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Temporal analysis of the performance of a RC storage tank considering the corrosion

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Abstract

The reinforced concrete (RC) water storage tanks are hydraulic structures that occupy a special place among civil engineering structures. Under the effect of hydrostatic and hydrodynamic loads, their walls undergo horizontal tensile stresses which are absorbed by horizontal reinforcements. Moreover, these structures are subjected to high aggressive atmospheric conditions that expose their walls to a risk of harmful corrosion. This dangerous phenomenon leads to the reduction of their steel reinforcement sections and consequently to the loss of their resistance and function. In this paper, we are interested in the performance analysis of RC storage tanks, taking into account the phenomenon of corrosion of strained reinforcements, considering the environments of different aggressiveness rates. Westergaard method is applied to evaluate the hydrodynamic pressure on the wall. A corrosion model is performed in order to determine the evolution in time of the reinforcement section for different environments considered. Several parameters influencing the corrosion are considered, such as the concrete cover of steel reinforcement and the concentration of chlorides ions.

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Keywords: Concrete tank, westergaard method, performance, corrosion, concrete cover, steel reinforcement;

1. Introduction

The corrosion of the steel reinforcements in concrete is one of the main pathologies of civil engineering structures. This corrosion causes a loss of section of these reinforcements which can lead to its fragile rupture and an alteration of the bearing capacity of the structure. The corrosion of the steel reinforcements can be presented in two

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forms: the uniform corrosion mainly due to the carbonation of the concrete cover by the carbon dioxide (CO_2) from the atmosphere and the pitting corrosion induced by penetration of chlorides ions (Duprat, 2006). In the service life of a RC structure, two phases can be distinguished for corrosion: an initiation phase, corresponding to the time required for the aggressive agents to penetrate into the concrete and attack the steel reinforcements and a propagation phase (Stewart et al, 1998). The Tutti diagram summarizes the two phases of the corrosion mechanism (Tutti, 1996). To predict the service life of the structures, it is necessary to evaluate the initiation phase of the corrosion. In addition, the current of corrosion is an important parameter for modeling the reinforcement’s corrosion of a structure. Several models are proposed in the literature for its determination; we can cite some empirical models, namely Duracrete (1998), Liu and Weyer (1998), Vu and Stewart (2000) and Otieno et al. (2012).

In this paper, we are interested in the performance analysis of the wall of RC water storage tank, under the seismic effect and taking into account the steel reinforcements corrosion effect by chlorides ions penetration (pitting corrosion). The initiation time is defined by the relation of Duracrete (2000). The current of corrosion is expressed by Liu and Weyers (1998) model taking into account several parameters; such as the concrete cover and the concentration of the chlorides ions at steel reinforcement’s surface, determined according to the aggressiveness of the environment. The steel reinforcement section after corrosion is determined as a function of time by Duprat (2006) relationship.

Finally, to illustrate the presented approach, a practical application will be conducted by considering the environments of different aggressiveness.

2. Deterministic model of the tank wall calculation

The wall of a concrete storage tank is subjected to the effect of hydrostatic loads and hydrodynamic loads under the seismic excitation. The hydrostatic pressure is given by the relation (1):

$$P=\omega.Z \tag{1}$$

ω is the water density and Z the depth considered from the free surface of water (Fig.1).

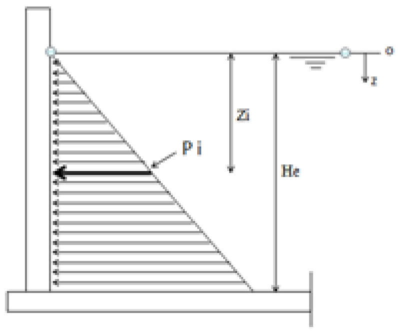


Fig.1. Hydrostatic pressures.

To evaluate the hydrodynamic pressures, we adopt the method formulated by Westergaard (1933) for an incompressible fluid and rigid structure (Fig.2). This method proposes a relationship that takes into account both the water depth in the tank (He) and the seismic acceleration (am), as follows:

$$P'=C_e.\frac{a_m}{g}.\omega.\sqrt{H_e.Z} \tag{2}$$

C_e is the Westergaard coefficient, g the gravity acceleration. The seismic acceleration is given by the Algerian seismic code (RPA 2003)

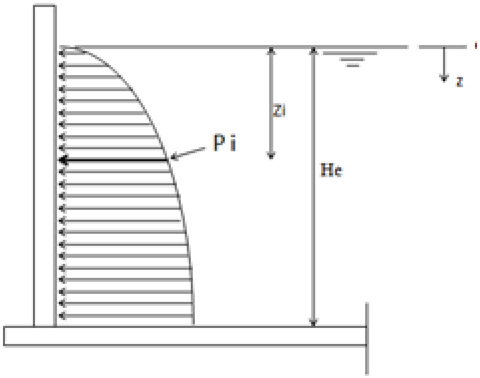


Fig. 2. Hydrodynamic pressures

These hydrostatics and hydrodynamics loads induce horizontal tensile stresses that are absorbed by the steel reinforcements of the tank wall. These reinforcements are determined according to RC limit state code (BAEL, 91) and Fascicle 74.

