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Influence of Hygro-Chemo-Mechanical Degradation on Performance of Concrete Gravity Dam

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Abstract**—**The degradation of concrete due to various hygro-chemo-mechanical actions is inevitable for the structures particularly built to store water. Therefore, it is essential to determine the material properties of dam-like structures due to ageing to predict the behavior of such structures after a certain age. The degraded material properties are calculated by introducing isotropic degradation index. The predicted material properties are used to study the behavior of aged dam at different ages. The dam is modeled by finite elements and displacement and is considered as an unknown variable. The parametric study reveals that the displacement is quite larger for comparatively lower design life of the structure because the degradation of elastic properties depends on the design life of the dam. The stresses in dam cam be unexpectedly large at any age with in the design life. The outcomes of the present study indicate the importance of the consideration ageing effect of concrete exposed to water for the safe design of dam throughout its life time.

Keywords**—**Hygro-chemo-mechanical, isotropic degradation, finite element method, Koyna earthquake.

I. INTRODUCTION

A CONCRETE gravity dam is a massive submerged structure and is built across the river mainly to harness the potential energy of river water for generation of hydroelectricity. These dams are expected to retain the reservoir during a severe earthquake. To evaluate the dynamic behavior of the concrete gravity dam, most of the researchers assumed that the modulus of elasticity of concrete of dam may remain constant throughout its design life. However, in reality due to aging, the dams are subjected to severe environmental effects, which lead to degradation of the dam concrete. Due to the continuous submerged off the dam, leaching of water saturates the numerous pores within the concrete. This phenomenon induces stresses in the concrete and as a result loss of elastic stiffness. Therefore, it is important to estimate the strength of the concrete at a later stage after construction because the structure may be hit by an earthquake long after it has been constructed or in other words, for the design of an earthquake-resistant dam and the seismic safety evaluation of existing dam at any age during its design life the degradation due to environmental conditions is recognized to be the major issue.

Byfors [1] stated that the hydration is the primary cause of ageing of concrete and at the micro level it is responsible to change the mechanical properties of the concrete. Bazant [2], and Ulm & Coussy [3] proposed a theory to model the reactive pores at an early age. Niu et al. [4] developed a finite element technique for describing the thermo-mechanical damage of early-age concrete in the construction of the large dam, and this model includes temperature-induced, creep-induced and autogenous deformations. Bazant et al. [5] proposed a new physical theory and constitutive model considering effects of long-term ageing and drying on concrete creep. This theory is an improvement over the solidification theory in which ageing is modeled by volume growth. The evolution of temperature, elastic moduli, compressive and tensile stress distribution inside the dam can be predicted in terms of ageing from the numerical model proposed by Cervera et al. [6]. Bangert et al. [7] evaluated the long-term material degradation in concrete structures due to a chemically induced degradation processes and calcium leaching. The ageing effect can also be modeled by the phenomena Alkali-Silica Reaction (Steffens et al. [8]). Gogoi & Maity [9] investigated the degradation of the strength of an aging concrete gravity dam adjacent to a reservoir in conjunction with the effects of sediment layers in the fluid-structure interaction analysis. In their work, the gain in compressive strength of concrete is obtained from experimental data published by Washa et al. [10] of fifty years of compressive strength of concrete by curve fitting procedures.

In this paper, the behavior of concrete gravity dam at its different ages has been studied. The dams are discretized by eight-node isoperimetric element and it is modeled based on the assumptions of plane strain. The elasticity properties of concrete at different ages are determined from the hygro-chemo-mechanical degradation model. A computer code in MATLAB environment has been developed to obtain seismic response of concrete dam at different ages considering the degradation due to hygro-chemo-mechanical actions.

II. THEORETICAL FORMULATION

The equation of motion of a dam-like structure subjected to external forces can be written in standard finite element form as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrix of the structure respectively, $\{\ddot{u}\}$,$\{\dot{u}\}$ and $\{u\}$ are nodal accelerations, velocities and displacements, $\{F\}$ is the nodal forces including hydrodynamic forces due to adjacent

