



THREE DIMENSIONAL THERMAL STRESS ANALYSIS OF CONCRETE ARCH DAMS INCLUDING EARTHQUAKE EFFECT

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SUMMARY

Arch dams are designed for the same loads as other dams with the exception of the temperature load, which has a significant influence in arch dam design as compared to gravity dam design [1]. In concrete arch dams, because of the particular geometry, solar radiation shares of exposed surfaces vary spatially through downstream face. In this case, three-dimensional temperature distribution analysis is unavoidable. When a transient heat transfer analysis is performed in a dam safety evaluation, it would be convenient to identify the most critical time to carry out a complete stress analysis [2]. To investigate the seismic safety of concrete dams, it is essential to quantify the static state of stress and strain that exist at the time the earthquake occurs, which may vary significantly from winter to summer conditions [3].

In this paper, a three dimensional finite element model is used for simulating the temperature behavior in operational phase of typical arch dam. Then an elastic analysis is carried out and the associated thermal stresses are calculated and combined with other static loadings (self-weight and hydrostatic) and dynamic one. For dynamic analysis, a coupled system of dam and reservoir is considered. The static loads are compared and combined with earthquake load. Results show significant thermally induced tensile stresses in the crest region and at the downstream face of the dam, which is the most vulnerable zone for seismic-induced damage. At the upstream face, due to the effect of reservoir water, the thermal tensile stresses have small magnitude while dynamic stresses are excessively increased.

INTRODUCTION

Temperature effects on arch dams can be studied in two distinct phases: construction phase and operation phase. Figure 1 shows thermal response of a typical arch dam [1].

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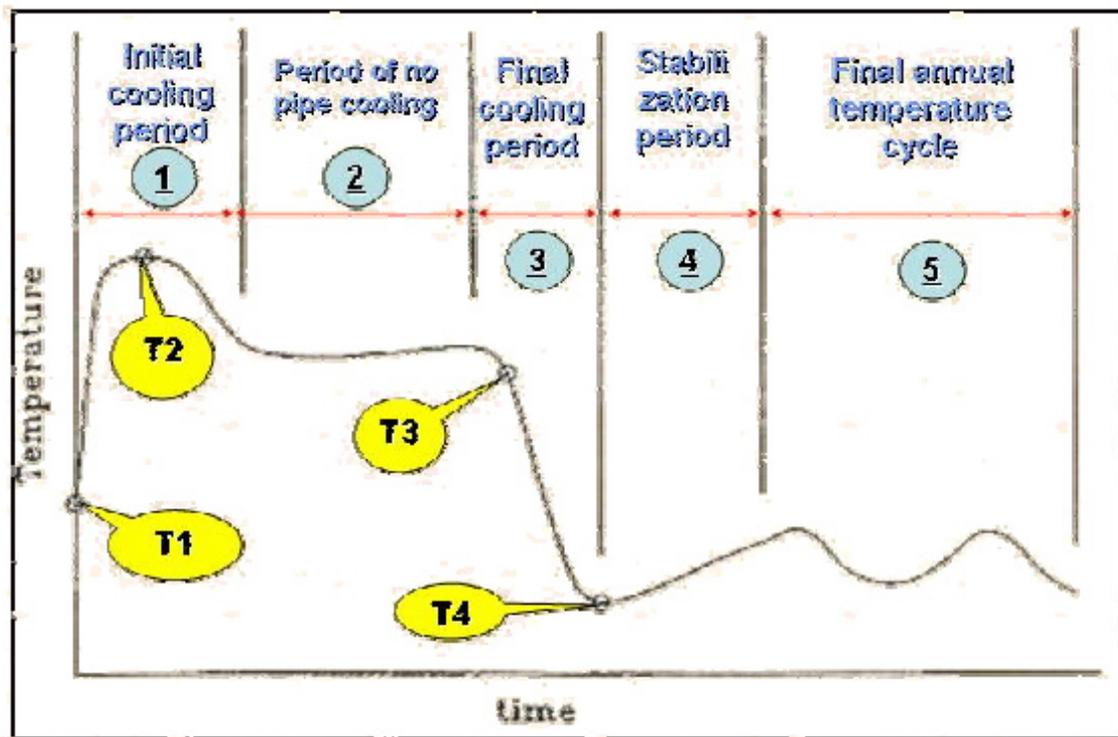


Figure 1. Temperature history of a typical concrete dam

In the figure, periods 1, 2 and 3 altogether represent construction phase and period 5 makes operation phase. The temperature shown in the figure is considered as an average temperature. In construction phase, from the viewpoint of heat transfer, dam is subjected to the variation of ambient temperature, solar radiations variation, hydration of cement aggregate and artificial cooling of cooling pipes. The main targets of thermal analysis of dams in this phase are: designing of concrete placement blocks dimensions and distance of adjacent monolith joints, definition of optimized conditions of flow and water temperature in cooling pipes for offsetting the hydration effects and also the most important of all, determination of optimized grout temperature. In operation phase, a concrete arch dam is subjected to the environmental action (ambient temperature and reservoir temperature variations as well as solar radiation variations). In this phase, the dam is considered as a continuous system and consequently differences between dam's temperature and closure temperature (grouting temperature) can cause compressive or tensile stresses. To obtain the temperatures and thermal stresses in the dam during the operation stage, Stucky and Derron (1957) proposed a simple way using analytical equations.

Agullo *et al.* [4] developed a one-dimensional explicit finite differences scheme. They proposed a simple analytical formula providing thermal behavior of different sections at given heights and variable thickness, mainly according to the dam height, at any instant. It was a simple model, which envisaged the thermal variables of concrete, the geometry and site of the dam, and the environmental action. They found that the mean temperature of the section depends basically on the annual mean ambient temperature, the annual mean temperature of the water and the mean annual total daily solar radiation at the site. The annual range of the mean temperature in the section is primarily influenced by its thickness, by the annual range of the ambient temperature and the water temperature. The solar radiation has the greatest effect on the temperature of each layer.

Zhang *et al.* [5] assumed unidirectional heat transfer and applied an analytical method to solve the temperature distribution and thermal stress in mass concrete structures subjected to thermal shock. Using the superposition method, they derived an analytical formula of temperature and stress field under triangular and sinusoidal air temperature drop. It was found that the highest temperature and temperature

gradient is induced in a very narrow region closed to exposed surface, and the stress concentration can be reduced by changing the property of concrete and heat transfer coefficient as a curing condition.

