

NONLINEAR ANALYSIS OF PINE FLAT DAM INCLUDING BASE SLIDING AND SEPARATION



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SUMMARY

Nonlinear earthquake response of the tallest, non-overflow monolith of Pine Flat Dam to Taft ground motion, scaled to 0.5g has been presented in this study so as to investigate the possibility of sliding and separation at the base of dam and to study its effect on the dynamic response of dam-foundation system. Proposed finite element based dynamic model has the ability to simulate radiation damping at the far field using a transient transmitting boundary. The interaction with both foundation and the reservoir has been considered. It has been found that both sliding and separation modes of the interface dominate the deformations as well as the principal stresses in the dam body. Moreover, sliding and rocking displacements have been found to be quite considerable, especially at the heel.

Key words: Transient transmitting boundary, Dynamic soil- structure interaction, Pine flat dam, Non-linear Analysis, Sliding and separation.

1. INTRODUCTION

Potential failure mode of a concrete gravity dam during an earthquake is extensive cracking and deformation in the region between the base of the dam and the foundation rock (base sliding displacement). Development of mathematical models for predicting the seismic response of concrete gravity dams, including interface zone deformation, is a complex problem due to interaction between the dam and compressible water and between the dam and the foundation rock (Chavez and Fenves 1995a, b). In the present study, nonlinear dynamic model, formulated directly in time domain (Al-Assady 2005), has been used to investigate the possibility of sliding and separation at the base of dam and to study its effect on the interactive dynamic response of Pine Flat Dam-foundation system. The model is based on the use of transient transmitting boundary to simulate a non-reflecting boundary at the far field (Al-Assady 2005). Nonlinearity of both concrete dam and the foundation material has been represented through proper constitutive modeling. Sliding and separation along the dam-foundation interface has also been considered through an interface element proposed by Al-Assady (2005).

2. EARLIER WORK

El-Aidi (1988) and Hall et al. (1991) studied the nonlinear response of Pine Flat Dam including the opening of crack and its propagation along dam-foundation interface using smeared crack approach. The foundation was represented by frequency-independent impedance coefficients. Study indicated that although uplift over part of the base can occur, rocking of dam about the base is not that important and there is a permanent slip at the base due to sliding of dam. Leger and Katsouli (1989) studied the stability of concrete gravity dam in which sliding at the interface was represented by gap-friction elements. The results suggested that nonlinear deformation of dam-foundation rock interface reduces the seismic response of the dam. Chopra and Zhang (1991) studied the sliding response of a gravity dam founded on

rigid rock using a simplified model. Base sliding was shown to be more important than rocking of dam about the toe or the heel. Danay and Adeghe (1993) developed an empirical expression based on a statistical regression analysis of many simplified dynamic studies for estimating the sliding displacement of gravity dams. Chavez and Fenves (1995a,b) developed a model for base sliding including dam-water body interaction considering the compressibility of water, reservoir bottom absorption, and dam-foundation interaction. Hybrid time-frequency domain procedure was used. The results suggested that sliding can occur during a moderate earthquake. Mir and Taylor (1996) performed numerical analysis for studying base sliding and rocking characteristics of a gravity dam using a Lagrangian contact surface algorithm. A comparison of experimental and analytical studies suggested that the algorithm could predict seismically induced slip with reasonable accuracy.

Most of the above investigations were conducted in frequency domain and thus excluded the effect of nonlinearity, which in most cases, governs the response of the dam to seismic excitation. Furthermore, earlier work generally focused on base sliding only while the possibility of separation and the corresponding opening/rocking displacements were ignored. These factors play a dominant role on the sliding response of gravity dams.

