light corrosion	Rx2 Medium corrosion	Rx3 Heavy corrosion (section reduction)	De1 Decay pheneomena (wet area. exfoliation)	De2 Cracking of plaster or veneer	De3 Detachment of plaster or veneer
				Strcture Damage — Macro Type	Ox Concrete Corrosion			Rx Reinforcement Corrosion			De Plaster or finiscing decay		
S1	Structural element	4.8	S1.1	Column	8	2	3	3	3	3	3		
			S1.2	Shaft RC wall									
		6.4	S1.3	Beam between columns	2		1	1		1	2		
			S1.4	Braced frame									
		3.4	S1.5	Reservoir RC side wall							1		
		3.8	S1.6	Reservoir RC base slab		1			1		1		
		6.3	S1.7	Top ring beam		1	1		1		1		
			S1.8	Intermediary ring beam									
		6.8	S1.9	Bottom ring beam	1		1			1	1		

Fig. 10 *Matrix of damage* of the tank ST16.

ST3	STRUCTURES	QUART DE POBLET	MATRIX OF DAMAGE
	ADDRESS	Av. Blasco Ibanez, 32	Registry data

Decision Support System – Survey output

Diameter of tank: 7.5 m
Volume: 265.07 m^3
Number of columns: n° 8
Construction typology: R.C.
Max height: 26 m
Average Knowledge degree: -
Max Cr: 1.5
Structure Condition Rating: 0.3

Macro-Element		Element classification			Ox			Rx			De		
				Macro Type	Concrete Corrosion			Reinforcement Corrosion			Plaster or finiscing decay		
				Code	Ox1	Ox2	Ox3	Rx1	Rx2	Rx3	De1	De2	De3
				Criticality	Cracks caused by rebar corrosion	Spalling	Heavy concrete spalling	Light corrosion	Medium corrosion	Heavy corrosion (section reduction)	Decay pheneomena (wet area. exfoliation)	Cracking of plaster or veneer	Detachment of plaster or veneer
Code	Code	***Ccr***	Code	Element									
S1	Structural element		S1.1	Column									
			S1.2	Shaft RC wall									
			S1.3	Beam between columns									
			S1.4	Braced frame									
			S1.5	Reservoir RC side wall									
		1.5	S1.6	Reservoir RC base slab							1		
			S1.7	Top ring beam									
			S1.8	Intermediary ring beam									
			S1.9	Bottom ring beam									

Fig. 11 *Matrix of damage* of the tank ST3.

By inspecting the values of the condition ratings reported in the *Matrix of damage* (Figure 10) and using the threshold values in Sangiorgio [20] (Figure 5), some preliminary concise observations can be made. For example, in tank ST16: (1) the maximum criticality condition rating 7.7 exceeds the threshold for serious danger, i.e. it can severely affect the performance of the structure; (2) the maximum *component condition ratings* suggests that all the beams of the tank are in a critical condition and the columns are in a medium-serious status. This situation can compromise the overall component effectiveness; (3) the structure condition rating also exceeds the threshold values in Sangiorgio et al. [20] i.e. the tank is in a critical state of conservation. In addition, in order to shows the difference of the condition ratings evaluation for structures in good condition Figure 11 shows the resulting *Matrix of damage* for the storage tank ST3. This is the structure in the best conditions among those investigated. The last damage surveyed regard a small exfoliation of the plaster *Ccr*=1.5. and the structure condition rating is *Scr* = 0.3.

4 Results

From the large-scale degradation analysis of all the case studies three main results can be obtained. Firstly, a map to locate the most seriously damaged structures can be obtained to identify the maintenance and intervention priorities. Secondly, the regional scale analysis of the structure identifies the most frequently damaged element and the most frequent serious damage to identify the main causes of these weaknesses. Thirdly, the best intervention strategies for these storage tanks are identified and discussed to obtain useful information for maintenance.