Meyer *et al.* [6] carried out a numerical analysis to evaluate the temperature variation and the associated thermal stresses, strains and displacements of the Vieux-Emosson arch-gravity dam (Valais, Switzerland). They used a three-dimensional finite element modeling to obtain the thermal behavior of the dam. They simplified the variation of solar radiation share of different region of exposed surface by separating the downstream in to three regions with varied solar radiation absorption. The results were not in accordance with data obtained by instrumentations. They found that modulus of elasticity of rock and concrete has no significant effect on the deformability of the dam whereas the thermal expansion coefficient plays a major role.

Leger *et al.* [3] proposed a numerical two-dimensional model to calculate the temperature field in a concrete gravity dam. They found that the temperature gradient near the exposed surface of the dam generates tensile stresses, which can cause surface cracks. These do not affect the stability of the dam but permit water penetration in to cracks and cause damage by freezing and thawing. The two dimensional analysis is accurately enough for the case of gravity dam which solar radiation share does not vary through the downstream and other exposed surfaces. Consequently, different cross sections of the dam have the same boundary conditions and heat will not be transferred in horizontal direction.

Daoud *et al.* [7] based on previous analysis, described a numerical analysis of the periodic temperature field in a concrete gravity dam using two-dimensional finite element modeling. They took in to account ambient temperature variation, solar radiation, snow cover, temperature gradients and ice formation in the reservoir water as well as different conductivities for saturated and unsaturated parts of the dam. They showed that an important difference in the temperature gradient at the interface occurs between the saturated and unsaturated parts of the dam even though the corresponding thermal conductivities differ by only 8 percent. Based on experimental relations between the limit tensile strain of concrete and the local amplitude of the seasonal temperature variation, thermal degradation will be restricted to a bound of approximately 1 m from the downstream exposed surface of the dam.

Both leger *et al.* [3] and Daoud *et al.* [7] simplified the variation of reservoir temperature profile. Bofang *et al.* [8] proposed a useful analytical formula for prediction of water temperature in deep reservoir as a prescribed boundary condition of heat transfer analysis in concrete dams.

Contrary to previous research, in this study the variation of solar radiation share through exposed surface and a realistic reservoir water temperature was considered.

Ghaemian *et al.* [9] proposed a time domain two dimensional analysis of dam-reservoir interaction using staggered solution method. The crack propagation in the dam was considered using smeared crack analysis. Based on numerical analysis, they concluded that the predicted crack pattern is different from that of the case when the dam-reservoir interaction is approximated using the added mass approach.

Tinavi *et al.* [2] developed finite element method to predict the response of a typical polygonal gravity dam under combination of static and dynamic loads. Two and three dimensional finite element analysis was carried out to predict the temperature distribution and stress response of the dam respectively. For a seismic analysis, the dam-reservoir interaction is considered by using the modified Westergard added mass technique. They showed that stability evaluation under two dimensional static conditions are generally conservative and three dimensional analysis should only be performed if adequate consideration of the vertical construction joints is accounted for in a thermal analysis or if thermal stresses are negligible and the joints are grouted and keyed. Three dimensional seismic analysis of discontinuous dams showed tensile stress concentration in upper part that were not present in two dimensional analysis.

The purpose of this paper is to develop a model to investigate temperatures and thermal stresses of concrete arch dam in operating phase. Then probable cracked areas and area with high concentration of tensile stress can be predicted. A three-dimensional finite element model was used for this purpose. In this model, air and reservoir temperature are predicted with reliable experimental formulae. The solar radiation shares of exposure surfaces of relative elements is specified with considering beam and diffuse radiation,

latitude, azimuth of the surface, declination of the sun, slope of the surface and reflectivity of the ground and water.

Because of the small thickness of arch dams adjacent to ground to comparison with other interfaces of a concrete arch dam and uncertainties about prescribed foundation temperature as a boundary condition in three-dimensional finite element modeling, the foundation was not considered in the model; also, the dependency of thermal and mechanical properties of concrete to temperature is relinquished. Because dams temperature varies in a relatively narrow range (255-300°K) [3] with no significant effects to thermal and mechanical properties variations, we assume uniform distribution of the thermal properties of concrete in the dam body.

Figure 2 shows heat sources and heat transfer process in concrete arch dam:

