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The Effect of Rehabilitation on the Vulnerability Evolution of an RC Water Tank throughout Its Lifecycle

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Abstract: In the field of civil engineering, reinforced concrete (RC) storage tanks are considered as important infrastructure that play a key role in the daily life of citizens, given their role of supply and storage of drinking water. These structures undergo regular monitoring and inspections as part of preventive maintenance programs to ensure their proper functioning and safety, as they are exposed to degradation and ageing due to natural hazards such as earthquakes, wind, and unfavorable weather. Expensive rehabilitation actions are often necessary to extend their lifecycle.In this context, a predictive model of vulnerability index evolution is developed, using a combined finite element approach with exponential extrapolation. This numerical model can predict the vulnerability evolution at any time in the lifecycle of the RC tank, following rehabilitation actions. This predictive model is successfully tested on a real case of RC storage tank located in the Tizi-Ouzou region (Algeria), and demonstrated its efficacy.

Keywords: Vulnerability, Concrete tanks, Rehabilitation, Predictive model, Lifecycle.

Introduction

In Algeria, drinking water reservoir infrastructures comprise approximately 40,000 tanks, the majority of which are constructed with reinforced concrete (Hammoum et al., 2012). These infrastructures, considered as specialized structures, hold a crucial position within civil engineering constructions. Their essential role in daily life gives them significant socio-economic importance. Owing to this, they are highly sensitive to public opinion. The closure of these tanks for maintenance or repair often causes negative reactions from consumers. In response to growing societal demand for water, the managers of these infrastructures must address numerous challenges, such as the ageing of the materials and structures, the increased risk of extreme climatic events, and the necessity to maintain or even improve service levels.

The assessment of the condition and behavior of these ageing storage structures, while taking into account these constraints, is therefore essential to ensure their continuous operation. The study of the degradation and ageing of these structures has been the focus of numerous research efforts. Several experts have developed methods and techniques for diagnosis, risk analysis (vulnerability), and the development of action and maintenance plans: Curt (2007) and Peyras (2002) have worked on dams, Serre (2009) on flood protection levees, while Hammoum (2011), Mathieu (2003), and Aliche (2016, 2017) have focused on storage tanks.

As part of this research, and in order to better manage rehabilitation interventions, which are often costly and complex, and to prioritize the structures to be rehabilitated, a novel approach is proposed, aiming at determining the impact of rehabilitation and maintenance actions on the vulnerability evolution of a reinforced concrete reservoir throughout its life cycle. Our approach is based on the predictive model developed by Aliche et al. (2017), assuming that the progression of ageing is known up to the time of intervention, a post-rehabilitation vulnerability model is proposed. The present case study yielded satisfactory results.

Methodology for Evaluation of the Vulnerability Index 'Iv'

The vulnerability index 'Iv' of a reinforced concrete storage tank at time (t) is obtained based on the method proposed by Hammoum (2011, 2012), involving thirteen (13) influential parameters: environmental, structural, and functional, as defined in Table 1.

Table 1. List of analysis parameters

Analysis type	N°	Definition of the parameters
Environmental Analysis	1	Tank location
	2	Seismic zone
	3	Soil type
	4	Snow zone
	5	Wind zone
Structural Analysis	6	Structure type
	7	Foundation type
	8	Sealing walls
	9	Sealing Cover
	10	Apparent defects
Functional Analysis	11	Tank role
	12	Tank importance
	13	Maintenance frequency

Each of these thirteen parameters will be assigned an elementary grading 'Nei'. The chosen grading principle corresponds to the criteria for amplifying grades based on vulnerability increasing risk. To each grade is assigned a weighting coefficient 'Pi'. Both the elementary grades Nei and weighting coefficient Pi for each parameter range from 1 to 4: where 1 corresponds to the ideal situation, while 4 to the critical situation. The partial grade of a parameter is then obtained through the product (Nei × Pi), and the vulnerability index 'Iv' is then expressed as the sum of the partial grades of the various parameters, as given by equation (1).

$$Iv = \sum_{i=1}^{13} N_{ei} . P_i = N_e + N_s + N_f \tag{1}$$

Considering all the analysis criteria listed above, a classification scale for reservoirs, classifying vulnerability into four levels is adopted (Table 2).