4.1 Georeferenced map of damaged structures

The first result can be obtained by the analysis of the *SCr* for all the structures (Figure 12). 22 storage tanks are in generally good condition with an *SCr* less than 3. Nine are in the south of the Valencia Region and are in a medium state of conservation with some elements in a critical condition (*SCr* between 3 and 5). The most seriously damaged tank is in Alfara del Patriarca, in the north of the region 7 km from the sea. The analysis reported an *SCr* equal to 5.23 for this structure, which exceeds the heavy damage threshold. This tank presents serious reinforced concrete degradation and rebar corrosion, principally in the lower part of the columns. Figure 12 shows its position on a Georeferenced map. In this figure, the state of conservation of the tanks (good, medium damage and serious damage) is indicated by green, yellow and red, respectively.

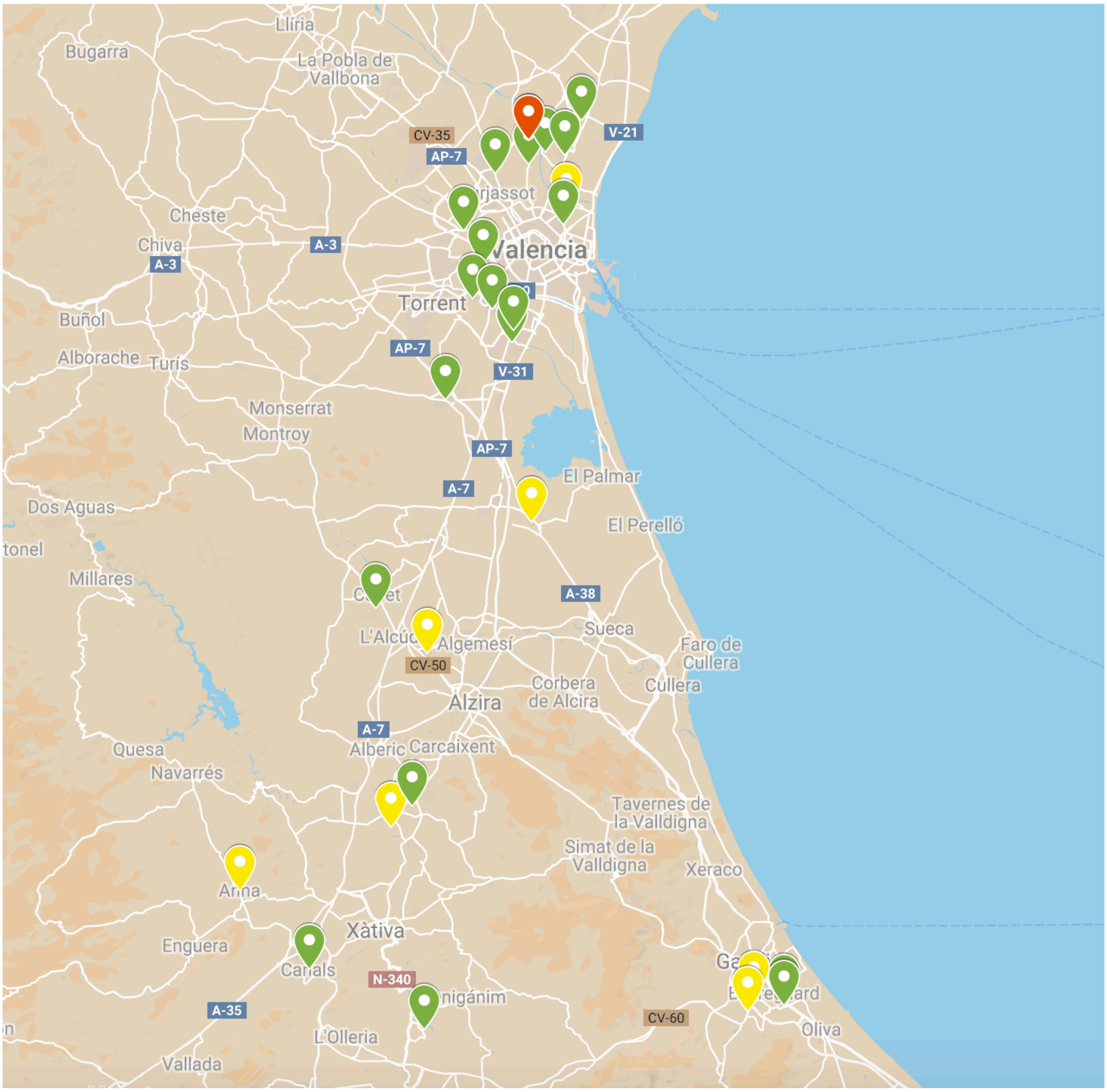


Fig. 12 Georeferenced map of damaged storage tanks based on *SCr*.

