Reliability Analysis of Water Seepage in Reinforced Concrete Water Tanks with Cracked and Non-Cracked Concrete Using Monte Carlo Simulation

Melika Feyzi, Afshin Firouzi, and Cyrus Mohammadzadeh
Department of Construction Engineering and Management, Islamic Azad University, Tehran, Iran
Email: feyzi.melika@gmail.com, firouzi@srbiau.ac.ir, c_mohammadzadeh@yahoo.com

***Abstract*—Seepage through water tank walls is one of the most important phenomena can get the operation into trouble. This paper introduces water seepage through cracked and non-cracked segments by corresponding theories for operation limit states and models governing parameters' uncertainties with random numbers. The probability of failure and reliability index of tank segment cracked concrete has calculated by Monte Carlo simulation. It is essential to have crack width extension model to estimate operation lifetime in tanks due to the crack width that often expands over time. Also, the probability of leakage starting during operation lifetime is calculated for non-cracked segments and sections which should be watertightness. In this type of structures, reliability analysis method presented in this paper can be used in designing of minimum width required and determination of concrete mix design properties and permeability by definition acceptable risk in structure lifetime.**

***Index Terms*— reliability analysis, water seepage, cracked concrete, non-cracked concrete, RC water tanks**

I. Introduction

Water scarcity is one of the most significant problems faced by many countries and the world in the 21st century [1]. The lack of water is an increasingly serious problem [2], [3]. In civil engineering, RC water retaining tanks are hydraulic structures and play an important role among the constructions [4]. For this reason, water retaining structures and their effectiveness of saving water, and problems such as cracking and seepage investigations are the attention of many researchers and owners of these assets. This paper focuses on RC water retaining tanks. Today, these structures are maintained by using systematic approaches. Most of the failures can be predicted and prevented by deterioration models. Experiences and records show cracks with constant width through some tank sections and cracks with reducing width in some other segments due to self-healing [5]. But in the most of the cases crack width increase by the time [6] so identifying the risk of tank damaged by water seepage is needed to extend the useful lifetime of the tank. Some tanks due to the nature of their use must be watertight. Therefore, the probability of the first occurrence of leaks in these structures is of particular importance to watertight structure concrete. On the other hand, since most of the variables used to model the water seepage are probabilistic and have uncertainties, developing probabilistic models as water seepage risk need structural reliability analysis methods. In this regard, Chung Xing Qian et al (2012) presented water seepage amount model for cracked and non-cracked concrete independent of the time [7].

It has been shown by Jiro Murata (2004), in a cracked concrete, seepage flow varies by the pressure [8]. In this case, Carola Edvardson (1999) explained decreasing water seepage model over time due to the self-healing in a cracked concrete [5]. Literature review shows laboratory result-based studies on the water seepage in tanks in which haven't done the probabilistic analysis of reliability. Therefore, in the beginning, the reliability theory explained to calculate reliability and risk of failure in tank structure. Hence failure mechanism of cracked tank segment is described in this paper. Afterward, uncertainties of water seepage model in a cracked concrete are modeled and the probability of failure corresponding to reference functions is determined over time [7]. Governing water flow equations in non-cracked concrete are used in the rest of this paper and probability of the first occurrence of seepage in non-cracked segments are calculated by the time [8].

II. Reliability Analysis

Limit state function of tank water seepage can be defined as two parameters: allowable amount of the water seepage and water seepage rate is followed [9]:

$$G(SP_{\lim},Q,t)=SP_{\lim}(t)-Q(t) \quad (1)$$

Where $G(SP_{\lim},Q,t)$ is the time-dependent limit state function. Each of the two functions in above

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equation, $SP_{\lim}(t)$ (allowable limit of time-dependent water seepage) and Q (time-dependent water seepage rate) are composed and influenced by several random variables following different probability distribution functions depending on the segment materials and loadings. Failure modes and corresponding probability $(G \le 0)$ are defined as follows [10]:

$$p_f(t) = p_r(G \le 0) = \iint_{G \le 0} f_{sp_{\lim},Q}(s,q)dsdq \quad (2)$$

Where $f_{sp_{\lim},Q}$ is the joint probability distribution function of two random variables $SP_{\lim}(t)$ and Q. Also, q is water seepage rate and s is the allowable limit of water seepage considering deterministic. the time-dependent probability of failure $p_f(t)$ is determined by calculating integral of (2). Meanwhile, in accordance with the definition, reliability index can be calculated by (3) [11].

