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PROBABLE ROLE OF SEFIDRUD RESERVOIR IN THE OCCURRENCE OF THE RUDBAR EARTHQUAKE OF 1990

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ABSTRACT

A highly simplified simulation of the Sefidurd reservoir load is used to estimate the resolved normal and shear stresses on the causative fault of the main Rudbar earthquake of 1990, as inferred from the fault plane solution interpreted in light of the local geology. The estimated stresses are small, being in the range of a few Kilopascal or less. We conclude that the influence of Sefidrud reservoir load was to oppose the occurrence of the Rudbar earthquake.

INTRODUCTION

Can a reservoir influence the occurrence of earthquakes in its vicinity ? The question is of considerable importance. But it is hard to answer because of difficulties in acquiring the necessary data from the hypocentral depths in the crust under a reservoir. Snow (1972) attempted to answer the question from rock mechanics considerations alone. He demonstrated lucidly that an infinite reservoir would promote earthquake occurrence in strike-slip and normal fault type ambient stress environments in the crust, but inhibit earthquake occurrence in the thrust fault environment. Recently Chander and Kalpana (1996) have generalised Snow's (1972) procedure to anlyse the influence of finite reservoirs on seismogenic faults in its vicinity. In this article we use that procedure to assess the role of the Sefidrud reservoir (Fig. 1), impounded in 1962. on the occurrence of the Rudbar earthquake in 1990.

Althrough both stress and pore pressures may act at the hypocentre of an earthquake, attention is focussed here initially on the load induced stress alone. The following theory is outlined accordingly by omitting the pore pressure term.

BASIC CONCEPT

Stresses due to many causes act at the hypocentre of a future earthquake. The most important of these are the stresses due to crustal over-burden, topography and tectonic effects. The construction of the dam and reservoir will produce its own stresses at the hypocentre. These reservoir induced stresses will be of relatively small magnitude and they will merely perturb the ambient stresses. The important question to decide, however, is whether the reservoir induced stresses assist or oppose the ambient stresses in the