Table 2. Classification of Reservoirs Based on their 'Iv'.

Vulnerability level	Green	Orange 1	Orange 2	Red
Vulnerability index IV	13 - 49	49 - 87	87 - 136	136– 196

The application of the vulnerability index method to the reservoir stock in the Tizi-Ouzou province has highlighted an evolution of the vulnerability index (Iv) throughout the life cycle of the tanks.

The methodology presented has been successfully tested on a real scale with a stock of 30 circular reinforced concrete tanks assessed in the Tizi-Ouzou province (northern Algeria). This region is classified as an area of moderate seismicity (Zone IIa) according to the Algerian Seismic Regulation (RPA99/2003). According to the Snow and Wind Regulation, the region is classified as Snow Zone A and Wind Zone I. The vulnerability index 'Iv' is determined for each tank based on the technical sheets were developed and completed during the assessment. Table 3 provides an example of an evaluation of the vulnerability index 'Iv' for the Touaresse tanks located in the centre of the Draa Ben Kheda district in the Tizi-Ouzou province.

Table 3. Evaluation of the Vulnerability Index 'Iv' of a tank.

Analysis	Elementary parameter	Scoring Criteria	N_{ei}	Weighting parameter	Scoring Criteria	Pi	$N_{ei}.P_i$
Environmental	Tank location	mountain	1.00	Hydraulic parameter	Center northern band	3.00	3.00
	Seismic zone	Zone IIa	2.00	Implantation site	Urban area	4.00	8.00
	Soil type	Loose soil	3.00	Site Effect	Risk of sliding	4.00	12.00
	Snow zone	Zone A	4.00	Roofing form	Vault	1.00	4.00
	Wind zone	Zone I	2.00	Height Land category Topographic site Surface state	Ph = 0,75, Pc = 0,50, Pt = 0,75, Ps = 0,75.	2.75	5.50
Structural	Type of tank	On ground	3.00	Material	Reinforced concrete	3.00	9.00
	Foundation type	General raft	2.00	Settlement state	No apparent	1.00	2.00
	Sealing walls	Classe B	2.00	Seal State	Moderately satisfactory	3.00	6.00
	Cover Type	Sealing by coating	2.00	Seal State	Anough satisfactory	2.00	4.00
	Gravity index	Level 3	3.00	Age of the tank	49 years	4.00	12.00
Functional	Tank role	Distribution	2.00	Accessibility to the tank	By paved road	1.00	2.00
	Importance of tank	For buildings (Group 1B)	3.00	Capacity of the tank	Capacity : 1000 m^3	2.00	6.00
	Maintenance frequency	Annual	4.00			4.00	4.00
					Vulnerability Index I_V		**77.50**

At the scale of the stock and for each tank, the vulnerability index was calculated on the day of the assessment, while the vulnerability index was simulated on the day of commissioning. The results of these calculations are illustrated in Table 5.

Predictive Model Iv(t)

Table 4. Evolution of the variation in the vulnerability index of a typical reservoir over time

N°	Location	Year of commissioning	Year of expertise	Whole domain	Elements	subdomains	Age of the tank (ti)	I_{vo}	I_{vi}	ΔI_{vi}
01	Taghanimth	2014	2014		1	Ω^1	0	47.50	47.50	00.00
02	Sidi-Namane (SR2)	2012	2014				2	53.50	54.50	01.00
03	Mouldiouane Zone	2010	2014				4	49.50	51.50	02.00
04	Megdoule 1	2008	2014		2	Ω^2	6	54.00	56.50	02.50
05	Taksebt	2000	2010				10	43.00	48.50	05.50
06	Sidi-Namane (SR1)	1999	2014				15	53.50	59.50	06.00
07	Behalil 1	1996	2014		3	Ω^3	18	46.00	53.00	07.00
08	Kaf Laagab	1988	2014	**$0 < t < 49$**			26	56.00	65.00	09.00
09	Tighilt Tiguerfiouine	1985	2014				29	56.00	66.00	10.00
10	Herrouka 2	1984	2014		4	Ω^4	30	46.00	56.50	10.50
11	Touares 2	1980	2014				34	61.00	72.00	11.00
12	Taghanimth	1972	2010				38	47.50	60.50	13.00
13	Mekla Chef-Lieu (SR2)	1975	2014		5	Ω^5	39	50.50	64.00	13.50
14	Herrouka 1	1972	2014				42	48.50	63.50	15.00
15	Touares 1	1965	2014				49	60.50	77.50	17.00