3. ANALYSIS OF PINE FLAT DAM INCLUDING BASE SLIDING AND SEPARATION

3.1 Modeling of dam - foundation system

Recently developed FEM based dynamic model (Al-Assady, 2005) has been employed to simulate the Pine Flat Dam (on King's river near Fresno in California, USA)-foundation system since it has been proved to yield accurate results. Far field has been represented by a transient transmitting boundary. **Figure 1** shows discretization of dam and its foundation including the interface zone along with those nodes and elements where displacements and stresses have been monitored. The size of foundation domain was decided based on the criterion available in the literature (Al-Assady 2005) according to which, the foundation domain extending to a distance of 1.5 times the base width of dam is enough to model the radiation damping since the foundation stiffness is high. The sliding and separation along dam-foundation interface was modeled through interface elements (Al-Assady 2005). A nonlinear elasto-plastic model with hardening was employed for both dam and its foundation with Mohr-Coulomb yield criterion for foundation rock and Owen and Figueiras (1984) yield criterion for concrete. The reservoir which was considered full during the analysis was modeled using the Westergaard approach and added mass concept (Westergaard, 1933).

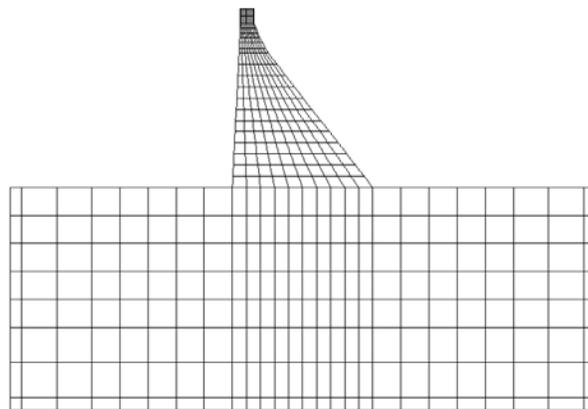


Figure 1. Finite element mesh used to model pine flat dam-foundation-reservoir system including interface zone

The material properties of Pine Flat Dam including its foundation and interface zone are:

Concrete Dam: $E_c = 22.41$ GPa, $\nu_c = 0.20$, $\rho_c = 2483$ kg/m³, Fracture Energy, $G_f = 75.00$ N.m/m², $f'_c = 22.41$ MPa, $f'_t = 2.241$ MPa, Strain at Peak Compressive Stress, $\epsilon_c = 0.0025$, Strain at Crack Condition, $\epsilon_{cr} = 0.00012$,

Rock Foundation: $E_f = 22.41$ GPa, $\nu_f = 0.333$, $\rho_f = 2644$ kg/m³, Cohesion, $c_f = 500.0$ kN/m², Friction angle, $\phi_f = 30^\circ$,

Interface Properties: Normal stiffness, $K_{nn} = 1000$ GPa /m, Shear stiffness, $K_{ss} = 100$ GPa/m, Coefficient of friction, $\mu = 0.5$,

Newmark's Integration Constants : $\alpha = 0.3025$, $\delta = 0.6000$, Time Step Size, $\Delta t = 0.002$ sec, Duration of Analysis = 16.0 sec.

In the system of dynamic equations of motion, the seismic loading was not applied to the foundation mass (Al-Assady 2005). The system was subjected to horizontal component of Taft ground motion (S69°E), recorded at the Lincoln School Tunnel during the 1952 Kern County earthquake. The horizontal component of the ground motion has been scaled to a peak ground acceleration of 0.5g as shown in **Fig. 2**, which is a typical scaling factor for strong earthquakes.

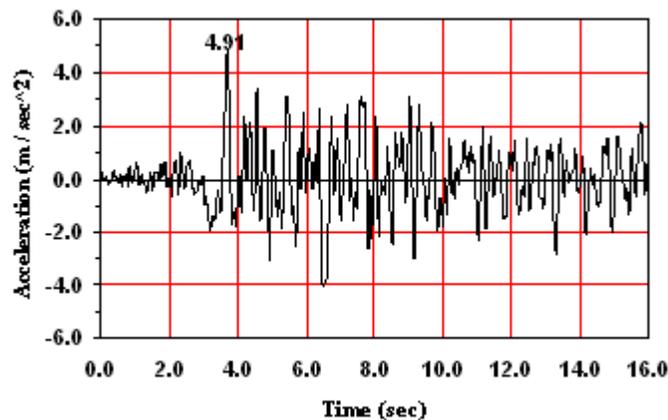


Figure 2. Ground acceleration record of horizontal component (S69E) of Taft earthquake (July 21, 1952)