$$\beta = -\Phi^{-1}(p_f(t)) \quad (3)$$

Where β is reliability index and Φ^{-1} is the inverse function of the Standard normal probability distribution. Analytical solution of linear and nonlinear limit state functions is possible using approximate reliability or numerical methods. It should be noted that the use of approximate methods, if random variables are following non-normal distribution or limit state functions are non-linear, answers with varying degrees of approximation will be obtained e.g., limit state function estimated with a linear equation each step being in the first order method of reliability (FORM[1]) by Taylor series expansion and first order terms. Calculations errors depend on the nonlinearity of the function and non-normality of the random variables. Monte Carlo simulation determines the amount of linear and nonlinear limit states functions as one of the numerical methods according to the production values of the variables by probability density functions. Since this method needs adequate iteration of simulation, the chief objection to it is the calculation of problems having a lot of random variables, especially when each simulation iteration is along with non-linear equations solutions. As there are a few random variables following normal distribution in the ongoing problem, Monte Carlo simulation with sufficient iterations is proper to solve above limit state function [9].

If an event is a result of two (or more) continuous random variables like x_2, x_1, probability of happening the event for known values of x_2, x_1 is explained by joint cumulative distribution function as follows [9]:

$$F_{X_1,X_2}(x_1,x_2) = P[(X_1 \le x_1) \cap (X_2 \le x_2)] = \int_{-\infty}^{x_1}\int_{\infty}^{x_2} f_{X_1X_2}(u,v)dudv \quad (4)$$

[1] First Order Reliability Method

Where $F_{X_1X_2}(x_1,x_2) \ge 0$ is Joint probability density function. Obviously if partial derivatives are exist [9]:

$$f_{X_1,X_2}(x_1,x_2) = \lim\left\{P\begin{bmatrix}(x_1 < X_1 \le x_1+\delta x_1)\cap \\ (x_2 < X_2 \le x_2+\delta x_2)\end{bmatrix}\right\} = \frac{\partial^2 F_{X_1X_2}(x_1,x_2)}{\partial x_1 \partial x_2} \quad (5)$$

And the correlation function (covariance) of these two variables is [11]:

$$\operatorname{cov}(X_1,X_2) = E[(X_1-\mu_{X_1})(X_2-\mu_{X2})] = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}(x_1-\mu_{X_1})(x_2-\mu_{X2})f_{X_1,X_2}(x_1,x_2)dx_1dx_2 \quad (6)$$

While there are more than two random variables, joint probability density function of these random variables is defined as followed by definition of correlation matrix Σ and mean vector μ for random variables which are all normal [9].

$$f(x) = \frac{1}{(2\pi)^{p/2}|\Sigma|^{1/2}}\exp\left\{-\frac{1}{2}(x-\mu)^T\Sigma^{-1}(X-\mu)\right\} \quad (7)$$

Reverse transfer technique is used to produce random variables in Monte Carlo method, if $F_{X_i}(x_i)$ is in range of $(0,1)$, reverse transfer technique acts by producing a random number following a uniform distribution r_i $(0 \le r_i \le 1)$ and equalizing to $F_{X_i}(x_i)$ [9].

$$F_{X_i}(x_i) = r_i \Rightarrow x_i = F_{x_i}^{-1}(r_i) \quad (8)$$

Monte Carlo simulation is performed based iteration. In each iteration of the simulation by replacing any of the values of random variables in the equation of limit state, occurrence of failure mode corresponded to calculation of value lower than zero for considered limit state function can be calculated in each iteration of simulation as follows [9]:

$$p_f(t) = j(t) = \int\ldots\int I[G(x,t) \le 0]f_X(x)dx \quad (9)$$

Where $I[\ ]$ is an indicator function equal to 1 If $[\ ]$ is correct and equal to 0 if $[\ ]$ is false. Here indicator roles recognition of the integral domain. If x_j defined as j^{th} vector of random observations taken from $fx(\ )$ then, using the sample survey topic directly concluded [9]:

$$p_f(t) \approx j_1(t) = \frac{1}{N}\sum_{j=1}^{N} I[G(x_j \le 0)] \quad (10)$$

Where N is the total number of simulation iterations and $G(x_j, t)$ is the amount of considered limit function in j^{th} iteration and time t. As the number of simulations required for a certain level of confidence is important, the first estimation of N for a given confidence level C and probability of failure P_f is determined as follows [9]:

$$N > \frac{-\ln(1-C)}{P_f} \tag{11}$$

Cracked and non-cracked concrete seepage mechanisms are provided respectively as follows.

III. Water Seepage Model in Tank Cracked Concrete

Tanks concrete structures exposed all kind of damages during their lifetime (Mechanical, thermal, chemical). Usually, most of these damages and operating losses are not enough to cause total destruction of concrete and create safety problems in structures. However, by time passing, erosion gathers and makes micro cracks and finally causes permeability changes. The model which used for analysis of initial water flow through cracks in water tank concrete (the flow before self-healing) has derived from parallel plates [7]. This model expresses the situation which an incompressible fluid between parallel plates with laminar flow is developed. The equation to estimate water flow through a concrete crack (straight and smooth cracks) is called cube law as follows [7]:

$$q = \frac{w^3 * 10^{-6} * L * \rho * g}{12 * \mu * \tau * m} * I \tag{12}$$

Where w is the crack width (mm), L is the visible crack length on structure surface (m), ρ is the water density (kg/m^3), g is the acceleration of gravity (m/s^2), τ is the crack curvature, m is the crack toughness, μ is the water viscosity ($kg/m.s$), q is the water flow through real cracks (lit/sec), I is the hydraulic gradient (m/m).

It should be noted that main properties of differences between real cracks and smooth cracks are the more curvature and toughness for real ones. So to change and edit the cube law, two parameters of curvature of crack (τ) and toughness of crack (m) are put into the equation, as shown in (12) [7].

IV. Crack Width Model in Tank Cracked Concrete and Damage Caused by It

When a crack in the concrete is created, its width is low in the early years, however, increases by the time, under the influence of external factors such as corrosion and other environmental factors and loading.

Crack width increasing by the time in structures which crack conformed Fig. 1 [6]. Hence a Logarithmic equation is fitted to this process according to (13) in this study.

$$w(t) = w_0 + \alpha * \ln(t) \tag{13}$$

These parameters values are determined by fitting available data of Fig. 1 to (13) which is presented per (14). It should be mentioned that (14) is used in Monte Carlo simulation and determining the probability of failure by (16) in this study. Nevertheless, sensitivity analysis have done on parameter $\propto$ per (13) and results have shown in Fig. 2.

$$w(t) = 0.01 + 0.2 * \ln(t) \tag{14}$$

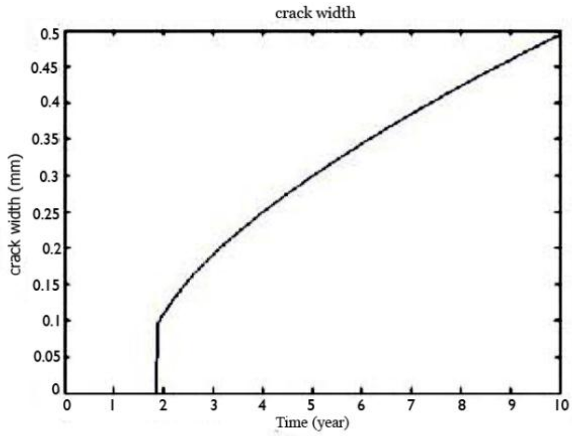

Figure 1. Diagram of crack width increasing over time.