4.2 Analysis of most frequent damages

The second result of the analysis was the detection and classification of the most frequent item detected in the structures, which was in the *beams* in the form of longitudinal *cracks* and *spalling of the concrete cover*. This was mostly found in the beams between the columns, where the concrete is more exposed to the external environment. Figure 13 shows an example of this type of damage accompanied by a descriptive sketch. The concrete loss is typically concentrated at the bottom of the beam due to being less exposed to solar radiation (greater probability of a moist environment). As can be seen, the cracks usually appear in the direction of the beam, coinciding with the position of the reinforcement ("B") with concrete spalling at the corners ("A").

Heavy concrete spalling was also found in many storage tank *columns*, especially near the foundations accompanied by large damp spots due to rising damp from the ground, which accelerates concrete degradation. Figure 14 shows an image and scheme of the cracks (A) damp areas, and heavy concrete spalling (B) in a column of ST16.

The third most frequently damaged element was the *tank base slab*, in which cracks and spalling allowed corrosion of the reinforcement. Nineteen of the 32 structures presented humidity and surface degradation, while the concrete had damp patches and damaged plaster.

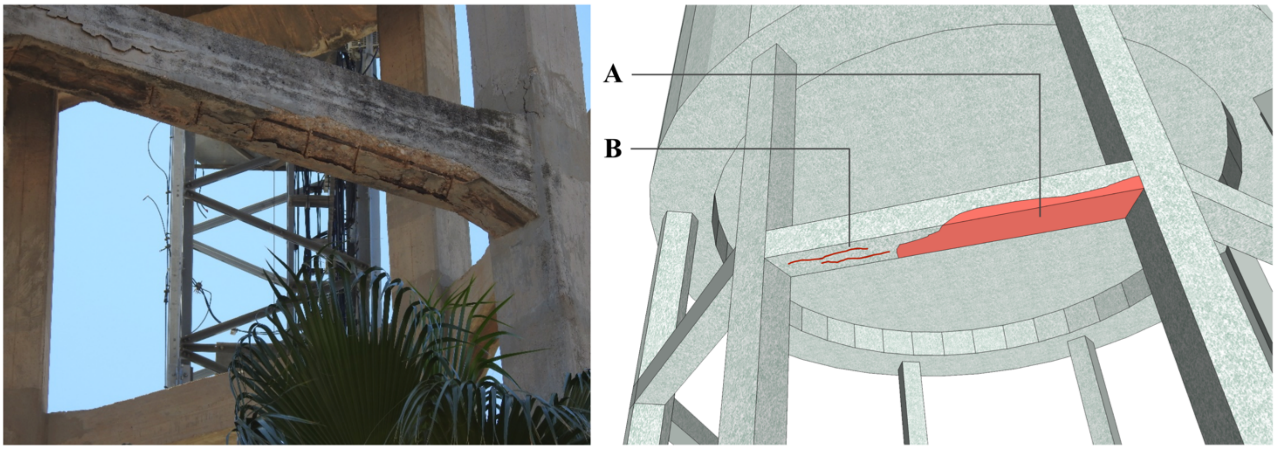


Fig. 13 Recurrent damage: *wet areas*, *cracks* and *heavy concrete spalling* in the lower parts of the beams