4. RESULTS AND DISCUSSION

4.1 Perfect Bond Case

Both linear and nonlinear analyses of Pine Flat Dam were carried out to investigate the response of dam to horizontal component of the Taft ground motion scaled up to 0.5 g with a perfect bond condition at the dam base. The time history of horizontal and vertical displacements at the crest (Node-A) has been presented in **Figs. 3a,b** for both linear as well as the nonlinear analysis. It can be seen that horizontal displacement of the crest increases from 110.98 mm in linear analysis to 257.47 mm in nonlinear analysis (132 %), while the vertical displacement of crest increases from 27.97 mm to 84.39 mm (202 %) respectively. In general, nonlinearity of both the dam and the rock foundation causes yielding of large zones, especially near the heel. It is well known that the true response of both dam- rock foundation is nonlinear, especially under severe earthquake.

It has been observed that major and minor principal stresses increase from 3.699 MPa and -4.921 MPa in linear analysis to 6.315 MPa and -8.202 MPa in a nonlinear analysis (70 % and 67 %) respectively (Fig. 4a,b). This increase can be attributed, on one hand, to the way the concrete behavior has been modeled where the cracking has not been allowed and on the other, due to large deformations of the dam caused by significant yielding of the foundations zones. It can be seen that nonlinearity of concrete and the foundation rock exerts a significant influence on the response of dam-foundation system wherein both deformations and principal stresses increase significantly.

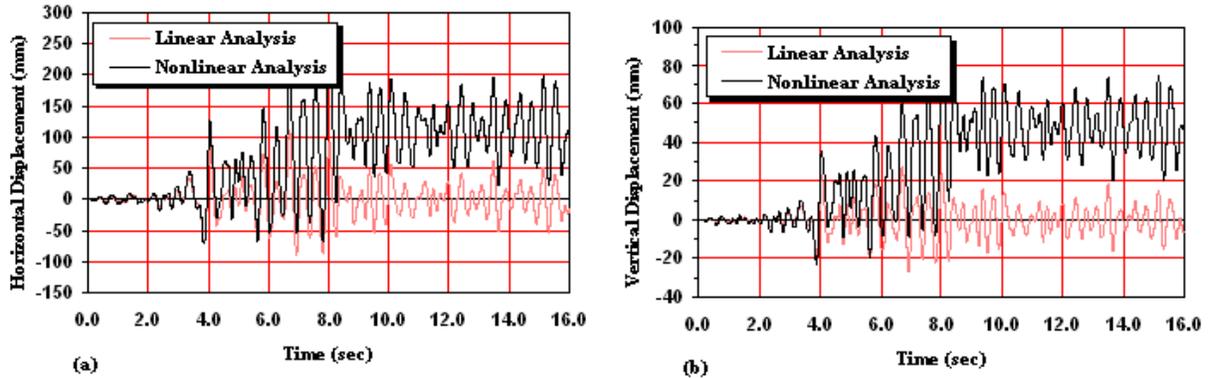


Figure 3. Time history of displacements at crest of pine flat dam for perfect bond case: linear Vs. nonlinear analysis; (a) horizontal displacement; and (b) vertical displacement