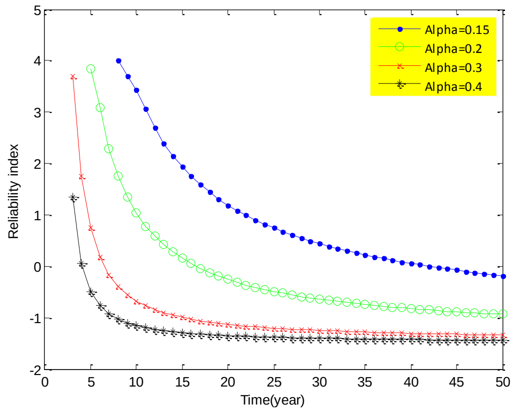

Figure 2. Diagrams of reliability index of water seepage model with different values of $\propto$ in cracked concrete.Non-Cracked Concrete in Tanks

When pressurized seepage flow begins to cross the section of the concrete member, the water seepage model in non-cracked concrete is applied. It is assumed that the section has no crack so it is watertight. Jiru Murata et al. (2004) showed in practical and theoretical when the water pressure is equal or lower than 0.15 MPa, seepage flow follows Darcy flow and when is more than 0.15 MPa seepage flow is the combination of diffusive and Darcy seepage flow [8].

A concrete member of tank under lower than 0.15 MPa water pressure is watertight when the follow relation is satisfied [8]:

$$(\gamma_i * \frac{d_{md}}{d}) \leq 1 \Rightarrow (\frac{\gamma_i}{d} * \sqrt{\frac{2 * \gamma_f * p_k * t_d * \gamma_c * \gamma_p * k}{\rho}}) \leq 1 \tag{15}$$

While the watertightness condition of concrete members of the tank under more than 0.15 MPa is as follows [8]:

$$(\gamma_i * \frac{D_{md} + d_{md}\,(p_d = 0.15mpa}{d}) \leq 1 \Rightarrow$$
$$(\frac{\gamma_i}{d} * (2 * \xi * \sqrt{\frac{t_d * \gamma_c * \gamma_p * \beta_0^2}{t_d^{\frac{3}{7}}}}) + \tag{16}$$
$$(\sqrt{\frac{2 * 0.15 * 10^6 * t_d * \gamma_c * \gamma_p * k}{\rho}})) \leq 1$$

Where γ_i is structure factor, d_{md} is design penetrate depth for Darcy seepage flow (m), D_{md} is design penetrate depth for diffusive seepage flow (m), p_d is design water pressure (Pa), t_d is design working life (s), ξ is a factor for water pressure, γ_f is the safety factor, p_k is the amount of water characteristic (Pa), γ_c concrete materials factor for watertighness for seepage factor, γ_p is safety factor, k is test value of seepage coefficient (m/s), β_0^2 test value of diffusion coefficient (m2/s).

V. Application of the Model in Reliability Analysis of the Amount of Water Seepage in A Tank Structure and Its Results Analysis

A cylindrical water tank with a radius of 18 meters, a height of 5 meters and a thickness of 0.5 meters is considered. The purpose is determining the probability of failure due to water seepage in the tank for a period of 50 years.

Limit state function of the amount of water seepage in cracked concrete in the tanks in the case of crack is expanding over time is presented per (17) by combining (12) and (14):

$$G_1(t) = SP_{\lim} - \frac{(0.01 + 0.2 * \ln(t))^3 * 10^{-6} * L * \rho * g}{12 * \mu * \tau * m} * I \tag{17}$$

Probability function of beginning occurrence of seepage in non-cracked concrete while water pressure in the tank is lower than 0.15 MPa is as follows considering (15) and (16):

$$G_{un \leq 0.15} = R - (\frac{\gamma_i}{d} * \sqrt{\frac{2 * \gamma_f * p_k * t_d * \gamma_c * \gamma_p * k}{\rho}}) \tag{18}$$

And for water pressure more than 0.15 MPa is:

$$G_{un \rangle 0.15} = R - (\frac{\gamma_i}{d} * (2 * \xi * \sqrt{\frac{t_d * \gamma_c * \gamma_p * \beta_0^2}{t_d^{\frac{3}{7}}}}) + \tag{19}$$
$$(\sqrt{\frac{2 * 0.15 * 10^6 * t_d * \gamma_c * \gamma_p * k}{\rho}}))$$

Mean and standard deviation values of random variables used in above models presented in Table I. It is noteworthy parameters $\gamma_f, p_k, k, \beta_0^2, \xi, w, L, m, \tau, I$ are random and have a normal joint function which their values are based on test data in Tables II to VII are estimated.

