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

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Abstract—Seepage through water tank walls is one of the most important phenomena that 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]:

\[
G(S_{\lim} Q, t) = S_{\lim}(t) - Q(t)
\]  

(1)

Where \(G(S_{\lim} Q, t)\) is the time-dependent limit state function. Each of the two functions in above
The joint probability distribution \( F_{X_1,X_2}(x_1,x_2) \) is the probability that \( X_1 \leq x_1 \) and \( X_2 \leq x_2 \). It can be expressed as a function of joint cumulative distribution function \( F(x_1,x_2) \) as follows [9]:

\[
F_{X_1,X_2}(x_1,x_2) = \int_{-\infty}^{x_2} \int_{-\infty}^{x_1} f_{X_1,X_2}(u,v) \, du \, dv
\]  

Where \( f_{X_1,X_2}(x_1,x_2) \) is the joint probability density function of random variables \( X_1 \) and \( X_2 \). The joint probability density function \( f_{X_1,X_2}(x_1,x_2) \) can be calculated in each iteration of simulation as follows [9]:

\[
f_{x_1,x_2}(x_1,x_2) = \lim_{\delta x_1, \delta x_2 \to 0} \frac{\partial^2 F_{X_1,X_2}(x_1,x_2)}{\partial x_1 \partial x_2}
\]

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

\[
\text{cov}(X_1,X_2) = E[(X_1 - \mu_{x_1})(X_2 - \mu_{x_2})] = \int \int_{-\infty}^{\infty} (x_1 - \mu_{x_1})(x_2 - \mu_{x_2}) f_{X_1,X_2}(x_1,x_2) \, dx_1 \, dx_2
\]

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 \( \Sigma \) and mean vector \( \mu \) for random variables which are all normal [9].

\[
f(x) = \frac{1}{(2\pi)^{\frac{k}{2}} |\Sigma|^{\frac{1}{2}}} \exp\left[-\frac{1}{2} (x - \mu)^\top \Sigma^{-1} (x - \mu)\right]
\]

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

\[
F_{x_j}(x_j) = r_j \Rightarrow x_j = F_{x_j}^{-1}(r_j)
\]

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]:

\[
p_j(t) = j(t) = \int \ldots \int I[G(x,t) \leq 0] f_X(x) \, dx
\]

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 \( x_j \) is defined as \( j^{th} \) vector of random observations taken from \( f_X(\cdot) \) then, using the sample survey topic directly concluded [9]:

\[
p_j(t) \approx j(t) = \frac{1}{N} \sum_{N}^{x} I[G(x_j \leq 0)]
\]

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
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 $\alpha$ per (13) and results have shown in Fig. 2.

$$w(t) = 0.01 + 0.2 \ln(t)$$  \hspace{1cm} (14)

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\[ (y_j \cdot \frac{D_{nd} + d_{nd}}{d} \cdot (p_d = 0.15 \text{mpa}) \leq 1 \Rightarrow \]
\[ (\frac{y_j}{d} \cdot (2 \cdot \xi \cdot \frac{\gamma f \cdot \gamma_c \cdot \beta w^2}{I_d} + \sqrt{\frac{2 \cdot 0.15 \cdot 10^6 \cdot t_d \cdot \gamma_c \cdot \gamma_p \cdot k}{\rho}})), \leq 1 \]  

Where \( \gamma_j \) is structure factor, \( d_{nd} \) is design penetrate depth for Darcy seepage flow (m), \( D_{nd} \) is design penetrate depth for diffusive seepage flow (m), \( p_d \) is design water pressure (Pa), \( I_d \) is design working life (s), \( \xi \) is a factor for water pressure, \( \gamma_f \) is the safety factor, \( p_s \) is the amount of water characteristic (Pa), \( \gamma_c \) concrete materials factor for watertightness for seepage factor, \( \gamma_p \) is safety factor, \( k \) is test value of seepage coefficient (m/s), \( \beta w^2 \) 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):

\[ G_{s}(t) = SP_{lm} \cdot \frac{(0.01 + 0.2 \cdot \text{ln}(t)) \cdot 10^{-6} \cdot L \cdot \rho \cdot g \cdot \gamma_c}{12 \cdot \mu \cdot \tau \cdot m} \]  