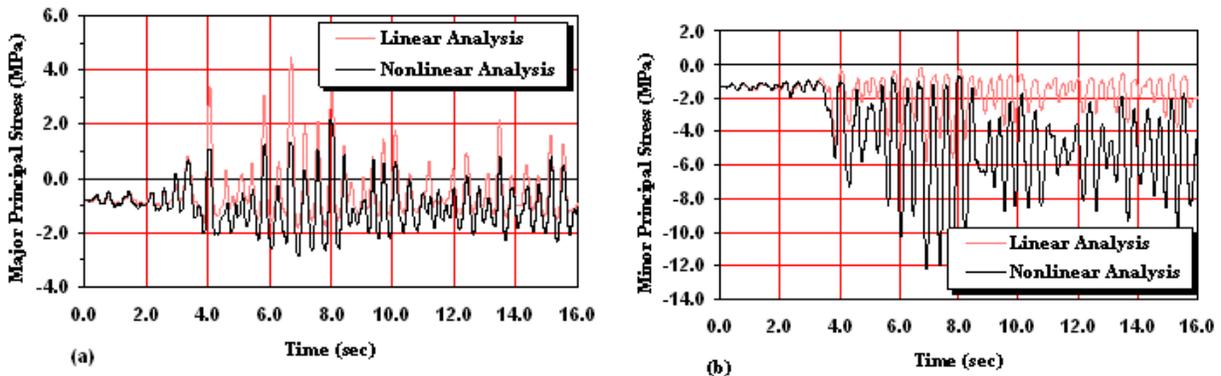


Figure 4. Time history of principal stresses in element-1 (Heel) of Pine Flat dam for perfect bond case: linear Vs. nonlinear analysis; (a) major principal stress; and (b) minor principal stress

4.2 Pure Sliding Case

Time history of horizontal and vertical displacements at the crest, Node-A, is presented in Figs. 5a, b for both - pure sliding case and the perfect bond case. The horizontal displacement of the crest has reduced from 257.47 mm for perfect bond case to -197.97 mm for the pure sliding case with a change in the direction of crest displacement. On the other hand, the vertical displacement of the crest has reduced by 43.7 % from 84.39 mm for the perfect bond case to the 47.5 mm for the pure sliding case. General reduction in the deformation response is due to energy dissipation within the interface zone when the dam is allowed to slide. This interface zone can be said to work as an *isolation device* while reducing the deformations.

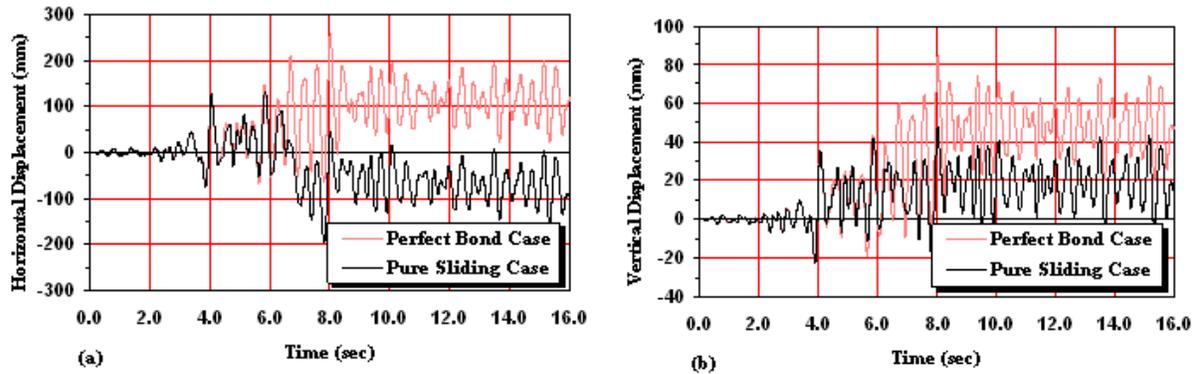


Figure 5. Time history of displacements at crest of Pine Flat dam for perfect bond case: linear Vs. pure sliding case; (a) horizontal displacement; and (b) vertical displacement

The time history of this sliding displacement has been depicted in **Fig. 6** for both heel and the toe of the dam. The maximum sliding displacement at the heel is -92.78 mm while it is -157.59 mm for the toe region. It is important to mention that this sliding displacement is local since the width of the dam is significant and some nodes, especially the central portion of the dam base, may still continue to remain in contact.