Obviously having more data and using statistical methods such as maximum likelihood estimates and then the goodness of fit test can fit a proper function to random variables.

The probability of failure and corresponding reliability index for limit state functions presented per (17) to (19) using (12) are estimated for tank structure lifetime.

TABLE I. Parameters Values of the Limit State Functions in Cracked and Non-Cracked Concrete

parameter	description	unit	value	mean	Standard deviation
d	Concrete structure thickness	m	0.6		
g	Acceleration of gravity	m/s^2	9.81		
I	Hydraulic gradient	m/m		1.781	1.176
k	test value of seepage coefficient	m/s		$5.37 \times 10^{(-12}$	$6.61 \times 10^{(-12}$
L	Crack length(visible crack length on structure surface)	m		1	0.20
m	Crack toughness	Dimension less		1.118	0.013
p_k	characteristic value of water pressure,	pa		$0.086 \times 10^{(6)}$	$0.046 \times 10^{(6)}$
R	Acceptable value	Dimension less	1		
$SP_{\lim}$	Water seepage acceptable value	lit/s	$1.15 \times 10^{(-7)}$		
w	Crack width	mm		0.282	0.0585
ρ	Water density for cracked concrete	kg/m^3	1000		
ρ	Water density for non-cracked concrete	N/m^3	$9.81 \times 10^{(3)}$		
μ	Viscosity of water	$kg/m.s$	0.001002		
τ	Tortuosity of crack	Dimension less		1.052	0.0192
γ_i	structure factor	Dimension less	1.1		
ξ	coefficient for water pressure	Dimension less		0.847	0.305
γ_f	safety factor	Dimension less		1.15	0.212
γ_c	material factor of	Dimension less	2-4		

	concrete for watertight ness				
γ_p	safety factor	Dimension less	1.30		
β_0^2	initial diffusion coefficient	m^2/s		$2.67 \times 10^{(-7)}$	$1.26 \times 10^{(-7)}$

CRACK WIDTH VALUES IN CRACKED CONCRETE

Random parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
$w\,(mm)$	0.24	0.30	0.21	0.36	0.30

TABLE II. HYDRAULIC GRADIENT VALUES

Random parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
I	0.25	0.5	1	1.5	2	2.5	3	3.5

TABLE III. TORTUOSITY AND TOUGHNESS OF CRACK COEFFICIENTS VALUES IN CRACKED CONCRETE

Random parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
τ	1.05	1.08	1.03	1.04	1.06
m	1.11	1.10	1.13	1.13	1.12

TABLE IV. CHARACTERISTIC VALUES OF WATER PRESSURE

Water pressure	Sampl e 1	Sampl e 2	Sampl e 3	Sampl e 4	Sampl e 5	Sampl e 6
$p_k\,(mpa)$	0.025	0.049	0.074	0.098	0.122	0.15

TABLE V. COEFFICIENT FOR DIFFERENT VALUES OF WATER PRESSURE

water pressure $p(mpa)$	0.35	0.50	1.00	1.50
ξ	0.477	0.733	1.018	1.163

TABLE VI. VALUES OF PERMEABILITY AND DIFFUSION COEFFICIENTS OF CONCRETE

concrete content kg/m^3	220	260	300	340
$k\,(m/s)$	$14.20 \times 10^{(-12)}$	$2.80 \times 10^{(-12)}$	$0.76 \times 10^{(-12)}$	$0.71 \times 10^{(-12)}$
$\beta_0^2(m^2/s)$	$43.3 \times 10^{(-8)}$	$29.30 \times 10^{(-8)}$	$19.10 \times 10^{(-8)}$	$15 \times 10^{(-8)}$

VI. SENSITIVITY ANALYSIS OF RESULTS AND DISCUSSION

Analysis results of tank concrete structure studies based on Monte Carlo method with 100,000 simulation iterations against water seepage are as follows:

At first, the crack width increases with time according to (14) as was assumed. Assuming different values of α from (13), the sensitivity analysis performed on results are shown in Fig. 2. Determining values of α plays a significant role in the accurate estimation of the probability of failure and reliability of tank structures against water seepage during its lifetime. Given the importance of seepage in tanks and results of this analysis, the issue needs further investigation based on modeling and testing methods.