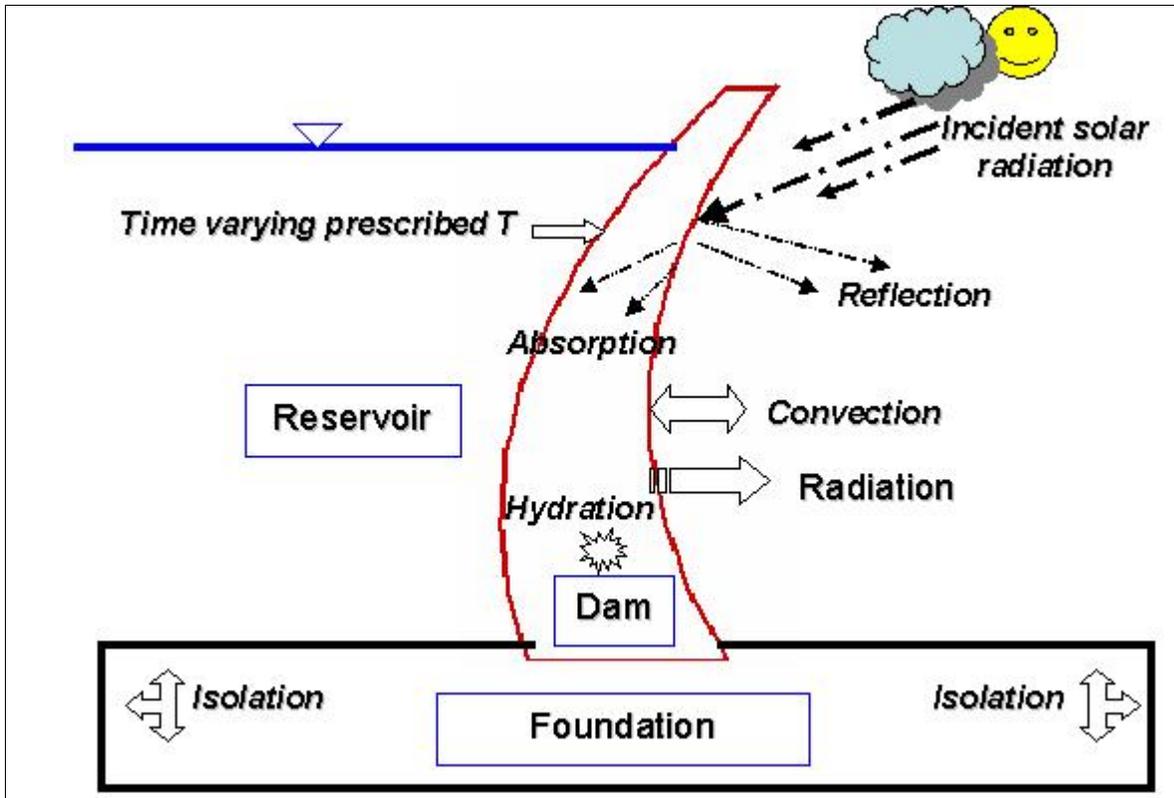


Figure 2. Heat transfer process for a dam

Under long-term action of stress, creep gives rise to an increase in the concrete strain, relieving some of the induced static stresses. The concrete creep mechanism depends on several factors such as the age of the structure at loading, the duration and time variation of loadings, the temperature, and the humidity. A rigorous stress-creep-temperature interaction study requires a coupled step-by-step stress-creep-temperature interaction analysis, which is beyond the scope of the present study. To obtain reasonable result based on previous researcher suggestion, it is assumed that the long-term temperature stress will be 65 percent of the result obtained by linear common elastic analysis [3,1].

For obtaining the static and dynamic stresses, it was assumed that concrete behave linearly.

Determination of hydrodynamic response of dam is possible with considering to coupled field system of the dam-reservoir which two physical system of fluid and structure interact only at the domain interface. It was assumed that water is linearly compressible and its viscosity is negligible. The reservoir boundaries are subjected to ground motion and they were allowed to absorb waves. The Sharan boundary condition [10] was applied at the far-end truncated boundaries. At The surface of the reservoir, the effect of surface

waves was neglected. The velocity of the pressure wave in water is taken 1438.66 m/sec. For solution of coupled equations of fluid-structure system, a time domain analysis using staggered displacement method was developed [9].

KARAJ CONCRETE ARCH DAM

Location, general data and dam geometry

Karaj dam is located at $35^{\circ} -57'$ latitude and $51^{\circ} -29'$ longitude near the city of Karaj in Iran. Karaj concrete dam is a double curvature dam, which horizontal arches are single-centered circular (without fillet with constant thickness) and vertical arches are parabolic. Table 1 shows the main characteristics of the dam.

Table 1. Main characteristics of Karaj concrete arch dam.

Maximum height above foundation	168 m
Foundation altitude	1606 masl
Crest altitude	1768 masl
Crest width	7.85 m
Buttress width	32 m
Crest length	384 m
Normal elevation of water	1765 masl
Minimum elevation of water	1692 masl
Reservoir normal capacity	203,000,000 m ³
Reservoir minimum capacity	33,000,000 m ³

Figure 3 shows plan view and characteristics of horizontal arches of Karaj arch dam.

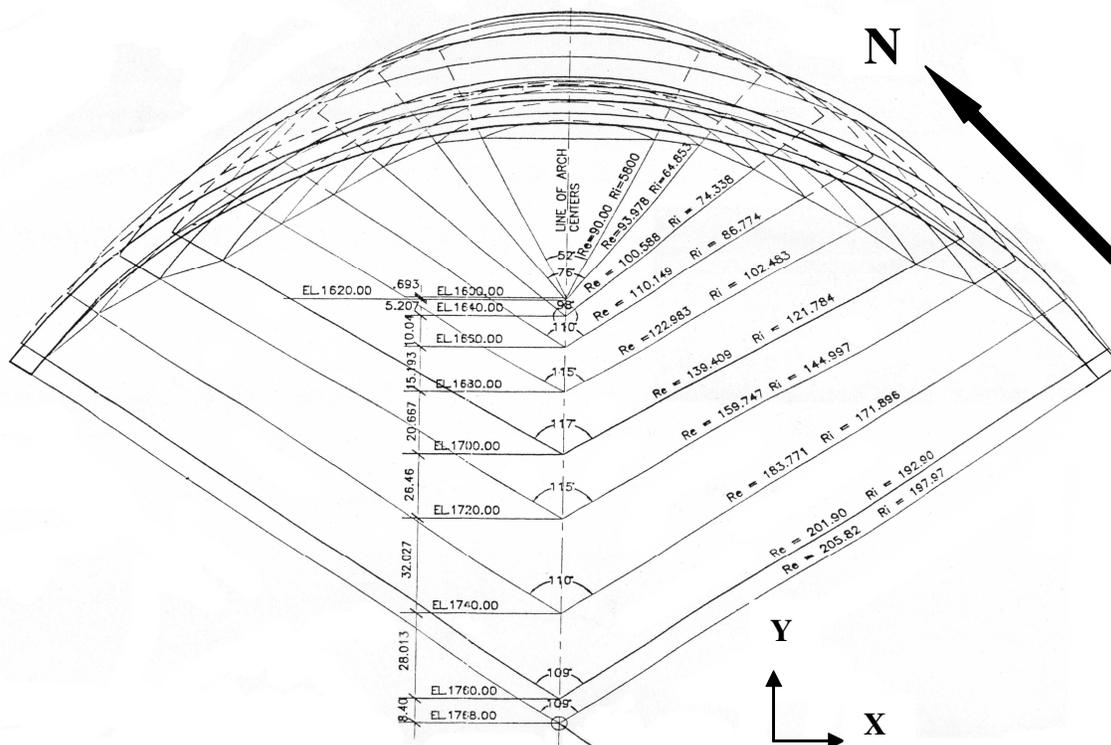


Figure 3. Plan view and characteristics of horizontal arches of Karaj arch dam

All of the readings from instruments are recorded since 1970. Variation of the reservoir depth is shown in Figure 4. Table 2 shows the closure temperature of the different point of the dam located in 7 separated layers. This information has been recorded at the time of grouting of monolith in different layers.