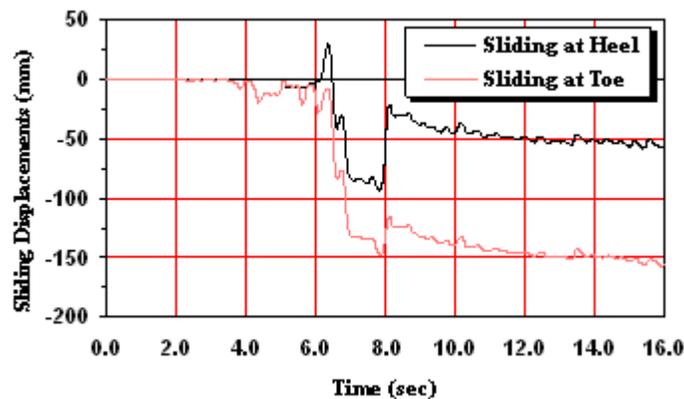


Figure 6. Time history of sliding displacement at heel and toe of Pine Flat dam: pure sliding case; nonlinear analysis

Figures 7a,b show the time history of major and minor principal stresses in the heel region. In general, allowing the dam to slide along its base helps in reducing the principal stresses in both the heel and the neck regions in comparison to the perfect bond case. For the perfect bond case, the major and minor principal stresses at the heel are 2.171 MPa and -12.570 MPa respectively, while these reduce to 1.672 MPa and -12.472 MPa respectively for the pure sliding case. A noticeable point is the maximum value of minor principal stress at the heel for pure sliding where it has not changed from the perfect bond case. This behavior may be due to the tendency of the heel to separate rather than to slide and it is believed that a major part of the sliding component comes from the separation mode, which is not allowed in a pure sliding case. Therefore, at this location, there is a resistance to sliding which increases the minor principal stress to a very high value and does not change much from the perfect bond case. The behavior in the neck region is different wherein both major and minor principal stresses have reduced from 6.315 MPa and -8.202 MPa for the perfect bond case to 5.177 MPa and -5.884 MPa for the pure sliding case (**Table 1**).

Therefore, it can be concluded that allowing the dam to slide along its base reduces significantly both deformations as well as the principal stresses in the dam body. Hence, a pre-formed joint, if properly constructed, may be able to eliminate the earthquake induced cracking altogether and thus confine the nonlinear behavior of the type associated with cracking to the plane of the interface itself. Such a model may be used as a defensive design measure against an earthquake and this point has also been noted in the earlier studies (Leger and Katsouli 1989, Hall et al. 1991).

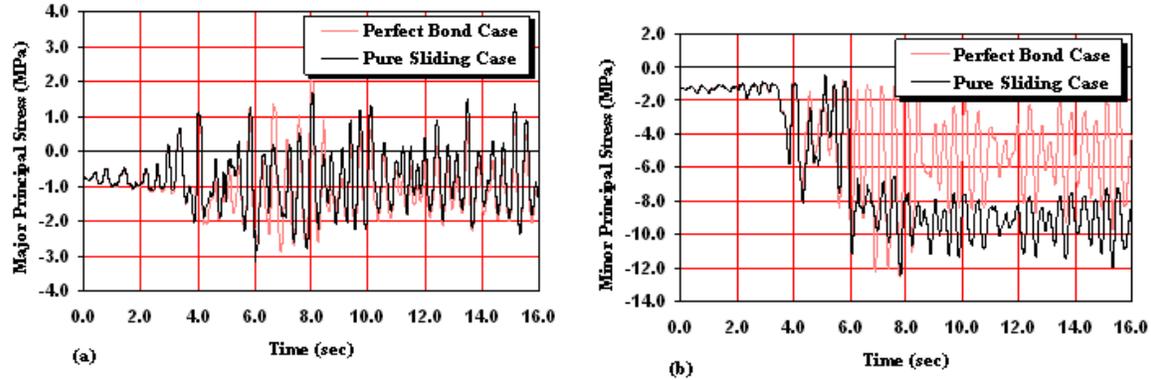


Figure 7. Time history of principal stresses in element-1 (Heel) of Pine Flat dam: linear Vs. pure sliding case; nonlinear analysis; (a) major principal stress; and (b) minor principal stress

Table 1. Comparison of Response Parameters of Pine Flat Dam for Different Interface Modes

Base Condn.	Crest Displ't.		Relative Displ't. at Heel		Relative Displ't. at Toe		Element-1		Element-2	
	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.	σ_1	σ_3	σ_1	σ_3
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(MPa)	(MPa)	(MPa)	(MPa)
Perfect Bond	257.47	84.39	-	-	-	-	2.17	-12.57	6.32	-8.20
Pure Sliding	-197.97	47.50	-92.78	-	157.59	-	1.67	-12.47	5.18	-5.88
Sliding and Separation	-162.60	-46.32	-177.10	-54.36	-81.03	-17.08	2.15	-5.53	4.94	-5.29