In the design of new structures, regulations calibrate the capacity reduction factor and the environmental effects increase of loads by determining the range of the target reliability indices for each user group of structure and its failure modes based on safety, economic, and social considerations. It is evident that the final reliability index is always greater than the operation reliability index [12].

As is clear, reliability index for the operation mode is not a large value, the index is a technical and economical variable often considered by the employer based on available funds and compliance with legal requirements and safety regulations. Therefore, considering a large value for the target reliability index means the frequency of inspections and repairs increases and thus more funding is needed. So in this paper, the reliability index of zero equals to the assumed probability of failure of 50%. In Fig. 3 the effect of increasing the width of cracks over time is displayed over the reliability indices. According to this figure, it is supposed that crack width increases under four modes.

In the event that target reliability index is assumed to be equal to zero, if $\alpha = 0.15$ in the 41st year, if $\alpha = 0.20$ in the 16th year, if $\alpha = 0.30$ in the 7th year and if $\alpha = 0.40$ in the 5th year, the seepage is more than 50%.

It should be mentioned that in the event that target reliability analysis is assumed to be equal to 1.5, if $\alpha = 0.15$ in the 18th year, if $\alpha = 0.20$ in the 9th year, if $\alpha = 0.30$ in the 5th year and if $\alpha = 0.40$ in the 3rd year it would happen. Accordingly, the failure is more likely to appear between the 16th to the 20th year. So on this basis, it is possible to determine the right time for inspection and repair, and it is very necessary for preventive maintenance. If the absence of cracks is assumed, in accordance with Fig. 3, it is shown the condition that the water pressure inside the tank is less than 0.15 MPa, the probability of starting the seepage is negligible until the 3rd year of the operation and after that, this probability Raises up to 10% in the 11th year and in the following it reaches to more than 50% in the 50th year. If the water pressure in the tank is more than 0.15 MPa, seepage starts from the first year with the probability of 7% and reaches to 93% at the end of the 50th year. This occurs for very high tanks.

Tank Probability of failure depends on the hydraulic gradient in cracked concrete. According to the Fig. 4 failure occurs earlier due to increasing of hydraulic gradient and seepage. If $I=1.78$ in the 40th year and, if $I=5.34$ in the 13th year, the tank comes to 50% of its failure which is equal to $\beta=0$. The probability of failure and reliability index of the non-cracked segment of the tank are shown in Fig. 5 and Fig. 6. In these figures tank is sensitivity analysis under different thicknesses of walls and permeability coefficients. As is shown in figures, failure occurs later by increasing walls thickness (d) and decreasing permeability coefficient (k).

According to above analysis results, in these tanks, even if assuming no concrete cracking, the water seepage probability is very high. If the watertightness of the tank is one of the operating requirements, it is necessary to use the appropriate materials, design appropriate thickness and dimensions of concrete segments of the tank to increased watertightness lifetime. It should be noted that in all above models, it is assumed that the random variables have normal distribution functions. Obviously, the change in distribution, mean and standard deviation of each variable leading to change in the results of reliability corresponding to the above models. In civil engineering projects, these parameters can be set and reviewed by designing and implementing proper local experiments and laboratory tests.

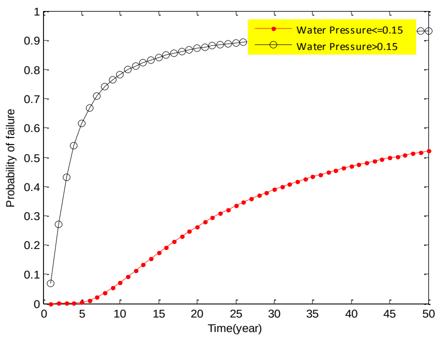

Figure 3. Diagram of structure probability of failure in non-cracked concrete.

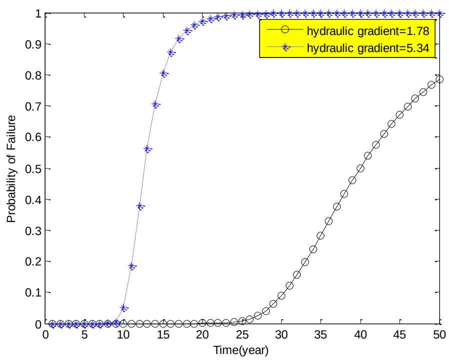

Figure 4. Effect of hydraulic gradients on probability of failure in cracked concrete.