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reservoir. In present investigation, the structure has been discretized by two-dimensional eight node rectangular elements. The dam body is assumed to be in a state of plane strain. The structural Rayleigh damping can be expressed as

$$[C] = a'[M] + b'[K] \tag{2}$$

where, a' and b' are called the proportional damping constants. The relationship between a', b' and the fraction of critical damping at a frequency ω is given by the following equation:

$$\xi' = \frac{1}{2}\left(a'\omega + \frac{b'}{\omega}\right) \tag{3}$$

Damping constants a' and b' are determined by choosing the fraction of critical damping ξ_1' and ξ_2' at two different frequencies ω_1 & ω_2 and solving simultaneously equations a' and b'. Thus:

$$\begin{aligned} a' &= \frac{2(\xi_2'\omega_2 - \xi_1'\omega_1)}{(\omega_2^2 - \omega_1^2)} \\ b' &= \frac{2\omega_1\omega_2(\xi_2'\omega_1 - \xi_1'\omega_2)}{(\omega_2^2 - \omega_1^2)} \end{aligned} \tag{4}$$

Usually, ω_1 is taken as the lowest natural frequency of the structure, and ω_2 is the highest frequency of interest in the loading or response. In the present study, the fraction of critical damping for both the frequencies are chosen as the same i.e. ξ_1' ' = ξ_2' ' = ξ'. Thus, above equation may be expressed as:

$$\begin{aligned} a' &= \frac{2\xi'}{(\omega_2 + \omega_1)} \\ b' &= \frac{2\xi'\omega_1\omega_2}{(\omega_2 + \omega_1)} \end{aligned} \tag{5}$$

III. Modeling of Aged Concrete

In normal practice, it is assumed that all the cement particles in concrete get hydrated in 28 days and concrete get its full compressive strength. But in reality concrete gains some compressive strength with age beyond 28 days. On the other hand, the durability of concrete is considerably affected due to damage resulting from time variant external loading, moisture and heat transport, freez-thaw actions, chemically expansive reaction and chemical dissolution. Out of the wide range of environmental induced mechanisms, damage due to chemical and mechanical degradation is modeled here to get reasonable elasticity properties of concrete at different ages of concrete.

IV. Gains in Compressive Strength with Time

The gain of compressive strength of concrete is predicted by curve fitting on 50 years of experiential data published by Washa el al. [10]. The authors proposed four different curves for different concretes. All the curves showed an increase in compressive strength roughly proportional to the logarithm of age during the first 10 years and very small variation thereafter. Gogoi & Maity [9] carried out a least square curve fitting analysis on the set of compressive strength data published by Washa el al. [10] and proposed following equation to predict the gain of compressive strength with passage of time in years.

$$f(t) = 3.57\ln(t) + 44.33 \tag{6}$$

Where $f(t)$ is the gain of compressive strength in SI unit, t is the age of concrete in years. The value of static modulus of elasticity of concrete in SI unit is obtained by the expression proposed by Neville & Brooks [11].

$$E_0 = 5000\sqrt{f(t)} \tag{7}$$

V. Degradation Model for Concrete

In present analysis, the degradation of concrete strength is described by the reduction of the net area capable of supporting stresses. The loss of elastic properties of concrete follows as a consequence of degradation of concrete due to various environmental and loading conditions. The orthotropic degradation index is given by

$$d_{gj} = \frac{\Psi_j - \Psi_j^d}{\Psi_j} \tag{8}$$

where, ψ_j is tributary area of the surface in direction j; and ψ_j^d is area affected by degradation. In a scale of 0 to 1, the orthotropic degradation index, d_{gj}= 0, indicates no degradation and d_{gj}= 1, indicates completely degraded material. The index j=1, 2corresponds with the Cartesian axes x and y in the two-dimensional case. The effective constitutive relationship for plane strain analysis can be expressed as

$$[D_g] = \frac{E_0}{(1+\mu)(1-2\mu)}\begin{bmatrix} (1-\mu)\Lambda_1^2 & \mu\Lambda_1\Lambda_2 & 0 \\ \mu\Lambda_1\Lambda_2 & (1-\mu)\Lambda_2^2 & 0 \\ 0 & 0 & (1-2\mu)\Lambda_1^2\Lambda_2^2/\left(\Lambda_1^2+\Lambda_2^2\right) \end{bmatrix} \tag{9}$$

where, Λ_1= $(1 - d_{g1})$andΛ_2= $(1 - d_{g2})$.In (9), Ed is the elastic modulus of the material without degradation. If $dg1 = dg2 = dg$, the isotropic degradation model is expressed as:

$$[D_g] = (1 - d_g)^2[D] \tag{10}$$

where,*[Dg]* and*[D]* are the constitutive matrices of the degraded and un-degraded model respectively.