(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):

\[ G_{nm(0.15)} = R - (\frac{y_j}{d} \cdot \sqrt{\frac{2 \cdot \gamma_j \cdot p_s \cdot t_d \cdot \gamma_c \cdot \beta w^2}{I_d} \cdot \gamma_p \cdot k}{\rho}), \]  

(18)

And for water pressure more than 0.15 MPa is:

\[ G_{nm(0.15)} = R - (\frac{y_j}{d} \cdot \sqrt{\frac{2 \cdot \gamma_j \cdot \gamma_p \cdot \beta w^2}{I_d} \cdot \gamma_c \cdot \gamma_p \cdot k}{\rho}} \]  

(19)

Mean and standard deviation values of random variables used in above models presented in Table I. It is noteworthy parameters \( \gamma_j, p_s, k, \beta w^2, \xi, \gamma_c, \gamma_p, L, m, \tau, I \) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>Concrete structure thickness</td>
<td>m</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity</td>
<td>m/s²</td>
<td>9.81</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Hydraulic gradient</td>
<td>m/m</td>
<td>1.781</td>
<td>1.176</td>
</tr>
<tr>
<td>k</td>
<td>Test value of seepage coefficient</td>
<td>m/s</td>
<td>5.37 × 10⁻¹²</td>
<td>6.61 × 10⁻¹²</td>
</tr>
<tr>
<td>m</td>
<td>Crack toughness</td>
<td>Dimension less</td>
<td>1.118</td>
<td>0.013</td>
</tr>
<tr>
<td>p_s</td>
<td>Characteristic value of water pressure</td>
<td>kPa</td>
<td>0.086 × 10⁶</td>
<td>0.046 × 10⁶</td>
</tr>
<tr>
<td>R</td>
<td>Acceptable value</td>
<td>Dimension less</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SP_{lm}</td>
<td>Water seepage acceptable value</td>
<td>m/s</td>
<td>1.15 × 10⁻²⁷</td>
<td></td>
</tr>
<tr>
<td>w</td>
<td>Crack width</td>
<td>mm</td>
<td>0.282</td>
<td>0.0585</td>
</tr>
<tr>
<td>ρ</td>
<td>Water density for cracked concrete</td>
<td>kg/m³</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Water density for non-cracked concrete</td>
<td>N/m³</td>
<td>9.81 × 10⁵</td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>Viscosity of water</td>
<td>kg/m/s</td>
<td>0.0010</td>
<td>02</td>
</tr>
<tr>
<td>τ</td>
<td>Tortuosity of crack</td>
<td>Dimension less</td>
<td>1.052</td>
<td>0.0192</td>
</tr>
<tr>
<td>γ_c</td>
<td>Structure factor</td>
<td>Dimension less</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>γ_p</td>
<td>Coefficient for water pressure</td>
<td>Dimension less</td>
<td>0.847</td>
<td>0.305</td>
</tr>
<tr>
<td>γ_j</td>
<td>Safety factor</td>
<td>Dimension less</td>
<td>1.15</td>
<td>0.212</td>
</tr>
<tr>
<td>γ_t</td>
<td>Material factor of</td>
<td>Dimension less</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>
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 water pressure increases.

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 \( \alpha \) from (13), the sensitivity analysis performed on results are shown in Fig. 2. Determining values of \( \alpha \) 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.

### TABLE V. COEFFICIENT FOR DIFFERENT VALUES OF WATER PRESSURE

<table>
<thead>
<tr>
<th>Water pressure ( p ) (mpa)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
<th>Sample 7</th>
<th>Sample 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi )</td>
<td>0.477</td>
<td>0.733</td>
<td>1.018</td>
<td>1.163</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE VI. VALUES OF PERMEABILITY AND DIFFUSION COEFFICIENTS OF CONCRETE

<table>
<thead>
<tr>
<th>Concrete content ( k ) (m/s)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k ) (m/s)</td>
<td>14.20</td>
<td>2.80</td>
<td>0.76</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_0 ) (m²/s)</td>
<td>43.3</td>
<td>29.30</td>
<td>19.10</td>
<td>15.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

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.

REFERENCES


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