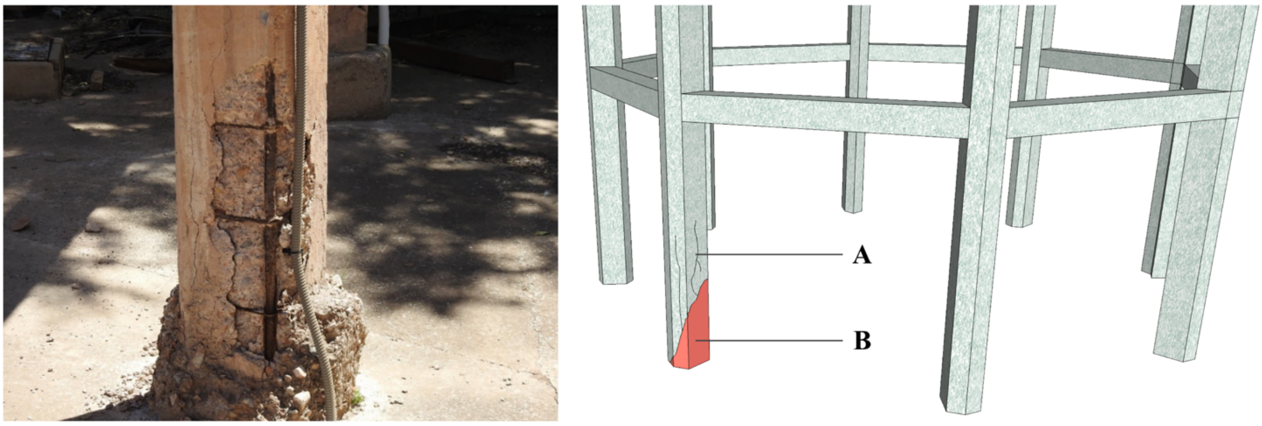


Fig. 14 Recurrent damage: *wet areas*, *cracks* and *heavy concrete spalling* columns near foundation.

4.3 Analysis of damage causes and potential effects

The causes of the large amount of detected damages on the storage tanks can be associated to both intrinsic and extrinsic causes.

The main intrinsic cause is the poor quality and the thickness of the concrete cover. During the survey it was verified that the storage tanks with the most serious spalling had only a thin layer of concrete cover (less than 2 cms). In addition, the poor quality of the concrete is connected to the presence of microcracks and high porosity of the material. These characteristics correspond to a performance loss that makes the storage tank less resistant to the humid environment. In this situation the water can be easily conveyed through the cracks and rapidly reaches the rebars reinforcement, accelerating the corrosion process. The principal consequences of this weakness are surveyed in the columns and beams degradation.

The other intrinsic cause is related to the loss of effectiveness of the reservoir interior waterproofing layer. Therefore, this issue creates infiltrations and wet areas in the bottom of the tank. The consequences of this phenomenon are visible as serious expulsions of the concrete cover and rebars oxidation in the intrados of the reservoir base slab.

None of the surveyed tanks presented a combination of damage attributable to failure of the foundations.

Moreover, there are some extrinsic causes that accelerate the degradation process and aggravate the condition. The principal cause is identified in the aggressive marine environment. In particular, storage tanks close to the sea are at high risk of suffering heavy damage, mainly due to the effects of chloride. This can be particularly severe if no attention was paid to this aspect during their construction or if no special protection has been implemented. In addition, some parts of the reservoirs are always in shaded areas due to the presence of large trees or buildings that block solar radiation. This condition contributes to create permanent wet areas on some components of the tanks that accelerate the degradation process. Another extrinsic cause can be identified in the lack of maintenance. This condition is principally present in some of the storage tanks far from the coast and located in the south of Valencia. Because of this, some tanks far from the coast are in worse condition if compared with other closer to the sea.

4.4 Intervention guidelines

In this section, some global and local intervention strategies are presented. It is worth noting that such proposed strategies are general interventions based on the large-scale study of degradation. Beyond this, the structures that are identified as the most damaged constructions can be investigated with more in-depth analysis to identify not only the repair approach to be followed, but also the retrofitting intervention strategies.

At the global level, the results underline the fact that one of the main causes of damage to the Valencia Storage tanks is related to the insufficient thickness of the concrete cover and the poor quality (high permeability) of the admixture.