In a professional context, it would be impractical to wait several decades to obtain a series of data for each assessed tank. To address this constraint, an alternative approach is suggested, based on the analysis of the thirteen parameters common to several tanks of different ages, in order to identify a typical tank that is the subject of study (Table 4) (Aliche et al., 2017).

The evolution of the vulnerability index of a typical tank over time, within a known domain, has resulted in the following mathematical model (Aliche et al., 2017):

$$I_v(t) = I_{v0} + \Delta I_v(t) \quad (2)$$

This evolution is illustrated in the case of the Touares tank, located in the Draa Ben Khedda district (Tizi-Ouzou, Algeria).

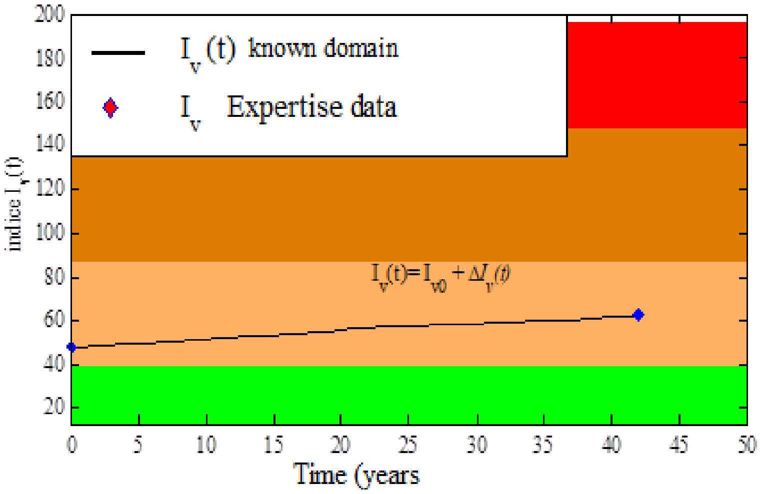

Figure 1. Evolution of the vulnerability index of the Touares tank

To assess the evolution of the ageing of a tank in an unknown domain, the extrapolation of the observed data into the future using an exponential model is performed, as shown in (Aliche et al., 2016):

$$I_v(t) = I_{v49} + \Delta I_{v39}\ e^{0.0231*(t-39)} \qquad \text{Pour } t > 49 \quad (3)$$

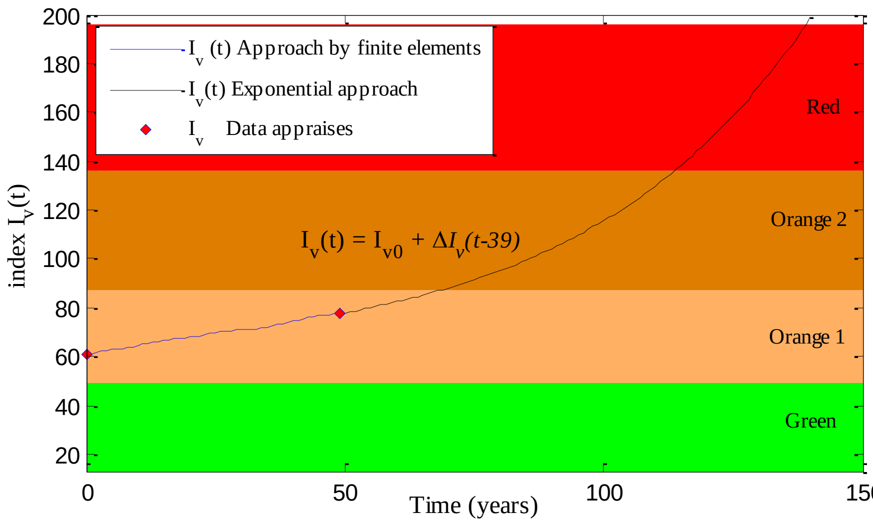

Figure 2. Evolution of the index $I_V(t)$ through the different levels of vulnerability of the Touares tank