3. Mechanical model of the steel reinforcement corrosion

To introduce the effect of the steel reinforcement's corrosion by pitting, we proceed to the calculation of residual section with time, as follows:

$$A_s(t)=n_b.A_r(t) \tag{3}$$

Where $A_r(t)$ is the residual section of a reinforcement bar after an effective corrosion period of (t) years, it is given by Duprat (2006) according to initial diameter do of the steel reinforcement bar, and the depth of the pitting noted p(t) (Fig.3). n_b designates the number of reinforcement bar in a wall band of 1m of length.

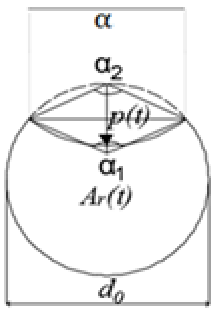


Fig. 3. Residual section of a reinforcement bar after corrosion (Duprat, 2006).

The maximum depth of the pitting p(t), due to the penetration of chlorides ions at time t, is determined by the following equation (Aoues, 2011):

$$p(t) = 0.0116\alpha \int_{t_{ini}}^{t} i_{corr} dt \tag{4}$$

α is the pitting factor taking into account non-unifom corrosion of the rebars (uA/cm2).

To express the corrosion current icorr, we adopted the Liu and Weyers (1998) model given as follows:

$$i_{corr} = \frac{1}{1.08} \exp\left[8.37 + 0.618 \ln(1.69 C_s) - \frac{3034}{T} - 0.000105 R_{be} + \frac{2.32}{t_{ini}^{0.215}}\right] \tag{5}$$

This model takes into account the concentration of chlorides ions Cs at the surface of the steel reinforcements, the ambient temperature T, the resistivity of the concrete R_{be} and the initiation time at corrosion tini which is expressed as follows (Duracrete, 2000):

$$t_{ini} = \left(\left(\frac{c^2}{4k_e.k_t.k_c.D_0.(t_0)^n}\right)[\mathrm{erf}^{-1}(1 - \frac{C_{cr}}{C_s})]^{-2}\right)^{\frac{1}{1-n}} \tag{6}$$

erf (.) is the error function, D_0 the diffusion coefficient (m²/s), C_{cr} the critical concentration of chlorides ions, k_e the environmental factor, k_t factor used to determine D_0, k_c the factor taking into account the cure time, to the time (days) for which D_0 was measured and n the aging factor.

4. Practical application

To illustrate the deterministic calculation at corrosion of the tank wall, presented above, we consider a circular storage tank made of RC and placed on the ground (Fig. 4), located in a high seismicity zone (Algeria). The geometric characteristics of the tank are given in Table 1.

Fig.4. General view of the RC storage tank.

For the calculation of the hydrostatic and hydrodynamic pressures, the water height (He) is subdivided into five bands of 1 m. The results of the hydrostatic linear loads Q and hydrodynamic linear loads Fa obtained, for each band, are presented in Table. 2

Table 1. Geometric characteristics of the tank

Parameters	**Values**	**Units**
Tank capacity	500	m^3
Total height of the tank	6,15	m
Maximum water height	5,00	m
Water density	1000	Kg/m^3
Wall Thickness	0.12	m
Internal diameter of the tank	11,00	m

Table 2 . Value of linear loads acting on the wall.

Band number	**Z (m)**	**P (kg/m^2)**	**Q (kg/ml)**	**P'(kg/m^2)**	**F_a (kg/ml)**
I	5,00	5 000,00	5 000,00	1 640,63	1 640,63
II	4,00	4 000,00	4 000,00	1 467,42	1 467,42
III	3,00	3 000,00	3 000,00	1 270,82	1 270,82
IV	2,00	2 000,00	2 000,00	1 037,62	1 037,62
V	1,00	1 000,00	1 000,00	733,71	733,71

Four load combinations are considered for the determination of tensile forces in the tank wall, according to the Fascicule 74, which are:

- Fundamental ultimate limit state combination # 1 : 1.5Q
- Fundamental ultimate limit state combination # 2 : 1.3Q
- Accidental ultimate limit state combination # 3 : $Q+F_a$
- Serviceability limit state combination # 4: Q

The tensile forces calculated at each band are given in Table 3.

Table 3. Values of the tensile forces Ti under the combinations of actions.