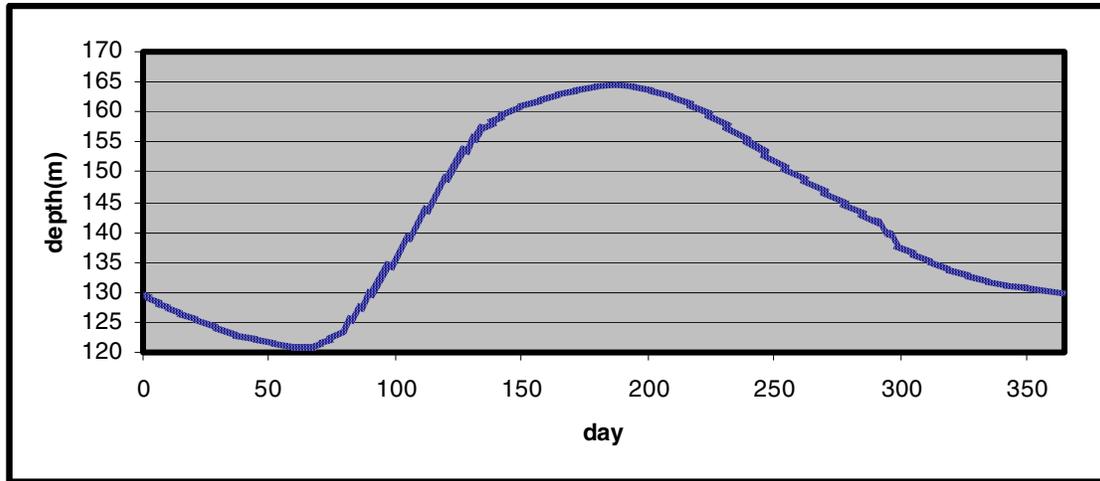


Figure 4. Mean annual reservoir depth

Table 2. Closure temperatures of separated layers of the dam

Layer Number	Altitude from foundation surface (m)		Closure Temperature (°C)
	From	To	
1	0	60	8
2	60	80	8
3	80	100	8.5
4	100	120	9.4
5	120	140	10.3
6	140	160	11.2
7	160	168	12.8

Construction material

A range of thermal and mechanical properties of mass concrete are listed in Table 3:

Table 3. Thermal and mechanical properties of the mass concrete

Specific heat [J/(kg °K)]	870-1080 (912)*
Thermal conductivity [W/(m °K)]	1.47-4.38 (2.62)
Convection coefficient [W/(m ² °K)]	23.2**
Solar absorptivity	0.5-0.65 (0.5)
Emissivity	0.65-0.9 (0.88)
Coefficient of thermal expansion [1/ °K]	8.05E-6
Static modulus of elasticity [MPa]	25480
Density [kg/m ³]	2450
Poisson's ratio	0.17
Static tensile strength [Mpa]	3.8
Dynamic tensile strength [Mpa]	4.6
* Values used in numerical model.	
** For average annual wind speed of 3.0 m/sec	

Seismology records

the main characteristics of this earthquake MCE (Maximum Credible Earthquake) is shown in Table 4. The Cartesian components of ground acceleration for these earthquake are presented in Figures 5(a, b and c).

Table 4. The main characteristics of MCE

Level of Design	Name of Earthquake	Date	Station	Return Period (year)	Maximum ground Acceleration	
					Horizontal	Vertical
MCL	MAJIL	Jun.20.1990	Abbar	>3000	0.43g	0.23g

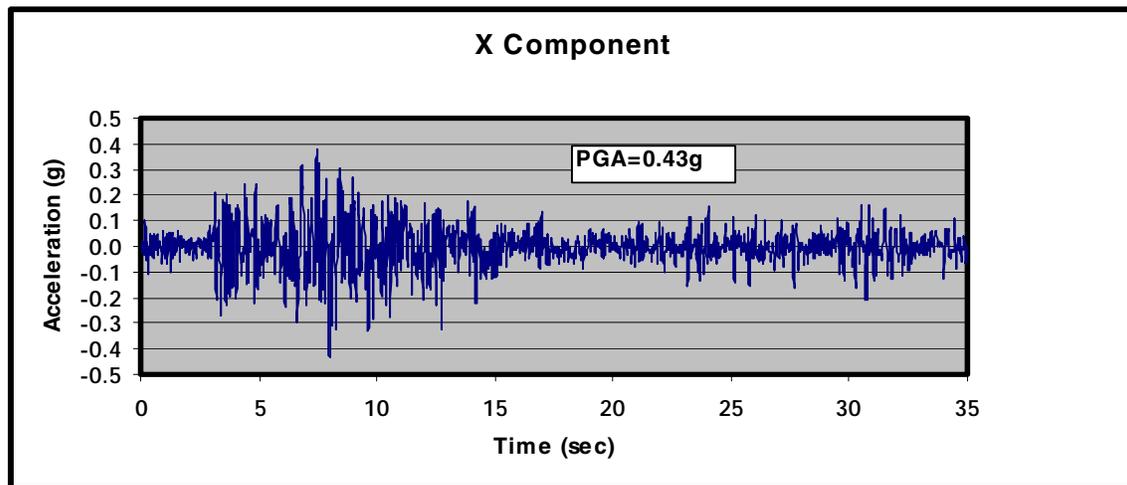


Figure 5(a). Accelerogram record for X component of ground acceleration.

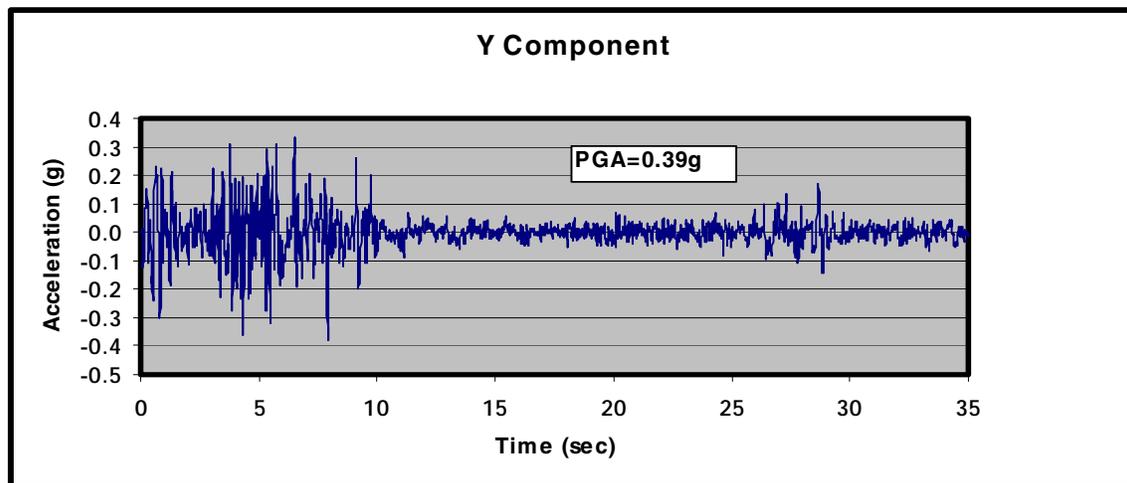


Figure 5(b). accelerogram record for Y component of ground acceleration.