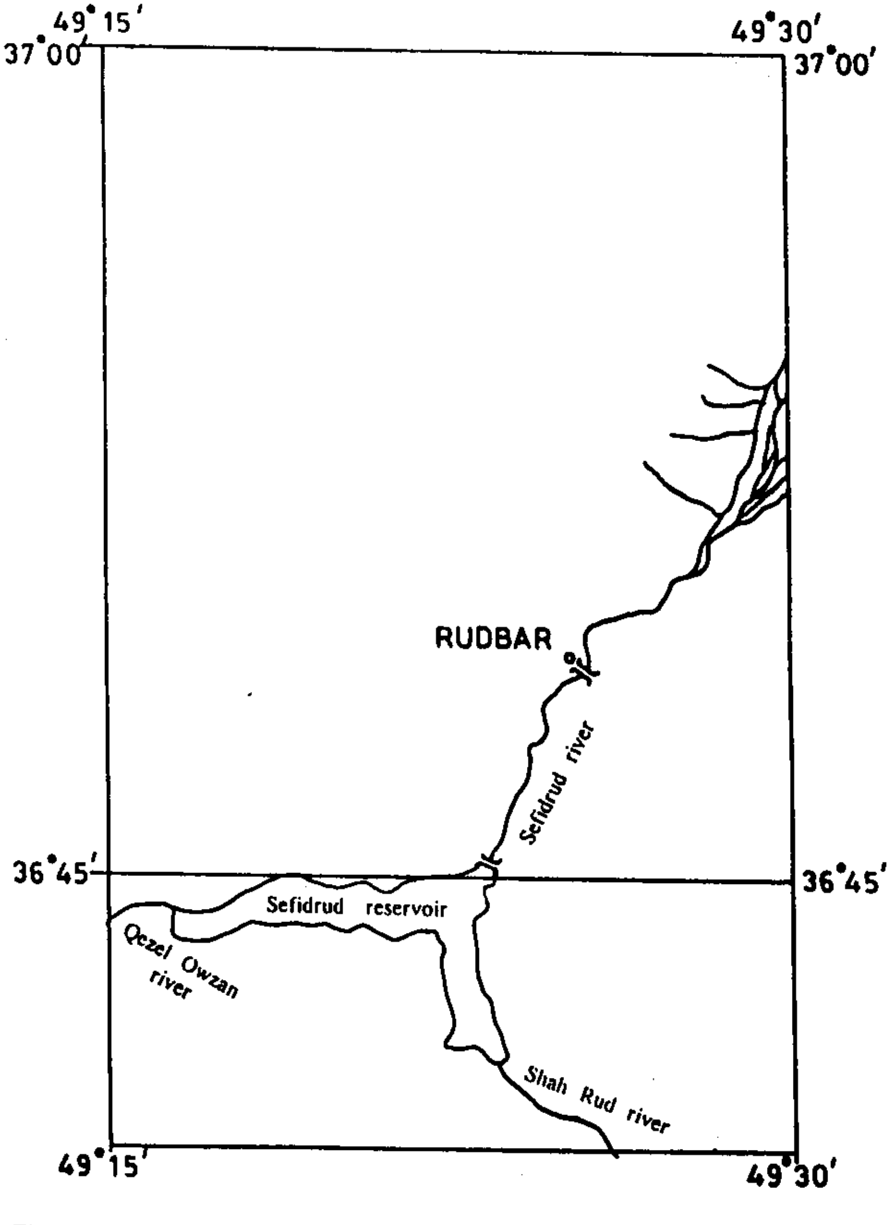

Fig. 1 Map showing Sefidrud reservoir. Extracted from the geological map of the region by Geological Survey of Iran, 1969, Geological Quadrangle No. D4.

occurrence of the earthquake. This may be done conveniently in three dimensions by resolving the contributions from all causes of stresses into normal and shear stress components on the causative fault of the earthquke at the hypocentre. The contribution from all causes other than the reservoir may be combined vectorially to yield the resultant ambient normal stress $\sigma_a(t)$ and the resultant ambient shear stress $\tau_a(t)$. The reservoir induced normal and shear stress are $\sigma_r(t)$ and $\subset_r(t)$. Here t is time.

The total normal stress on the fault at the hypocentre is then

$$\sigma_T(t) = \sigma_a(t) + \sigma_r(t) \tag{1}$$

The total shear stress on the fault is

$$\tau_T(t) = \left[\tau_a^2(t) + \tau^2(t) + 2\tau_a(t)\ \tau_r(t)\ cos\theta(t)\right]^{1/2}$$

where $\theta(t)$ is the angle between $\tau_a(t)$ and $\tau_r(t)$ measured in the plane of the fault at the hypocentre. As mentioned above, $\tau_r(t)$ will be much smaller than $\tau_a(t)$ in general. Therefore, correct to first order of small quantities.

$$\tau_T(t) = \tau_a(t) + \tau_r(t)\cos\theta(t) \tag{2}$$

The question of reservoir induced stresses aiding or opposing ambient stress may be settled using the concept of fault stability. Total fault stability (Bell and Nur, 1978; Roeloffs, 1988) may be defiened as :

$$S_T(t) = \sigma_T(t)\tan\varphi(t) - \tau_T(t) \tag{3}$$

Here $\varphi(t)$ is the time dependent angle of friction on the fault. Substituting from equations (5.1) and (5.2), we may write

$$S_T(t) = S_a(t) + S_r(t) \tag{4}$$

where

$$S_a(t) = \sigma_a(t)\tan\varphi(t) - \tau_a(t) \tag{5}$$

and

$$S_r(t) = \sigma_r(t)\tan\varphi(t) - \tau_r(t)\cos\theta(t) \tag{6}$$

As explained by Chander and Kalpana (1996), the reservoir may be regarded as opposing or assisting the occurrence of an earthquake as follows.

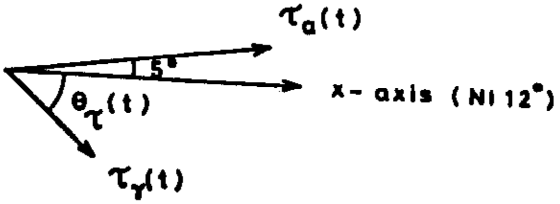

Fig.2 The ambient and reservoir induced shear stresses in the fault plane may not be collinear and the resultant may be found by vector addition precisely or by an approximation as dissucssed in text.

$S_r(t) > 0$; reservoir opposes the occurrence of earthquake
$S_r(t) < 0$; reservoir assists the occurrence of earthquake.
$S_r(t) = 0$; reservoir neither opposes nor assists the occurrence of the earthquake.

The meaning of opposing the earthquake is that ambient shear stress $\tau_a(t)$ on the fault has to accumulate for a longer time for the earthquake to occur. The earthquake is delayed due to the reservoir. Similarly assisting the occurrence of earthquake means that ambient shear stress $\tau_a(t)$ has to accumulate for a shorter time. The time of the earthquake is advanced due to the reservoir impoundment.