4.3 Sliding and Separation Case

Time history of horizontal and vertical displacements at the crest has been presented in **Figs. 8a, b**. For the sake of comparison, time history for the perfect bond case has also been superimposed in these plots. For the perfect bond case, the horizontal crest deformation is 257.47 mm and the vertical component of deformation is 84.39 mm. When both the sliding and separation are allowed, horizontal displacement

reduces to -162.60 mm (36.8 %) and the vertical displacement, to -46.32 mm (45.1 %). The interface zone works as an isolator device and dissipates the energy within the interface itself.

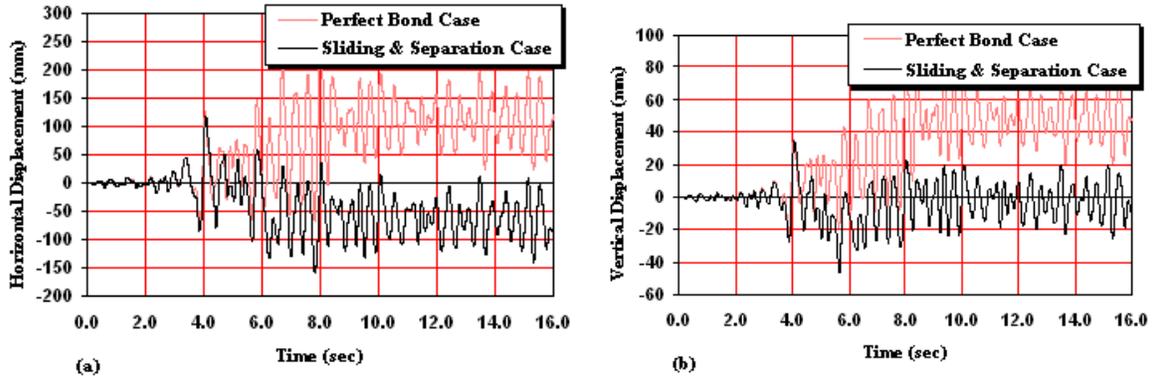


Figure 8. Time history of displacements at crest of Pine Flat dam: perfect bond Vs. sliding & separation case; nonlinear analysis; (a) horizontal displacement; and (b) vertical displacement

The time history of sliding and rocking displacements presented in **Figs. 9a,b** for both the heel and the toe shows a tendency of Pine Flat dam to slide as well as to separate from its base. The maximum sliding and rocking displacements at heel are -177.1 mm and -54.36 mm while the corresponding values at the toe are -81.03 mm and -17.08 mm. It can be seen that there is a tendency of the dam to overturn about the heel and a significant part of sliding may develop due to this rocking movement. On the other hand, the toe shows a tendency of sliding only as rocking is almost insignificant.

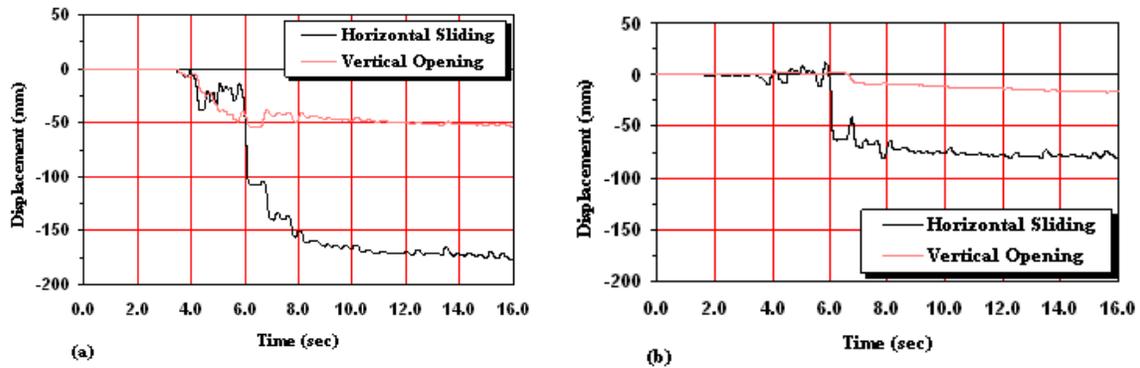


Figure 9. Time history of sliding and opening displacements at heel and toe of Pine Flat dam for sliding & separation case; nonlinear analysis; (a) at heel; and (b) at toe