VI. EVALUATION OF DEGRADATION INDEX

The compressive strength of concrete is expected to decrease with its age due to chemical and mechanical degradation, and this degradation is measured in terms of degradation index. In present work, the degradation due to hygro-chemo-mechanical actions is implemented and the total porosity, ϕ which is the sum of the initial porosity ϕ_0 , the porosity due to matrix dissolution ϕ_c and the apparent porosity ϕ_m is considered as the measurement of degradation index. Bangert et al. [7] and Kuhl et al. [12] have suggested the following relationship to relate these parameters.

$$\phi = [\phi_0 + \phi_c + \phi_m] \tag{11}$$

The parameter ϕ_m is obtained as:

$$\phi_m = [1 - \phi_0 - \phi_c] d_g \tag{12}$$

here, d_g is the scalar degradation index. Gogoi & Maity [9] proposed the following equation to obtained degradation index.

$$d_g = \alpha_s - \frac{k^0}{k}\left[1 - \alpha_c + \alpha_c e^{(\beta_c [k^0 - k])}\right] \tag{13}$$

where k^0 and k are values of strain that represent the initial threshold degradation and the internal variable defining the current damage threshold depending on the loading history and α_s, α_c and β_c are material parameters.k_0 is given by f_l/E_0, where f_l is the static tensile strength and E_0 is the elastic modulus of non-degraded material. For no degradation due to mechanical loading, k may be considered equal to k_0. Bangert et al., 2003 outlined the procedure to calculate the values of parameter α and β_c. The values of α_s are considered to lie between 1.0 and 0.0, indicating complete and no degradation respectively. Atkin [13] also made a study on the process of degradation and introduced a new parameter ζ. The value of ζ is zero for fresh concrete and ζ =1 for fully degraded concrete and proposed the following relationship.

$$\dot{\varsigma} = \frac{1}{T_a}[1 - \varsigma] \tag{14}$$

where T_a=design life of the structure. Integrating (14) the following equation can be obtained.

$$1 - \varsigma = e^{(-\frac{t}{T_a})} \tag{15}$$

Replacing ζ with dg in (15), the degradation index with time can be obtained as:

$$d_g = 1 - e^{(-\frac{t}{T_a})} \tag{16}$$

where, t is the time corresponding to which degradation index is required. The relation between degraded modulus of elasticity, E_g and modulus of elasticity after strength gain at a particular age, E_0 is given as:

$$E_g = (1 - d_g) E_0 \tag{17}$$

The dimensionless total porosity is obtained by the following equation:

$$E_g = (1 - \phi)^{\frac{t}{T_a}} E_0 \tag{18}$$

VII. VALIDATION OF PRESENT ALGORITHM

To examine the accuracy of the proposed algorithm, a benchmark problem on Pine flat has been solved and results are compared with existing literature Fenves & Chopra [14]. The material properties of the dam in present study are same as considered by Fenves and Chopra [14]. Geometric details and a typical finite element discretization for the dam are shown in Fig. 1. The fundamental time period of the dam and maximum crest displacements due to the South East (S69E) component of the ground motion at Taft Lincoln School Tunnel on 21st July, 1952 are presented in Table I for comparison. A little variation in the results is observed which may be due to different finite element mesh sizes and other parameters for representing the dam.

TABLE I
FUNDAMENTAL PERIOD AND MAXIMUM CREST DISPLACEMENT OF PINE FLAT DAM

Fundamental period (rad/sec)		Max Crest Displacement (mm)	
Fenves & Chopra [14]	Present	Fenves & Chopra [14]	Present
0.317	0.320	26.93	26.58