Figure 2 illustrates the evolution of index Iv(t) of the Touares tank, showing the different levels of vulnerability that it may reach during its life cycle, based on the developed model. It can be observed that at commissioning, the tank was at level orange 1; it reaches level orange 2 at 68 years and then level red at the age of 114 years, where it should be taken out of service or, at least, immediately placed under usage restrictions. It will reach the extreme level of ruin at the age of 139 years.

Impact of Maintenance on the Evolution of the Vulnerability Index

The Reinforced concrete water storage tanks, like all civil engineering structures, age and deteriorate over their life cycle; this is why these structures enter a new era that requires maintenance actions. One can mention two main maintenance strategies (3): corrective maintenance and preventive maintenance (Figure 3). The choice of one strategy over the other varies depending on the element considered, as well as the type of structure and the operational and monitoring policy (Cremona, 2011).

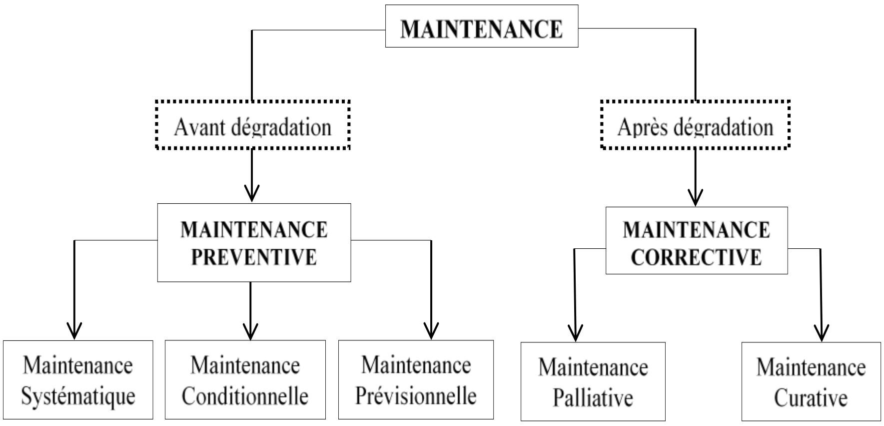

Figure 3. Maintenance strategies (Zwingelstein, 1996)

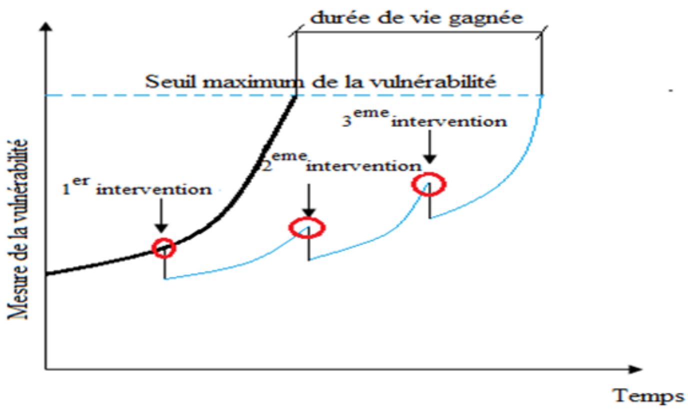

Figure 4. Impact of maintenance on the evolution of vulnerability in the life cycle of the structure (Cremona, 2011)

In real-life scenarios, it is recommended that the manager organizes frequent maintenance and reinforcement actions for the improved ageing behavior of these structures. Figure 4 shows the effect of certain maintenance actions on the evolution of the vulnerability index Iv(t). These actions theoretically allow the vulnerability state of the structure to be returned to a previous condition, which, in most cases, lies between the initial vulnerability state and the state prior to intervention. The effect of this action on the life cycle of the structure is represented by the gained life span referred to as 'time gained,' as illustrated in Figure 4 (Zwingelstein et al, 1996).