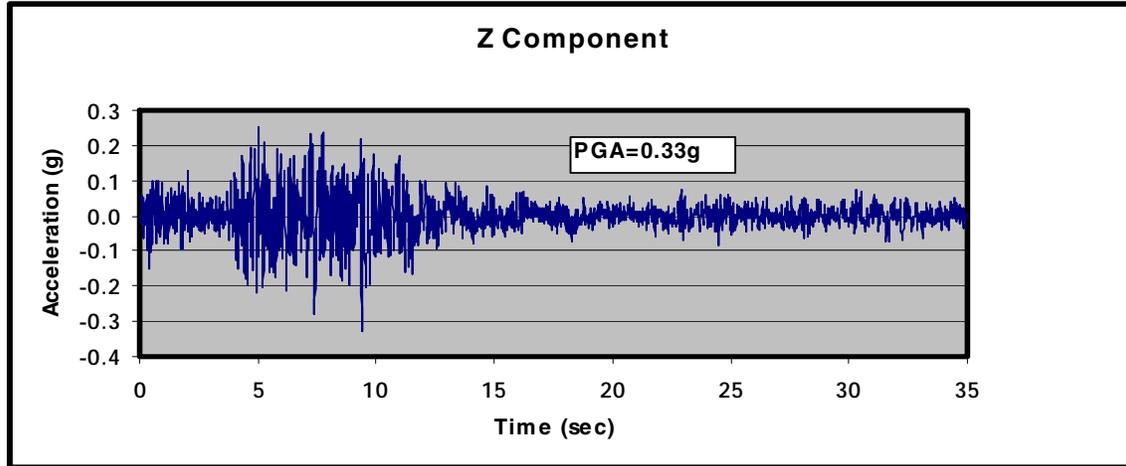


Figure 5(c). accelogram record for Z component of ground acceleration.

The velocity of the pressure wave in water is taken 1438.66 m/sec.

Environmental parameters

All the environmental and meteorological records were obtained from The Iran Meteorology Organization for a weather station located in Karaj. The average daily and the daily design temperatures are shown in Figure 6. The weather design temperature can be predicted as follows:

$$T_a(t) = 11.7 \sin\left(\frac{2\pi(t-113)}{365}\right) + 14.6 \quad (1)$$

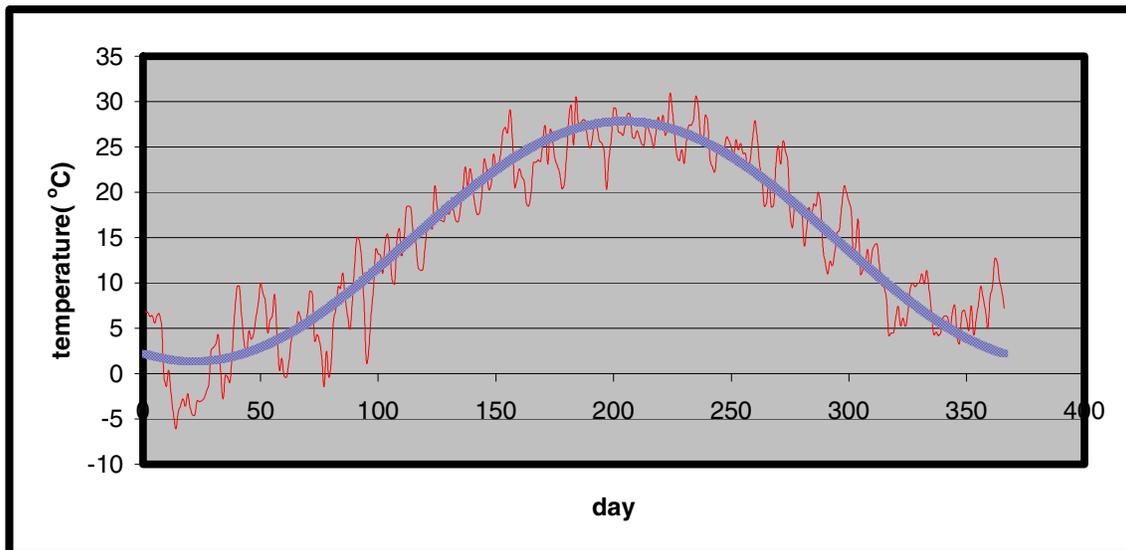


Figure 6. Average air temperature (daily average and sinusoidal representation of daily average temperature)

Daily variation of total, diffuse and beam solar radiation for horizontal surface are indicated in Figure 7. Collares-Pereire's suggestion is developed [11] and the diffuse and beam radiation data on a horizontal surface were deduced by the authors from total horizontal solar radiation data obtaining in weather station located in Karaj.

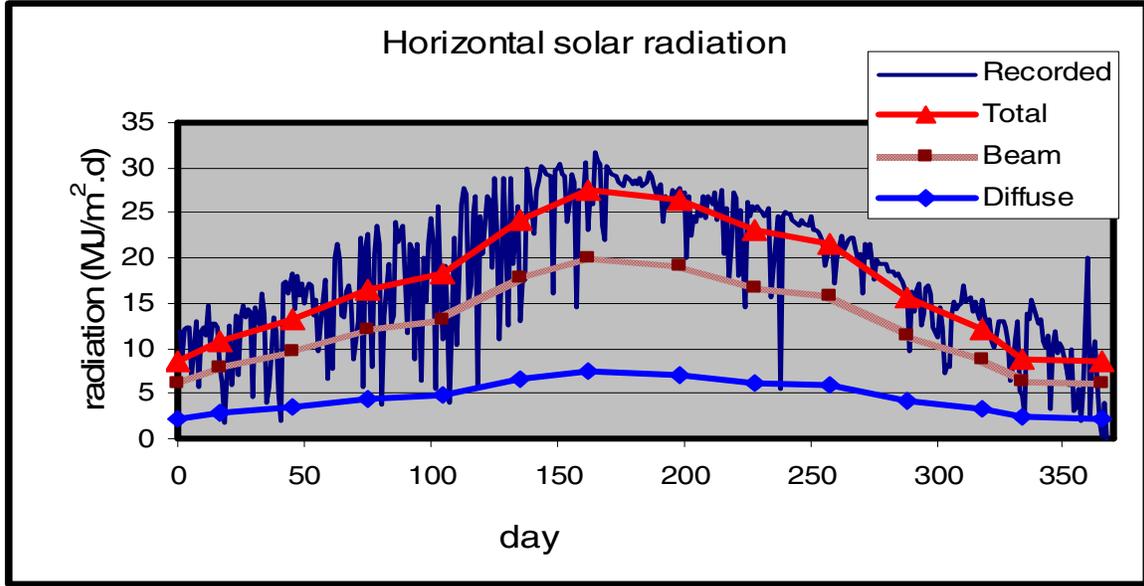


Figure 7. Variation of daily registered and design global, diffuse and beam solar radiations