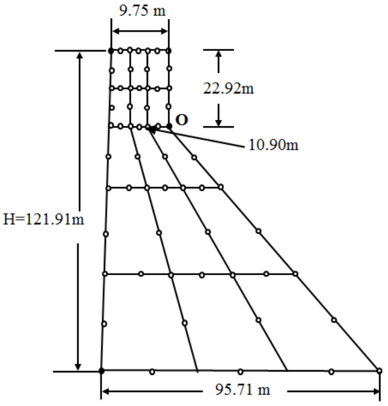

Fig. 1 Geometry and finite element discretization of Pine flat dam

VIII. AGEING EFFECT ON MODULUS OF CONCRETE ELASTICITY

In normal practice, it is assumed that the concrete get its full compressive strength in 28 days but in reality concrete gains some compressive strength with age beyond 28 days. In present study, this gain of compressive strength is determined from the curve proposed by Gogoi & Maity [9]. The scalar degradation parameter, dg is evaluated by (13) using following material properties $\alpha_m = 0.9$, $\beta_m = 1000$, and $\alpha_0 = 0.2$ (Kuhl et al [12]). The value of ϕ_c may be considered as 0.2. The allowable degradation due to mechanically induced porosity can be predefined between 1.0 and 0.0, indicating 100 percent and no degradation respectively. Here, the value of as for a design life of 100 years is taken in the range of 0.4 to 1.0. The variation of elastic modulus of damaged concrete with design life of 100 years is plotted and compare with those values of without degradation in Fig.3.It is observed from Fig. 3 that if degradation of concrete is considered, the elastic modulus of the concrete decreases significantly and the decrease is more when the value of αs is equal to 1.0.

IX. AGEING EFFECT ON FUNDAMENTAL FREQUENCY OF DAM

The ageing effect of concrete on the frequency of dam-reservoir system is studied considering Pine flat dam. For prediction of dynamic behavior of an ageing dam, a new paradigm is introduced defining extent of degradation of the dam due to the effect of hygro-chemo-mechanical (HCM) effects. During the lifetime of the structure, the original safety margin will be reduced by deterioration of structural strength, reflected in the time evolution of the stiffness matrix, the most suitable assemblage of structural degradation information. These degradation of concrete in dam may result in loss of strength of the material along horizontal, vertical or in both the directions. A study is carried out to evaluate the response of the dam due to damage along the width and height of the dam. It is observed from Fig. 3 that with an increase in damage caused by degradation, the natural frequency of the dam reduces. This behavior is mainly due to the reduction stiffness of the structure with increased degradation. Moreover, the decrement in frequency is high in case of isotropic damage model as compared to orthotropic degradation. The damage along vertical direction also has a similar effect as that in the isotropic case, as this is the primary source of stiffness. The effect isotropic degradation due to hygro-chemo-mechanical action for different design life structure is also studied. In Table II the frequency of Pine flat dam of different design life is summarized. The fundamental frequency for a particular design life decreases with the increases of age of the dam. However, the decrease in frequency is comparatively less when the design life of the dam is higher.

TABLE II
FUNDAMENTAL FREQUENCY OF AGED DAM

	Fundamental frequency (rad/sec)
No degradation in dam	23.60
After 25 years, design life 50 yrs	15.42
After 50 years, design life 50 yrs	10.07
After 25 years, design life 100 yrs	19.08
After 50 years, design life 100 yrs	15.45