ESTIMATION OF RESERVOIR INDUCED STRESSES

Boussinesq point load theory may be used to compute $\sigma_r(t)$ and $\tau_r(t)$ due to a finite reservoir. This involves dividing a given reservoir load into an array of point loads and then adding stress contributions of all them at the hypocentre.

Simulation of the Sefidrud Reservoir Load

We simulate the Sefidrud reservoir as two long triangular pyramids. One of the pyramids is in the E-W direction approximately and it simulates the Shah Rud river branch of the reservoir. The second is in the N-S direction approximatelu and it simulates the Qezel Owxan river branch of the reservoir. The maximum depth of the water is taken to be 100 in and it is assumed that it decreases linearly away from the dam in each reservoir branch. The first pyramid is divided into ten parts and the second is divided into six parts. For each of these 16 parts, the point load is calculated by.

$$P_i(t) = pV_i(t)g \qquad , i = 1,2, \ldots, 16 \qquad (7)$$

where p is density of water, g the acceleration due to gravity is considered to be 10 m/s^2 and $V_i(t)$ is volume of the ith part at time t.

Causative Fault of the Main Rudbar Earthquake

We adopt the fault plane solution of Berberian et al. (1992) for the main Rudbar earthquake to simulate the causative fault. The vertical nodal plane striking N112° is adopted as the fault plane. According to Berberian, et al., (1992) the slip vector across this plane was such as to cause rocks on the SSW of the fault to move mainly eastward and slightly upwards along a line making an angle of 5° with the horizontal (Fig. 2).

This is deduced from the slip vector of the chosen nodal plane in the fault plane solution. The angle $\theta(t)$ of equation (6) is measured in the fault plane from this direction.

Orientation of the X and Y axis of the Coordinate System

For computational convenience, we chose the X-axis of the coordinate system along the strike and Y-axis normal to the chosen fault plane. The positive directions of these axes have azimuths of N112° and N202° respectively, Z-axis points vertically down.

Expressions for Stress Components

Then the normal stress $\sigma_r(t)$ of Equation (6), in terms of the above coordinate system.

$$\sigma_r(t) = \sum_{i=1}^{16} \sigma_{y_i}(X_H, Y_H, Z_H, t) \tag{8}$$

Here X_H, Y_H *and* Z_H are the coordinates of the hypocentre. The magnitude of shear stress $\tau_r(t)$ of Equation (6) is

$$\tau_r(t) = \left[\left(\sum_{i=1}^{16} \tau_{yx_i}(X_H, Y_H, Z_H, t)\right)^2 + \left(\sum_{i=1}^{16} \tau_{yz_i}(X_H, Y_H, Z_H, t)\right)^2\right]^{1/2} \tag{9}$$

The direction of $\tau_r(t)$ makes angle

$$\theta_r(t) = \tan^{-1} \frac{\sum_{i=1}^{16} \tau_{yz_i}(X_H, Y_H, Z_H, t)}{\sum_{i=1}^{16} \tau_{yx_i}(X_H, Y_H, Z_H, t)} \tag{10}$$

with the X-axis.

The desired $\theta(t)$ of equation (6) in the present case is then

$$\theta(t) = \theta_r(t) + 5^\circ \tag{11}$$

STABILITY COMPUTATION AT THE HYPOCENTRE

The computer stresses σ_r, τ_r at the hypocentre of the 1990 Rudbar earthquake are listed in Table 1. The estimated stresses are small, being in the range of a few kpa or less.