Bofang's suggestion [8] with some small modifications for prediction of water temperature was used for the reservoir temperature by using the air-recorded temperatures. The water temperature T at depth y and time t becomes for reservoir of Karaj dam as follows:

$$T(y, t) = T_m(y) + A(y) \cos(\omega(t - t_0 - \xi)) \quad (T \geq 4.0^\circ C) \quad (2)$$

With

$$T_m(y) = C + (17.6 - C) \exp(-0.04y) \quad (2-a)$$

$$C = \frac{6 - 17.6g}{1 - g} \quad (2-b)$$

$$g = \exp(-0.04H) \quad (2-c)$$

$$A(y) = 13.25 \exp(-0.018y) \quad (2-d)$$

$$\xi = 65.4 - 39.42 \exp(-0.085y) \quad (2-e)$$

$$\omega = \frac{2\pi}{365} \quad (2-f)$$

Where

y = depth of water (m).

t = time (day).
 $T(y,t)$ = water temperature at depth y and time t ($^{\circ}\text{C}$).
 t_0 = the day which the air temperature is maximum (=203).
 H = depth of reservoir (m).

Figure 8 shows design daily variation of water temperature in various depth of Karaj dam reservoir.

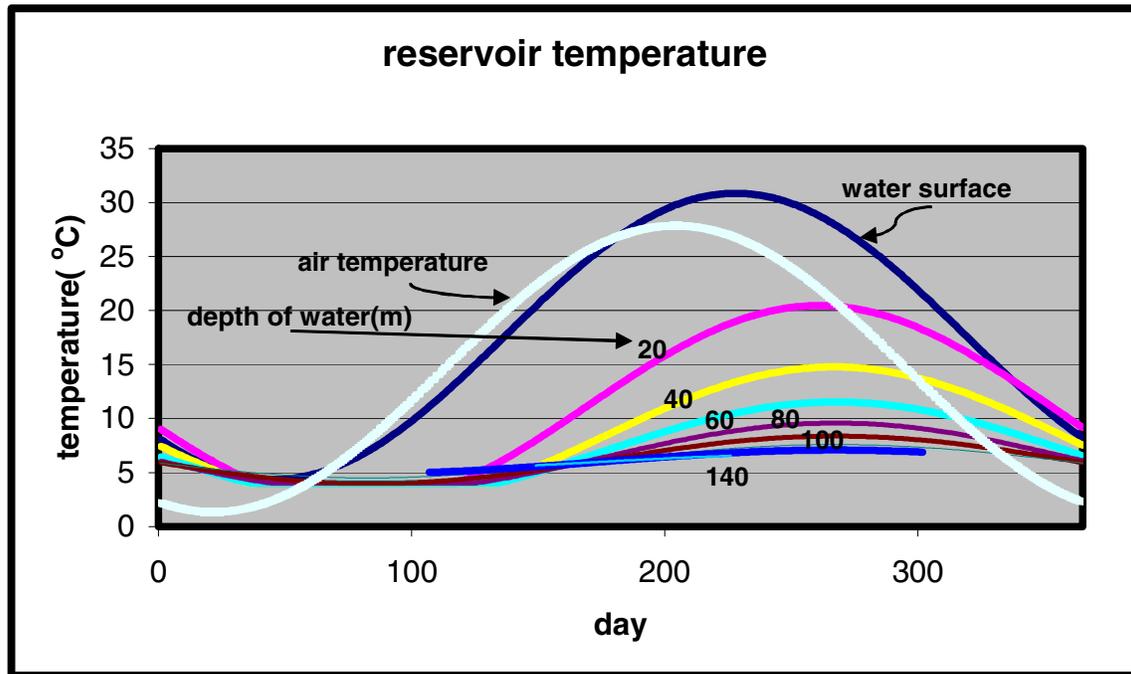


Figure 8. Design water temperature of Karaj Dam Reservoir.

It was assumed that the average values for ground and water reflectivity are 0.2 and 0.15 respectively.

RESULTS

The finite element mesh of Karaj dam for temperature distribution and static stress analysis consists of 3456 finite linear brick elements and 4675 nodes. For the purpose of dynamic stress evaluation, Sharan boundary condition is applied at a distance of $3H$ from the dam where H is the height of the dam. In dynamic analysis, the stiffness and mass proportional damping factor are obtained with considering to the 5% and 10% damping factor at the first and second modes respectively. The α -method of time integration with intervals of 0.02 is utilized. Figure 9(a) shows the maximum tensile stresses envelop distribution due to combination of static (temperature, self-weight and hydrostatic) loads and dynamic load. At the downstream face. Figure 9(b) shows the month when these maximum stresses occur. The maximum of tensile stresses in downstream face are estimated to occur in summer months (i.e. August and September). The figure shows that superficial tensile stresses are excessively increased at the downstream face and the probable cracks are expected in this region. These high-level of tensile stresses is predicted to be due the effect of temperature and hydrodynamic loads.