Band number	**T_1 (kg)**	**T_2 (kg)**	**T_3 (kg)**	**T_4 (kg)**
I	41 250,00	35 750,00	36 523,44	27 500,00
II	33 000,00	28 600,00	30 070,81	22 000,00
III	24 750,00	21 450,00	23 489,52	16 500,00
IV	16 500,00	14 300,00	16 706,92	11 000,00
V	8 250,00	7 150,00	9 535,40	5 500,00

The reinforcement sections for the different load combinations, as well as the minimum section of non-fragility condition (BAEL, 91), are presented in Table 4. It should be noted that the most important reinforcement sections is obtained for combination # 4, not the combination # 3. Whatever the seismic zone, the reinforcement adopted remains valid, which leads us to rule out the influence of this parameter on the performance of the tank wall.

Table 4. Values of reinforcement sections under different load combinations

Band number	**A_1(cm²)**	**A_2(cm²)**	**A_3(cm²)**	**A_4(cm²)**	**A_{min}(cm²) (CNF)**	**A_{nec}(cm²)**	**A(cm²) adopted**
I	11,86	10,28	9,13	17,05	6,30	17,05	18,47
II	9,49	8,22	7,52	13,64	6,30	13,64	15,83
III	7,12	6,17	5,87	10,23	6,30	10,23	13,57
IV	4,74	4,11	4,18	6,82	6,30	6,82	11,31
V	2,37	2,06	2,38	3,41	6,30	6,30	11,31

4.1. Influence of corrosion on the reinforcement section

To study the effect of corrosion on steel reinforcement, we considered an atmospheric zone and four environments with different rates of aggressiveness. The values of the chlorides ions concentration (C_s), corresponding to each environment, are given in Table 5. The used values of concrete cover (c) are those fixed by Fascicule 74, considering an ambient temperature of 25 °C. The data used for the corrosion model are summarized in Table 6.

Table 5. Average values of the parameters (C_s and c) depending on the environment (McGee, 1999)

Environment	Description	C_s (kg/m^3)	c (mm)
1	Environment of low aggressiveness : structure located at 3 km or more from the coast	0.35	30
2	Environment of moderate aggressiveness: structure located between 0.1 km and 3 km from the coast without direct contact with sea water.	1.15	40
3	Environment of high aggressiveness: structure located less than 100 m from the coast without direct contact with sea water.	2.95	50
4	Environment of extreme aggressiveness: structure subject to cycles of humidification and drying by sea water.	7.35	60

The results of initiation time for pitting corrosion, calculated for the various considered environments, are shown in Table 7. We notice that the corrosion of the steel reinforcements is rapidly initiated in environments of high and extreme aggressiveness, but very slowly initiated in the environment of moderate and low aggressiveness.

The evolution as function of time of the residual sections $A_s(t)$ of the steel reinforcement after corrosion, for the environments of the different aggressiveness considered is illustrated in Figure 5.

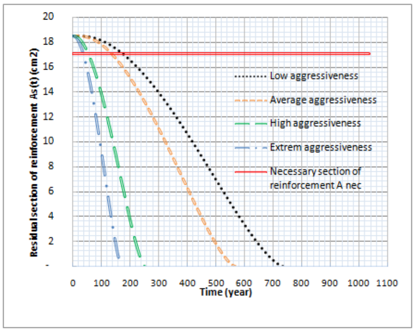
Table 6. The used parameters in corrosion model

Variable	Units	Values	Reference
Ambient temperature T	K	25+273	Liu et Weyers, 1998
Resistivity of the concrete cover R_{be}	Ohm	1500	Liu et Weyers, 1998
Diffusion coefficient D_0	m^2/s	3·10-11	Bastidas et al, 2015
Coefficient α	-	5.65	Aoues et al, 2011
Critical concentration of chlorides (ordinary concrete) C_{cr}	Kg/m^3	0.5	Aoues et al, 2011
Factor k_e (atmospheric environment, cement OPC)	-	0.676	Aoues et al, 2011
Aging factor n (atmospheric environment, cement OPC)	-	0.65	Duracrete, 1998
Test type factor k_t	-	0,8	Duracrete, 1998
Factor k_c (28 days)	-	4.445	Duracrete, 1998
Cure time t_0	days	28	Duracrete 1998

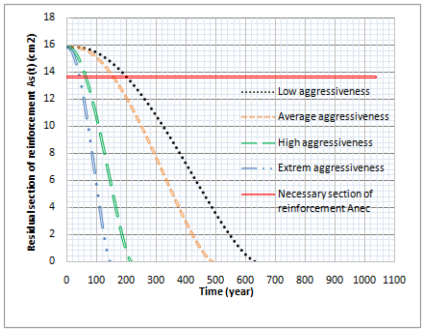
Table 7. Corrosion initiation time values at each environment.