The time history of major and minor principal stresses in the heel region, Element-1, is presented in **Figs. 10a,b**. In the heel region, there is only a marginal change of major principal stress for both the cases. However, the minor principal stress reduces from -12.557 MPa to -5.525 MPa (56 %) when both sliding and separation are allowed. The behavior at the neck region is somewhat different where both major and minor principal stresses have reduced from 6.315 MPa and -8.202 MPa for the perfect bond case to 4.935 MPa (22 %) and -5.288 MPa (35.5 %) for the case of sliding and separation respectively (Table 2). In general, the principal stresses in both the heel and neck regions have reduced once the combined sliding and separation modes are allowed. However, this reduction is more pronounced in the neck region, especially for the minor principal stress.

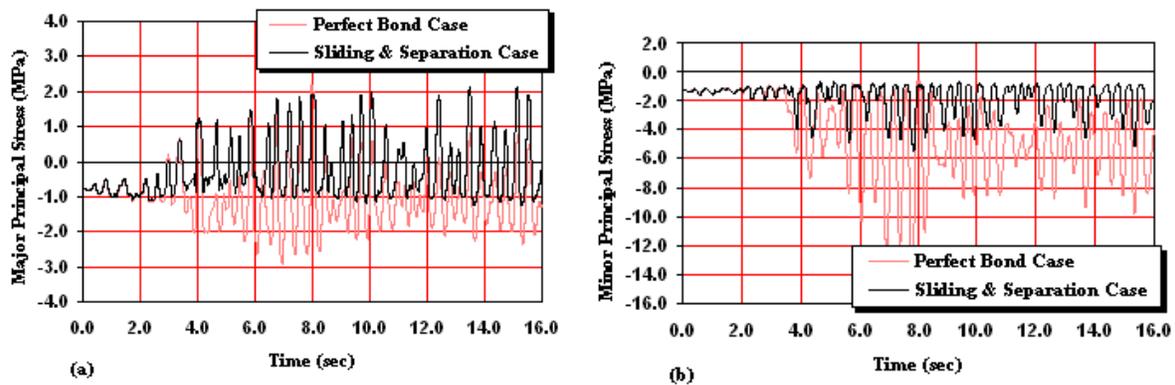


Figure 10. Time history of principal stresses in element-1 (Heel) of Pine Flat dam: perfect bond Vs. sliding & separation case; nonlinear analysis; (a) major principal stress; and (b) minor principal stress

5. CONCLUSIONS

Based on the study of the influence of interface characteristics, particularly the sliding and separation along the base of the dam, the following conclusions can be drawn:

- i) Nonlinear analysis of dam-foundation system with perfect bond condition at the base of dam results in significantly high values of deformation at the crest and stresses at the heel and near the neck region of dam.
- ii) Allowing the dam to slide along its base or to slide as well as to separate at the interface zone reduces significantly both the deformations as well as the principal stresses in the dam body. Hence, a preformed-joint, if properly constructed, may be able to eliminate the earthquake induced cracking altogether and thus confine the nonlinear behavior of the type associated with cracking to the plane of the interface itself. Such a model may be used as a defensive design measure against earthquake.
- iii) Nonlinear analysis of dam-foundation system considering both sliding and separation modes at the interface results in significant sliding and rocking displacements, especially at the heel and therefore, the base condition is an important parameter in the earthquake response of concrete gravity dams.
- iv) Modeling the separation mode in addition to sliding mode causes a significant contribution to sliding displacements at the heel, therefore, the sliding displacement increases in case of the sliding and separation mode.

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