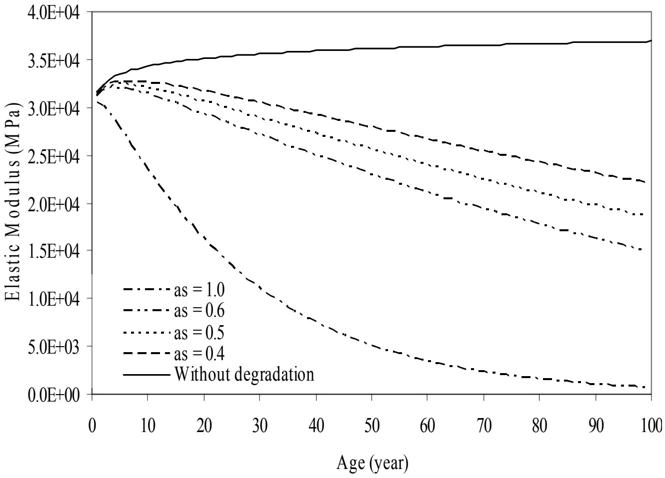

Fig. 2 Variation modulus of elasticity with age

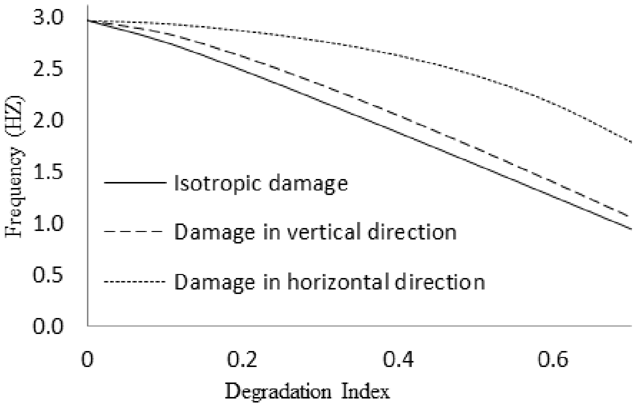

Fig. 3 Variation of frequency of dam with degradation

X. RESPONSE OF AGED DAM DUE TO EARTHQUAKE ACCELERATION

In the present section, the ageing effect of concrete in dam is studied considering Pine flat dam shown in Fig.1. The study is carried out with following material and geometric properties: mass density of concrete = 2400 kg/m^3 , Poisons ratio=0.235, structural damping = 3% and the dam is discretized by 8 × 10 (i.e. $N_h = 8$ and $N_v = 10$). The crest displacements of the dam at an age of 25 years with different design life of the dam are plotted in Fig. 4; which shows the effects of damage due to hygro-chemo-mechanical degradation on displacements of the dam due to seismic excitation. It is observed from the graphical results that the displacement is more in case of a lower design life. Displacement responses of the dam for different ages of the concrete with same design life are also studied and compared in Fig. 5. Here, three different age of concrete, i.e., immediate after construction, 25 years and 50 years are considered and the design life of the dam is considered as 100 years. Crest displacement is determined by considering Koyna acceleration as an external excitation. The maximum horizontal displacements at the crest are observed as 38.0 mm, 59.6 mm and 70.1 mm at the age of immediate after construction, 25 years and 50 years respectively. Therefore, the displacement of the dam increases with the age of the concrete because degradation of concrete is more at letter age. Similar analysis is carried out in order to compare the principal stresses at the point O (Fig. 1). Both the principal stresses at different ages of the concrete are plotted in Fig. 6 and Fig. 7 respectively. It is observed from the Fig. 6 that the major principal stresses decrease with the age of concrete because the concrete experienced more degradation. However, for minor principal stresses (Fig. 7), the maximum value is noted at the age of 25 years. In general, the stress in a structure is directly proportional to the amount of displacement and the constitutive properties of the material. Due to the degradation of concrete, two different phenomena occur within the concrete. Firstly, the constitutive property decreases and as a results the stresses decreases. Secondly, the displacement of the dam increases which results more stress within the dam. Here, the increase of stresses duo to the increases of displacement is dominating over the decrease of stresses due to the reduction of constitutive properties.

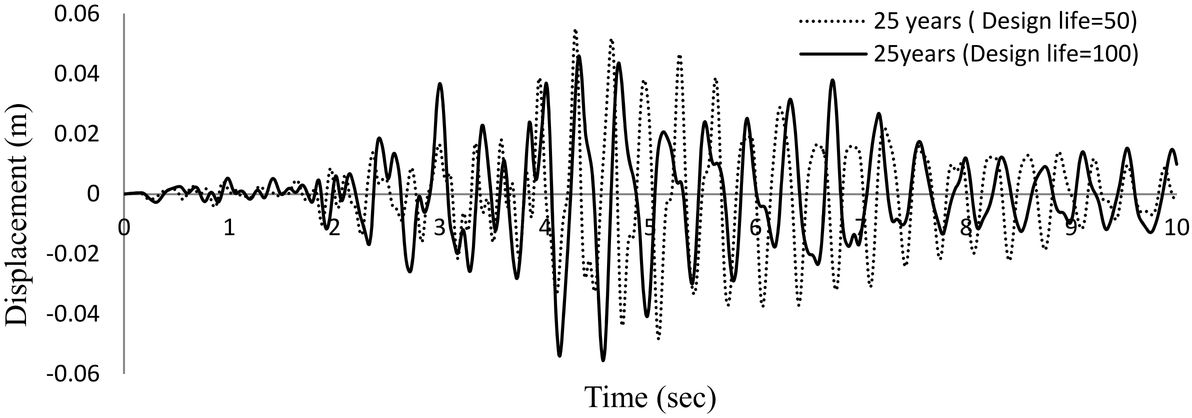

Fig. 4 Effect of degradation on horizontal crest displacement due to Koyna earthquake