Environment aggressiveness	t_{ini} (years)
Environment of low aggressiveness	30
Environment of moderate aggressiveness	24
Environment of high aggressiveness	3
Environment of extreme aggressiveness	2

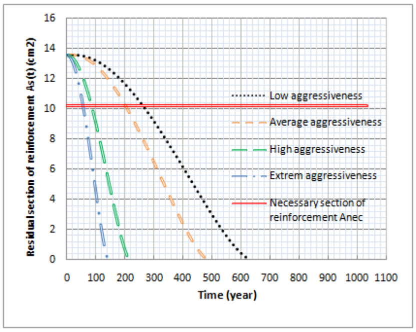
Through the illustrated results, we notice that the initiation phase in the environment of high and extreme aggressiveness is insignificant and the propagation phase begins immediately, so the concentration of chlorides ions at the surface of the steel reinforcements has reached the critical threshold of chlorides ions concentration rapidly. In contrast, in the environment of an medium and low aggressiveness, the initiation phase is elongated and the phase of propagation of the corrosion is delayed. Moreover, by superimposing the variation of the residual section with the necessary section called A_{nec} (Table 7), we notice that the critical threshold of corrosion (the residual section is below the necessary section) is reached around 50 years in environments of high and extreme aggressiveness for band 1. For environments with medium and low aggressiveness, the critical value is reached well beyond 100 years. This explains that the tank, which is the subject of our study, is not adapted to environmental conditions of high and extreme aggressiveness, since the service life of a civil engineering structure is greater than 50 years (Dimitri, 2003). To better control the durability of the tank wall, we propose to study the influence of some parameters on the initiation time at the corrosion of its steel reinforcements, namely the concrete cover c and the concentration of chlorides ions Cs.



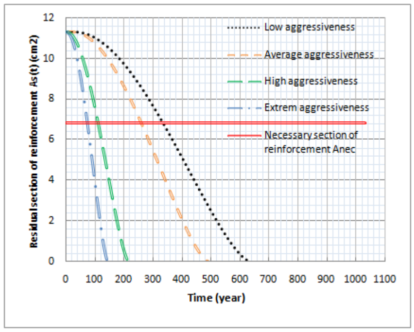
Bande I



Bande II



Bande III



Bande IV

Fig. 5. Evolution of the reinforcement residual section as function of time, after corrosion.

4.2. Influence of the concentration of the chlorides ions and the concrete cover

The evolution of the initiation time according to the concrete cover is illustrated in Figure 6, for different chlorides ions concentrations. We notice that the initiation time increases with the increase of the concrete cover and this increase is more rapid in the environment of medium and low aggressiveness. This explains clearly that the concrete cover has a disabling effect on the ability of chloride ions to diffuse into the concrete but not enough in environment of high aggressiveness. Furthermore, for a given concrete cover, it is clear that the initiation time decreases when the distance between the tank and the sea decrease and consequently the initiation at corrosion increases. We also note that by increasing the value of the concrete cover, we can extend this time initiation and therefore the service life of the tank, but not at same way for the different environments. Of course, the values of the concrete cover and the chlorides ions concentration shown in Figure 6 are average values. So, it would be interesting to integrate the variability of these parameters in our research.

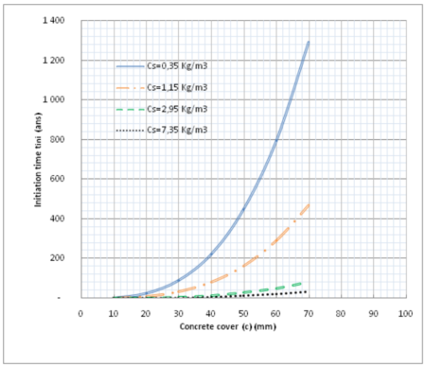


Fig. 6. Influence of the concentration of the chloride ions and the concrete cover on the initiation time to corrosion.

5. Conclusion

The deterministic corrosion analysis of the RC storage tank wall was conducted, in this research, considering an atmospheric environment with different aggressiveness (from the weakest to the extreme) and for different concrete cover thickness, defined in Fascicule 74. The calculation of the residual section of steel reinforcement with time, after corrosion, has shown that this section decreases and quickly reaches the critical threshold at the environment of high and extreme aggressiveness. Of course, this affects the service life of the tank wall, which is reduced by more than half from low aggressiveness environment to high aggressiveness environment, despite that the concrete cover being important. This explains that the tank, subject of this study, is not suitable for these aggressiveness environmental conditions in accordance with recommendations relating to civil engineering structures. For this, the consideration of the environmental criterion when designing RC tanks imposes. The analysis of the corrosion according to some parameters influencing the initiation time, such as the concrete cover and the concentration of the chlorides ions has shown that the service life of the tank can be lengthened by providing a large concrete cover, but this is not sufficient in the environment of high aggressiveness. Finally, it is recommended to include the environmental criteria with their variabilities in design codes as sources of aggression in definition of the exposure classes, in order to design more sustainable structures in aggressive environments.

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