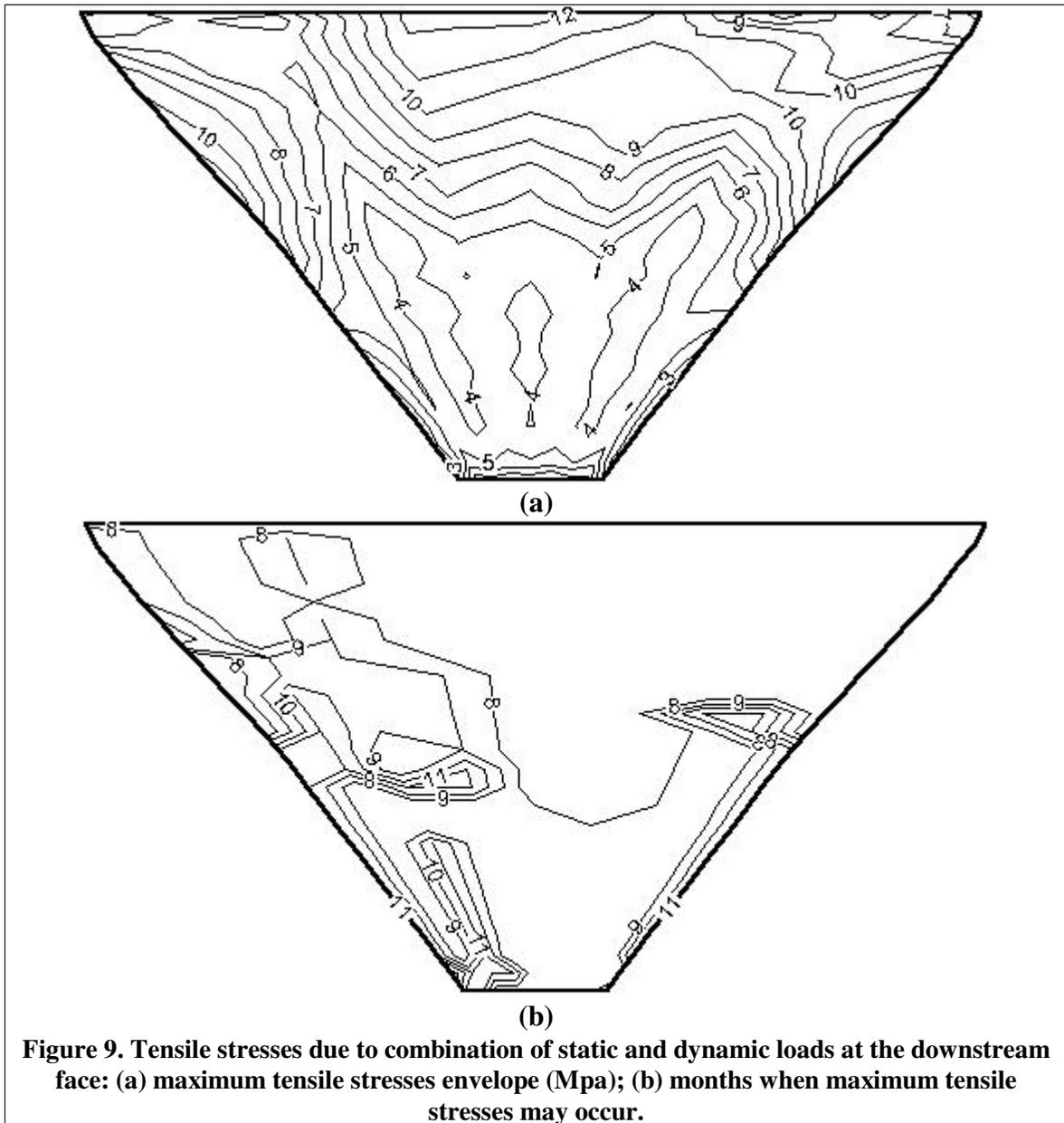


Figure 10(a and b) are related to maximum tensile stresses at upstream face due to combination of static and dynamic loads. The magnitude of tensile stresses in the upstream face regions, which located above the average of annual water level (i.e. 140m height from the foundation surface) are in a high level (more than the dynamic tensile strength of the mass concrete, i.e. 4.6 Mpa). The stress concentration is shown at the dam-foundation interface. The end of summer and beginning of fall seems to be critical from the viewpoint of high tensile stresses due to combination of static loads and propale earthquake load.