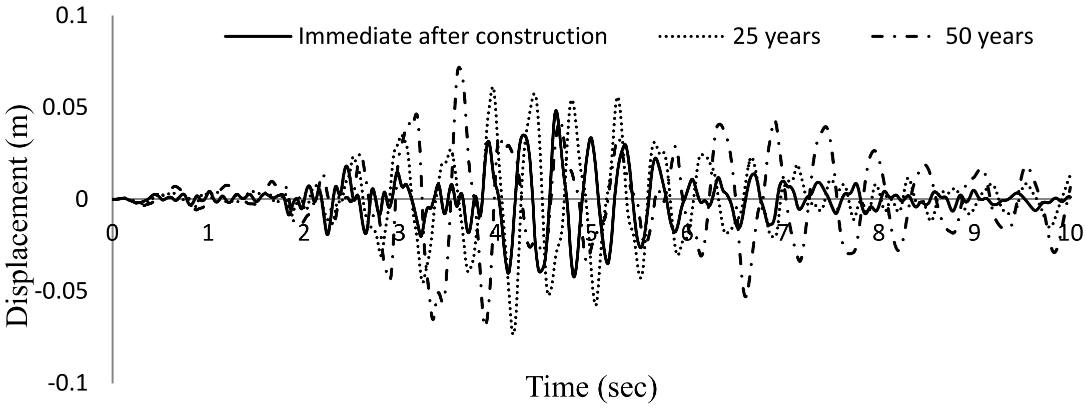

Fig. 5 Effect of degradation on horizontal displacement due to Koyna earthquake

XI. CONCLUSIONS

The response of coupled dam at its different age under external excitation is presented. The hygro-chemo-mechanical degradation causes decreases in modulus of elasticity that leads to the changes in behavior of dam with time. The dam remains relatively stiff at the age immediate after construction; as a result, the displacement and stresses of dam have higher values. In general, the stresses in dam decrease with its age due to reduction of modulus of elasticity of concrete because of degradation. However, in the present study it is observed that the magnitude of stresses increases at the age of 25 years under earthquake excitation. Such type of behavior at the particular age is observed because the increase of stress due to the increase of displacement is dominating over the decrease of stress due to the decrease of modulus of elasticity due to hygro-chemo-mechanical degradation. Therefore, for design of an earthquake resistant dam, degradation due hygro-chemo-mechanical action is necessary to calculate the stress at any age during it design life.

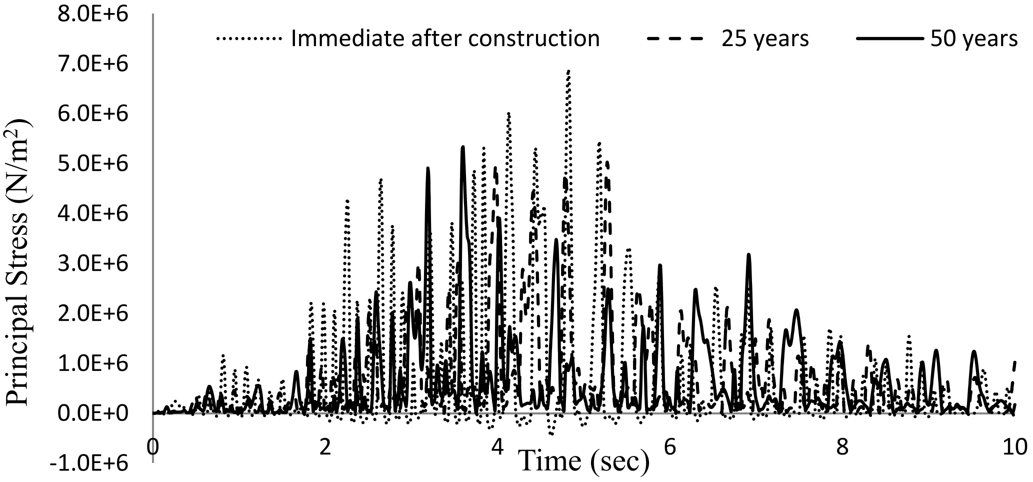

Fig. 6 Variation of major principal stress at the neck (point O) due to Koyna earthquake