Presentation of the Model: Rehabilitation Actions

In order to introduce a 'Rehabilitation Actions' module into the model developed in the previous section, the impact assessment of one or more rehabilitation actions on the evolution of the vulnerability index, during the life cycle of tanks from the assessed stock was performed. These actions should be undertaken while the vulnerability index of the structure is at the 'moderately vulnerable' level, which is, within the limits of the end of the orange 1 range and the beginning of the orange 2 range. The idea is to enhance the performance of the structure and prevent it from entering the advanced vulnerability zone, (the red range), where it would be taken out of service.

To highlight the impact of the rehabilitation action, the example of the Touares tank discussed in the previous section will be revisited. Let us assume that the first rehabilitation action is carried out on this tank at the boundary between the orange 1 and orange 2 domains, addressing its structural and functional parameters. This first rehabilitation action will reduce the index of the structure from Iv = 87 to Iv_R = 72.50 (Figure 5).

Thus, the evolution law of the vulnerability index of the structure at a time ($t > t_R$) after rehabilitation becomes:

$$I_v^R(t) = I_{v0} + \Delta I_{v0}^R e^{0.231(t - t_R)} \tag{4}$$

With:

$$\Delta I_{v0}^R = I_v^R(t_R) - I_{v0} \tag{5}$$

$I_v^R(t_R)$ Denotes the vulnerability index of the structure after rehabilitation at age t_R.

After this first rehabilitation action, the red vulnerability level is reached at the age of 151 instead of 114 years, which corresponds to a lifespan gain of 37 years. If a second rehabilitation action was to be carried out at the age of t_{R2} = 105 years, corresponding to the boundary of the orange 2 domain, the vulnerability index of the structure would decrease from 87 to 76, and the red vulnerability level would be reached at the age of 174 years, representing a second lifespan gain of 23 years. With these two rehabilitation actions, the tank will gain a lifespan of 60 years (Figure 6).

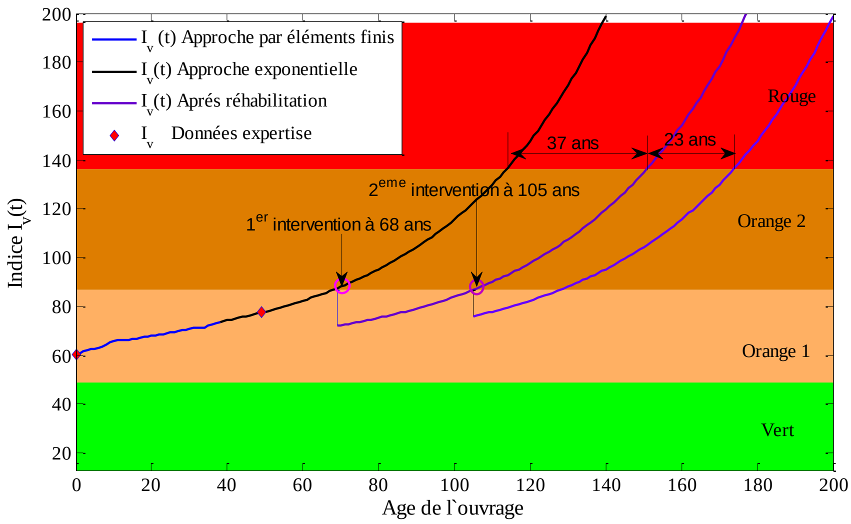

Figure 5. Evaluation of the index I_V after the rehabilitation action

Conclusion

In this research, a model for the vulnerability evolution of ageing concrete tanks, incorporating the concept of rehabilitation is proposed. The developed relationships allow for a simplified and rapid assessment of vulnerability related to the ageing of tanks at any point in their life cycle. For managers, this model provides insight into the lifespan that a structure can gain after a rehabilitation action, facilitating the establishment of a priority intervention plan within their rehabilitation or repair program, thus optimizing the management of the infrastructure stock and allowing for proactive planning of financial investments, particularly in the case of significant budget constraints. Furthermore, for engineers in design offices, these relationships can be used from the design phase of the structure, enabling the simulation of the vulnerability index during its operation and predicting the frequency of monitoring.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

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