The following interventions can be recommended to improve the service life of the structures in the Valencia region. The highest priority refers to the removal and reconstruction of the concrete cover as follows:

a) Removing damaged concrete;
b) Cleaning concrete surfaces (e.g. by means of bus hammering);
c) Cleaning reinforcement rebars to assess their condition;
d) If rebars are in an advanced state of corrosion or are evidently insufficient:
    - Total removal of the section of rebar affected by corrosion;
    - Reinforcement with new rebars welded to the interrupted sections;
    - Strengthening with new rebars if necessary
e) Direct application of a corrosion inhibitor onto the reinforcement bars.
f) Cleaning and moistening the support surface and concrete restoration by premixed mortars prepared on site to increase the thickness of the concrete cover.

The second intervention regards the local criticality of the *RC base slab*. In this case, firstly there is a need to investigate the probable loss of water resistance of the reservoir interior. Secondly, if the tank is still in operation and the waterproof layer is damaged, the following steps are necessary:

a) Removing damaged concrete and waterproof layer;
b) Cleaning concrete surfaces (e.g. by means of bus hammering);
c) Cleaning reinforcement rebars to assess their condition;
d) If rebars appear in an advanced state of corrosion:
    - Total removal of the section of rebar affected by corrosion;
    - Reinforcement with new rebars welded to the interrupted sections;
e) Direct application of a corrosion inhibitor onto the reinforcement bars.
f) Cleaning and humidifying the support surface (completely remove all traces of dirt by high-pressure water washing) and concrete restoration by applying waterproofing admixtures.
g) Application of a new waterproofing layer.
    - Creation of rounded edges between wall and floor (if not already existing) using a fibre-reinforced high-strength concrete-based mortar with compensated shrinkage, selected aggregates, synthetic fibres and additives which guarantee excellent workability, adhesion, thixotropy for applications with thicknesses of 4-5 cm.
    - Application of a coat of anchoring agent and primer acting as vapour barrier in order to make a waterproofing coating on concrete surfaces, grouts and smoothing works.
    - Application of a non-toxic water-based two-component epoxy coating.

5. Conclusions

This paper proposes a method of performing a degradation analysis of R.C. elevated storage tanks on a regional scale. The procedure was adapted to the specific case of these tanks by following the classical Alert-D method. Four phases were defined: i) an on-desk study, ii) an on-site survey, iii) a diagnostic approach, iv) a ranking and priorities. Novel *survey tabs*, *diagnostics tabs*, *matrix of damages* and formulas were customized to cover all the tank elements.

The novelty of this paper is threefold.

For the first time a visual-survey-based approach is developed for the large scale analysis of elevated storage tanks involving new data acquisition tabs, damage classification and synthetic formulas to quantify the condition. The development of this approach involved interdisciplinary skills, including structural engineering, forensic engineering, statistics and multi-criteria analysis.

Secondly, the study analysed 32 water towers in 27 different towns in the Valencia Region to show the potential of the method and to obtain useful information on typology and causes of the most important damages.

Thirdly, the outcome of the large-scale analysis achieved three important results of interest for tank maintenance:

i) a georeferenced map with the most heavily damaged structures to suggest maintenance and intervention priorities;

ii) the identification of the most recurrent damaged element, the most serious damage found and the analysis of the main causes of these criticalities. The main weaknesses were found to be due to inadequate concrete quality and the thickness of concrete cover;

iii) the best intervention strategies for the storage tanks were identified and discussed to provide useful information for local technicians and companies.

This approach could be used by researchers, engineers and those performing degradation analyses of these storage tanks and improving existing management and maintenance tools to prioritize in-depth analysis, interventions and identify an effective maintenance strategy.

Future research will integrates storage tank analysis with a vulnerability evaluation. In particular some FEM analyses will be performed in order to identify the structural behaviour of the various typology of surveyed tanks in relation with the potential plastic hinge region of the structure. In this way it will be possible to combine the information about the structural degradation studied in the present work with the structural vulnerability of the tanks on the Valencian coast. Finally, it will be possible to include seismic risks analysis to provide a regional risk classification.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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