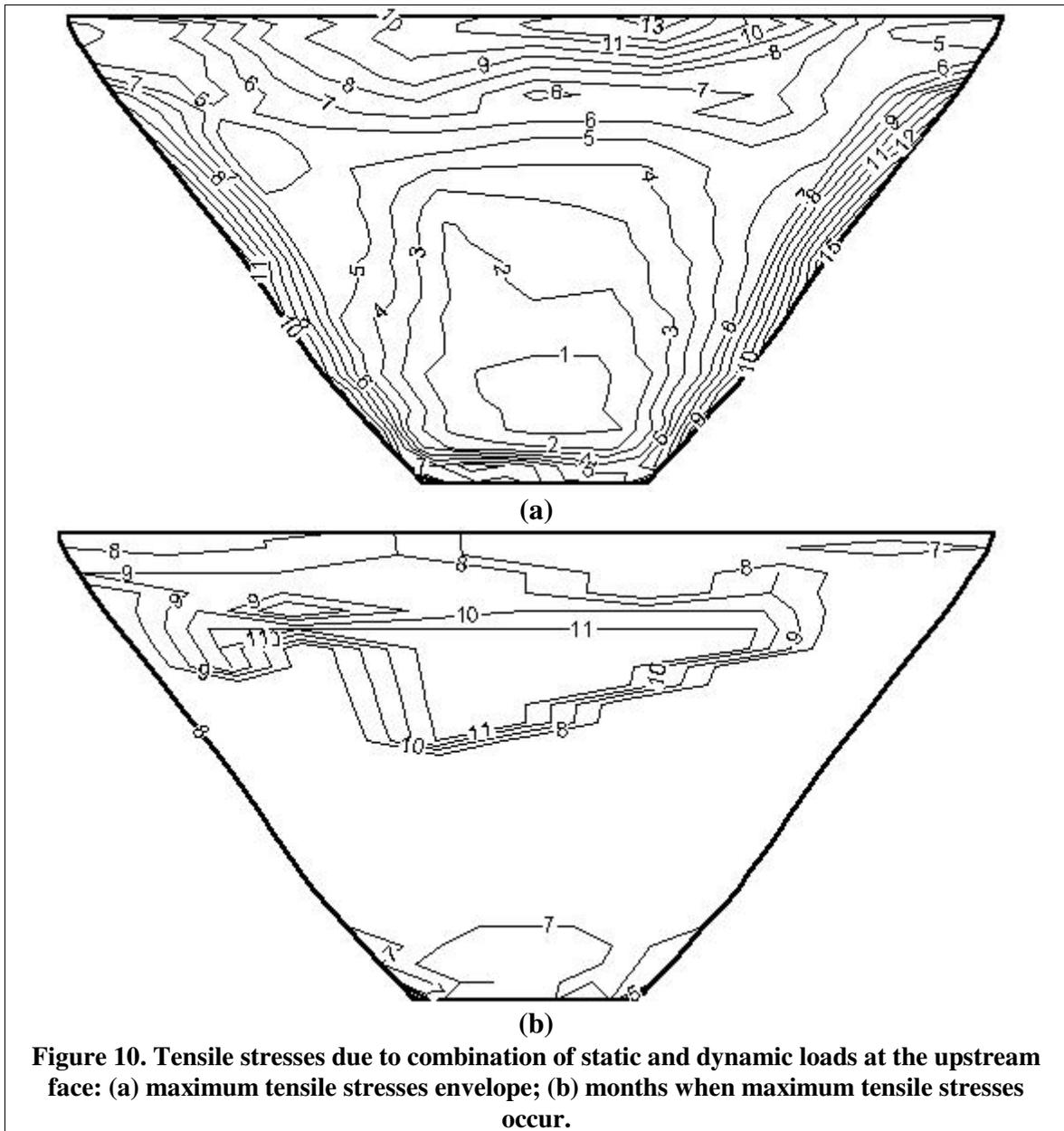
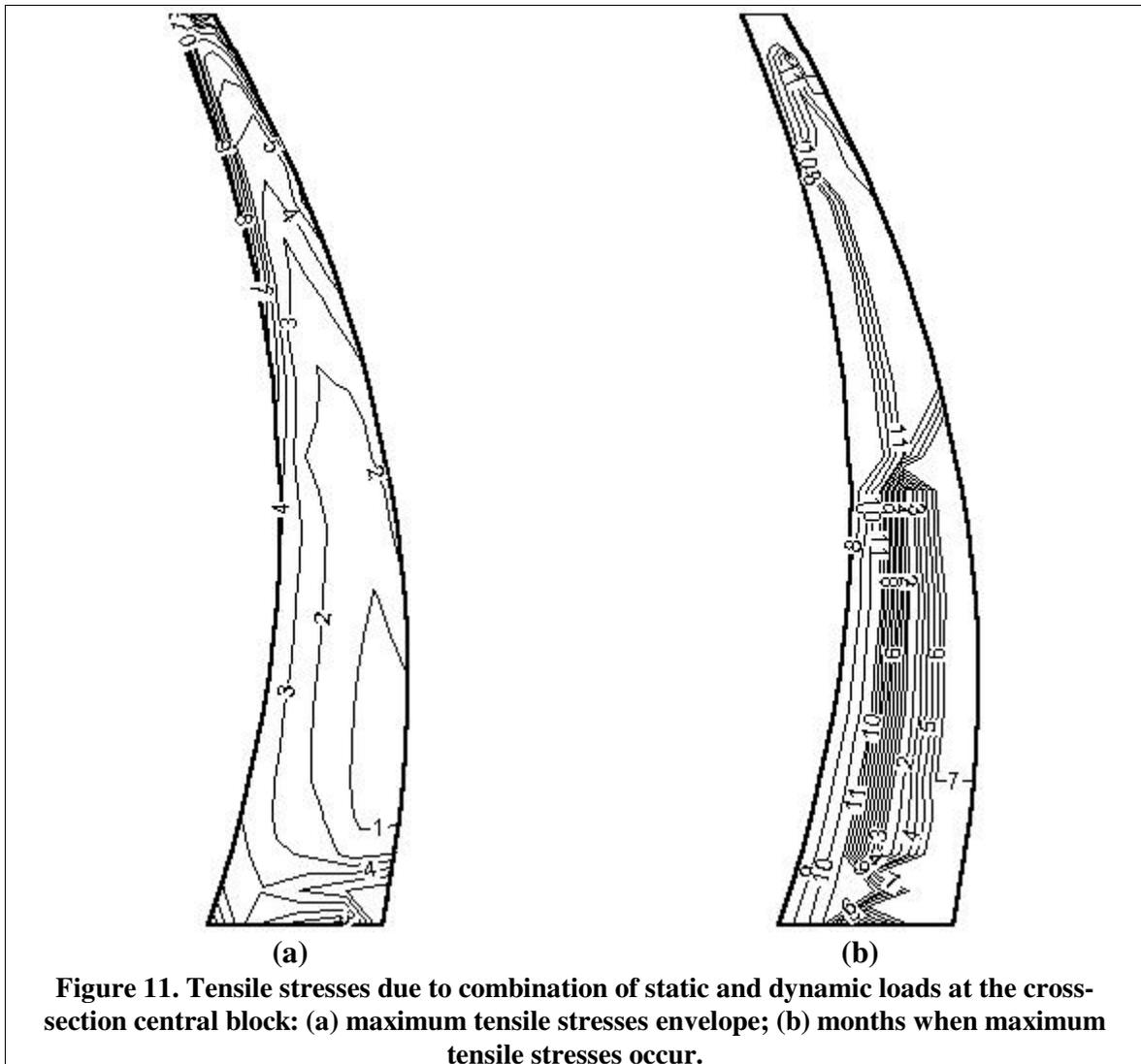


Figure 11(a and b) are related to maximum tensile stresses at the cross-section of central block due to combination of static and dynamic loads. The Figure shows that the crest region experiences high level of tensile stresses but the tensile stresses at inner region of the dam are not considerable in comparison with dynamic tensile strength of the concrete.



CONCLUSION

Based on the study carried out in this investigation the following results can be made:

- a. The end of summer and begin of fall seems to be critical from the viewpoint of high tensile stresses at different part of the dam. In the other words it is predicted that if Maximum Credible Earthquake occurs in this period, Karaj concrete dam bears the most damage.
- b. Due to the temperature and hydrodynamic loads, the tensile stresses are increased at the downstream face. In the other hand, the high level of tensile stresses at the upstream face is due to earthquake.

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REFERENCES

1. Us Army Corps Of Engineering, "Arch dam design." Engineer Manual 110-2-2201, 1994, Chapter 8, 1-15.
2. Tinavi R, Marchand J, Leger P. "Three dimensional static, thermal and seismic analysis of polygonal gravity dams." Dam Engineering 1994; V(3): 29-57.
3. Leger P, Venturelli J, Bhattacharjee S S. "Seasonal temperature and stress distributions in concrete gravity dams (part 1& 2).", Canadian Journal of Civil Engineering 1993; 20: 999-1025,
4. Agullo L, Aguado A. "Thermal behavior of concrete dams due to environmental actions." Dam Engineering 1995; VI(1): 3-21.
5. Zhang Z, Garga V K. "State of temperature and thermal stress in mass concrete structures subjected to thermal shock." Dam Engineering 1996; VIII (4): 337-351.
6. Meyer T, Mouvet L. "Behavior analysis of the Vieux-Emosson arch-gravity dam under thermal loads." Dam Engineering 1995; VI (4):
7. Daoud M, Galanis N, Ballivy G. "Calculation of the temperature field in a concrete dam." Canadian Journal of Civil Engineering 1997; 24: 772-784.
8. Bofang Z. "Prediction of water temperature in deep reservoir." Dam Engineering 1997; VIII (1): 13-25.
9. Ghaemian M, Ghobarah A. "nonlinear seismic response of concrete gravity dams with dam-reservoir interaction." Engineering Structures 1999; 21: 306-315.
10. Sharan S. "modeling of radiation damping in fluids by finite elemnt." Internatinal Journal of Numerical Methods in Engineering 1986; 23: 945-57.
11. Duffie J, Beckman W. "Solar engineering of thermal processes.", John Wiley & Sons, 1980,1-140.