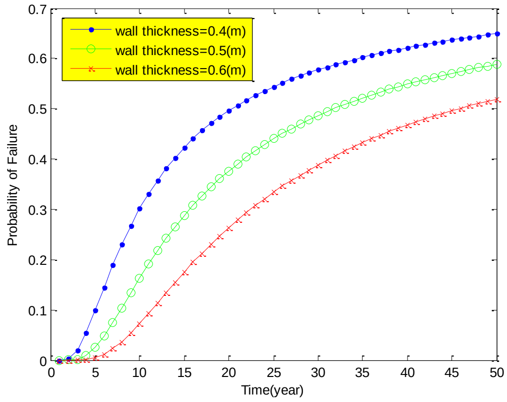

Figure 5. Effect of wall thickness on probability of failure in non-cracked concrete.

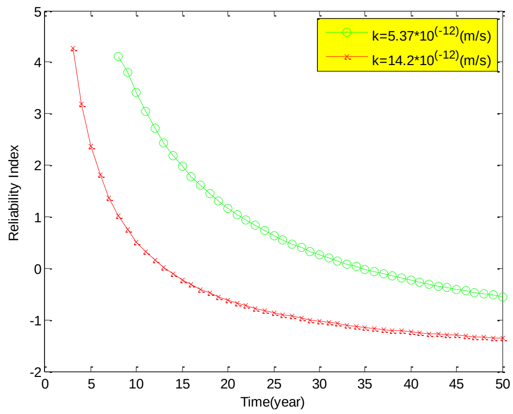

Figure 6. Effect of permeability coefficient on reliability index in non-cracked concrete.

VII. Conclusion

Water seepage in concrete structures, especially in the tanks is a remarkable issue in the operation. In this article, in addition to providing a review of existing theories about water seepage in the cracked and non-cracked concrete, this problem is modeled as a structural reliability analysis problem and limit state functions are introduced due to existing uncertainties in the most of the available parameters and estimates the probability of the tank water seepage. In the cracked state, it is supposed that cracks increase over time, and the probability of failure during 50 years of operation of the tank is calculated using Monte Carlo simulation assuming certain thresholds and acceptable seepage.

Sensitivity analysis of the crack width model showed that reliability indices in the tanks affected by seepage are usually more than target reliability index is considered to be equal to zero between the 16th and 20th years. Therefore, regular inspection and maintenance plan must be adopted. It is worth noting that in important structures it is needed to be sure of watertightness of the tank structure, and the more testing is needed for the accuracy of this model. Also, about structures of the very high tanks, despite presuming the absence of cracks, the probability of seepage in concrete is great due to the high pressure of water. Also wall thickness and permeability coefficient of the tank are significant parameters in non-cracked segments. In these structures, reliability analysis method provided in this paper can be applied to design the thickness of concrete and, the mix design specifications can be determined by definition the considered risk.

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Afshin Firouzi is an assistant professor at Science and Research Branch of Islamic Azad University, Tehran, Iran. He obtained his BSc in Civil Engineering from Sharif University of Technology, both his MSc and Ph.D. in Construction Engineering and Management from Amirkabir University of Technology, Tehran, Iran. He further pursued his research on Structure Reliability Analysis at RMIT Melbourne, Australia, from 2013 to 2016. His research results have been published in prestigious journals such as Engineering Mechanics ASCE.

Melika Feyzi was born in 1991 and lives in Tehran, Iran. She has a BSc. degree in civil engineering from Shahid Beheshti University, Tehran, and currently pursues her interests as MSc. student at Department of Construction Engineering and Management in Science and Research Branch of Islamic Azad University, Tehran, Iran.

Cyrus Mohammadzadeh was born in 1982 and lives in Tehran, Iran. He graduated in MSc. from Department of Construction Engineering and Management in Science and Research Branch of Islamic Azad University, Tehran, Iran. He has been working in Tehran Urban and Suburban Railway Operation Co. for more than twelve years.