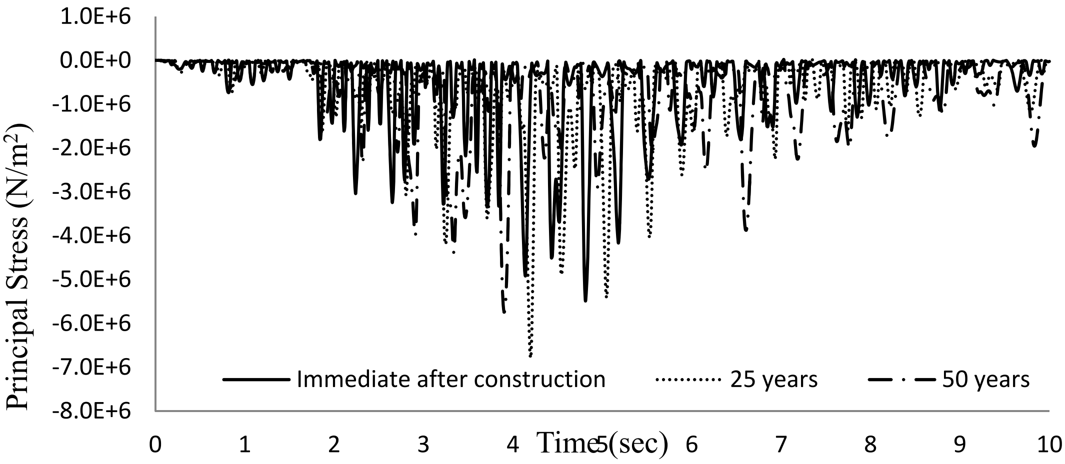

Fig. 7 Variation of minor principal stress at the neck (point 0) due to Koyna earthquake

REFERENCES

[1] J. Byfors, “Plain concrete at early ages”, Research Report F3:80, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 1980, pp. 216-224.

[2] Z. P. Bazant, “Creep and thermal effects in concrete structures: a conceptus of some new developments”, Computational modelling of Concrete Structures, International Conf. EURO-C, H. Mang, N. Bicanic and R. de Borst. eds., Pineridge Press, Swansea, Wales, 1994, pp. 461-480.

[3] F. J. Ulm, and O. Coussy, “Modelling of thermochemomechanical couplings of concrete at early ages”, Journal of Engineering Mechanics, ASCE, 1995, Vol. 121(7), pp. 785-794.

[4] Y. Z. Niu, C. L. Tu, R. Y. Liang, and S. W. Zhang, “Modeling of thermo-chemical damage of early-age concrete”, Journal of Structural Engineering, ASCE, 1995, Vol. 121(4), pp. 717-726.

[5] Z. P. Bazant, A. B. Hauggaard, S. Baweja and F. J. Ulm, “Microprestress-solidification theory for concrete creep. I: Aging and drying effects”, Journal of Engineering Mechanics, ASCE, 1997, Vol. 123(11), pp. 1188-1194.

[6] M. Cervera, J. Oliver, and T. Prato, “Simulation of construction of RCC dams I: Temperature and aging”, Journal of Structural Engineering, ASCE, 2000, Vol. 126(9), pp. 1053-1061.

[7] F. Bangert, S. Grasberger, D. Kuhl, and G. Meschke, “Environmentally induced deterioration of concrete: physical motivation and numerical modelling”, Engineering Fracture Mechanics, 2003, Vol. 70, pp. 891–910.

[8] A. Steffens, K. Li, O. Coussy, O. “Ageing approach to water effect on alkali–silica reaction degradation of structures”, Journal of Engineering Mechanics, ASCE, 2003, Vol. 129(1), pp. 50-59.

[9] I. Gogoi and D. Maity, “Influence of sediment layers on dynamic behavior of aged concrete dams” Journal of Engineering Mechanics, ASCE, 2007, Vol. 133(4), pp. 400-413.

[10] G. W. Washa, J. C. Saemann and S. M. Cramer, “Fifty year properties of concrete made in 1937”, ACI Materials Journal, 1989, Vol. 86(4), pp. 367-371.

[11] A. Neville, M. J. J, “Elasticity and creep, Concrete Technology”, Pearson Education (Singapore) Pte. Ltd. 1987,4th Indian Reprint, pp. 209-234.

[12] D. Kuhl, F. Bangert and G. Meschke, “Coupled chemo-mechanical deterioration of cementitious materials. Part I: Modeling”, International Journal of Solids and Structures, 2004, Vol. 41, pp. 15 - 40.

[13] P. W. Atkin, P. W, “Physical Chemistry, 5th Edition”, Oxford University Press Oxford, U.K. 1994.

[14] G. L. Fenvesand A .K. Chopra, “Simplified analysis of concrete gravity dams”, Journal of Structural Engineering, ASCE, 1987, Vol. 113(8), pp. 1688-1708.