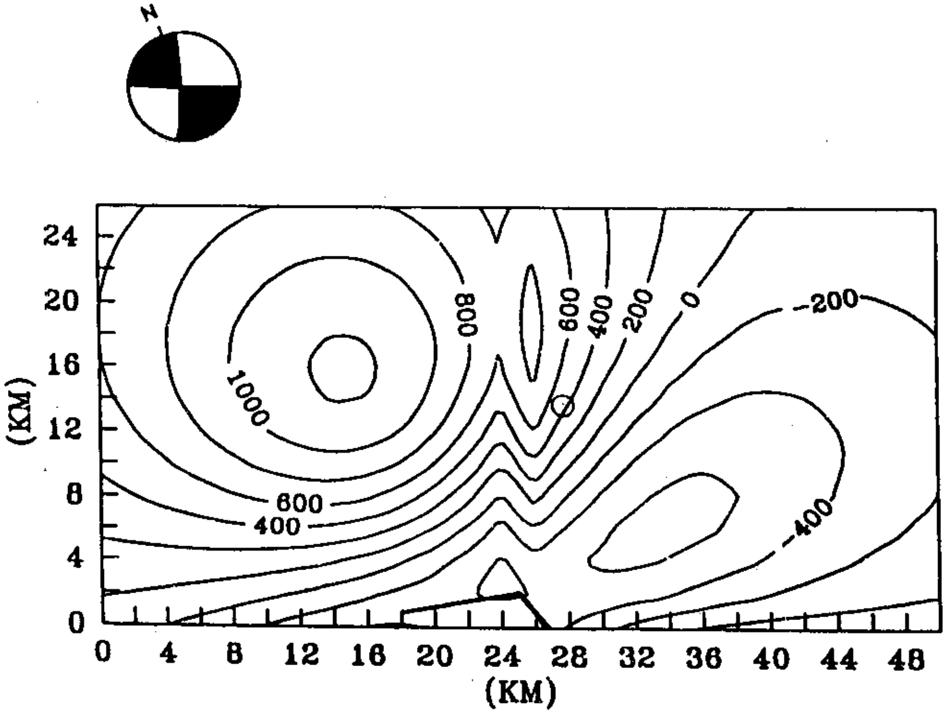

Fig.3 Contours of reservoir induced stability at a depth of 19 km for the selected nodal of the causative fault of the main Rudbar earthquake. The interpolated value at a given point in the map is the stability of the fault if the expected epicentre of the main Rudbar earthquake were to coincide with that point. The circle marks the epicentral position estimated by Institute of Geophysics, Tehran University. The position of the Sefidrud reservoir is indicated by thick lines at the bottom centre of the figure. The falut plane solution according to Berberian et. al. (1992) is shown at the top. The north direction of the map is the same as in the fault plane soluton. The steeper nodal plane is the chosen fault plane. The lower left corner of the figure is at 36.80° N and 49.05° E.

Table 1 Computed stresses at the hypocentre of the 1990 Rudbar earthquake

σ_r	τ_r	$\sigma_r \tan\phi$	θ	$\tau_r \cos\theta$	$\sigma_r(t)$
1213 (pa)	3265 (pa)	700 (pa)	85°.8	239 (pa)	465 (pa)

Equation 6 was used to compute $S_r(t)$ using a constant value of 0.57 for $\tan\phi(t)$. The resultant value of $S_r(t)$ is 465 Pa, positive. It implies that Sefidrud reservoir load exerted a stablising influence on the deduced causative fault of the Rudbar earthquake at the reported hypocentre. In other words, the dam delayed the occurrence of the earthquake. The extent of the delay cannot be ascertained because the rate of stress accumulation in the region is unknown. But it should be less than the 28 years that elapsed between the completion of the dam and the occurrence of the Rudbar earthquake.

Stability Contours

Realising that the reported epicentre of the Rudbar earthquake may be in error, we have considered the possibility that the hypocentre may be anywhere in a 50 km x 26km area around the reported hypocentre at a depth of 19 km, the reported hypocentral depth. To consider the stability through out this area we have drawn the stability contour map Fig. 3. We infer from this figure that if the hypocentre was towards the southeastern part of the investigated area, then the Sefidrud reservoir may have assisted the occurrence of the earthquake rather than opposing it.

Similarly contour map may be drawn at different depths if the hypocentral depth is also deemed to be in error. But that exercise was not undertaken here.

DISCUSSION

The most serious limitation of the foregoing analysis is that the pore pressure effects have not been simulated. The main reason for this is that the hydraulic properties of the uppar crust down to hypocentral depths around the Sefidrud reservoir are not known. There is also the question whether a direct hydraulic connection between the reservoir and the hypocentre at an estimated depth of 19 km could exist. The fact also remains that the main Rudbar earthquake occurred almost 28 years after the impoundment of the reservoir was initiated.

The most conservative approach in our opinion is to assume that pore pressure effects could arise in the present case from compression of pore water that may exist in the hypocentral region of the earthquake already. This will lead to small instantaneous pore pressure changes due to compression under the reservoir load. These would be a commensurate decrease in stability of the causative fault of the earthquake. We are reluctant to assume that this pore pressure could wipe out the estimated load induced stability, though the possibility cannot be ruled out. Much would depend on the magnitude of the Skempton coefficient B in the hypocentral regions of the earthquake. But there is no way to estimate the value of B in situ at hypocentral depths in the Rudbar region.

CONCLUSION

It appears that, with the reported hypocentre and preferred nodal plane of the fault plane solution, the Sefidrud reservoir load may have opposed the occurrence of the Rudbar earthquake be delaying it for a period of something less than 28 years.

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