No correlation between Anderson Reservoir stage level and underlying Calaveras fault seismicity despite calculated differential stress increases

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ABSTRACT

Concerns have been raised that stresses from reservoir impoundment may trigger damaging earthquakes because rate changes have been associated with reservoir impoundment or stage-level changes globally. Here, the idea is tested blindly using Anderson Reservoir, which lies atop the seismically active Calaveras fault. The only knowledge held by the author going into the study was the expectation that reservoir levels change cyclically because of seasonal rainfall. Examination of seismicity rates near the reservoir reveals variability, but no correlation with stage-level changes. Three-dimensional finite-element modeling shows stress changes sufficient for earthquake triggering along the Calaveras fault zone. Since many of the reported cases of induced triggering come from low-strain settings, it is speculated that gradual stressing from stage-level changes in high-strain settings may not be significant. From this study, it can be concluded that reservoirs are not necessarily risky in active tectonic settings.

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INTRODUCTION

Suggestions that reservoir impoundment and attendant water-level rise may have triggered the M = 8.0 2008 Wenchuan earthquake in China (Klose, 2008; Lei et al., 2008) raise concerns (cf. Kerr and Stone, 2009; Yong, 2009) about dams in tectonically active areas. Since Carder (1945) first noted the effect at Hoover Dam, many correlations between seismicity rate changes and initial reservoir impoundment, as well as stage-level fluctuations, have been made globally (e.g., Gupta and Rastogi, 1976; Rastogi and Talwani, 1980; Muirhead, 1981; Stein et al., 1982; Kebeasy et al., 1987; Chung and Chao, 1992; Hu and Hu, 1992; Talwani, 1997; Gupta, 2002; do Nascimento et al., 2004; Torcal et al., 2005; Lamontagne et al., 2006; Matcharashvili et al., 2008). Causes are usually attributed to a combination of stressing related to the weight of the water column and hydrologic effects within faults (e.g., Talwani, 1997). Conclusions on the importance of impoundment and/or stage-level change on large earthquake triggering are somewhat difficult to reach because there is a tendency to report cases mainly where anomalous seismicity is noted; an exception is a comprehensive analysis of Japanese reservoirs by Ohtake (1986), who found that ~20% of the total number of reservoirs were associated with seismicity rate changes.

In this paper, I take the approach of selecting a case study not by primary identification of seismicity changes, but instead by proximity of a reservoir that has significant annual stage-level variations (mean = 6.3 m, σ = 8 m) to a major seismically active fault. Constructed in 1950, Anderson Reservoir lies directly above the right-lateral Calaveras fault in the San Francisco Bay region of California; it is ~10 km long, ~1 km wide, and up to 0.2 km deep. It is comparable in size to the reservoir behind the Zipingpu Dam, which lies above the Wenchuan earthquake hypocenter, and which measures ~7.5 km long, up to 0.16 km deep, and ~2 km at its widest point. Detailed stage-level data from the Anderson Reservoir date back to 1980, as does a local network earthquake catalog complete above M = 2 (source: Northern California Seismic Network [NCSN]).

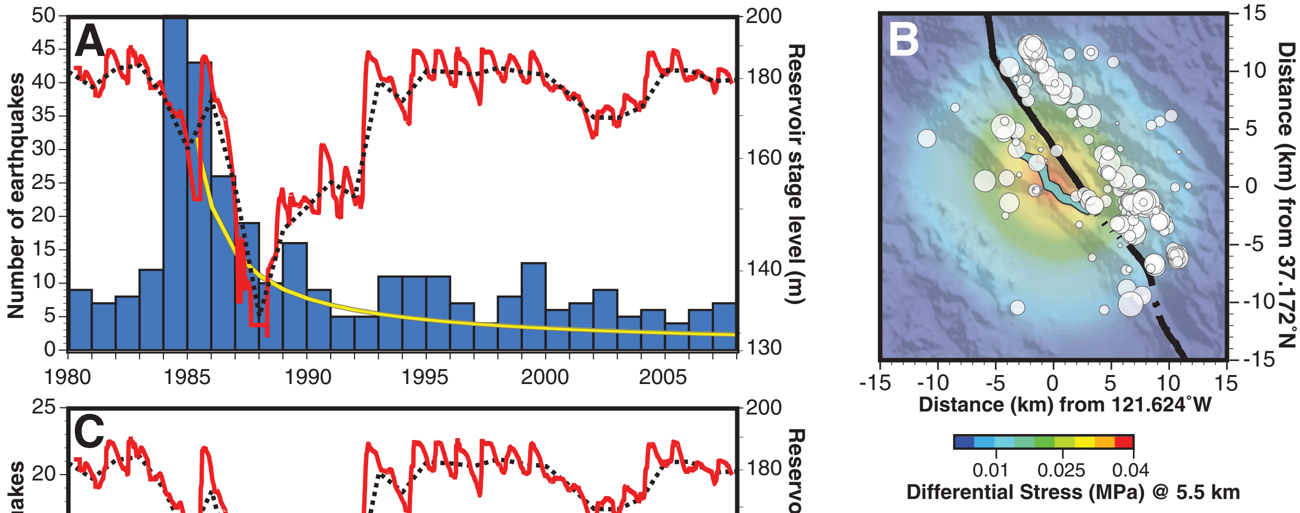
The San Francisco Bay region is sliced by a series of near-vertical right-lateral strike-slip faults of the San Andreas system. About 30–40 mm/yr of plate-boundary deformation is accommodated by this subparallel fault set (De Mets et al., 1994; Savage et al., 1999; d'Alessio et al., 2005). The right-lateral Calaveras fault splits off to the east of the San Andreas fault and has a long-term geologic slip rate of 12–18 mm/yr (Working Group on California Earthquake Probabilities, 2003). About 160–170 km of displacement has occurred on the Calaveras fault since slip began in the East Bay fault zone ca. 8 Ma (McLaughlin et al., 1996). Twelve M ≥5 earthquakes have occurred on the Calaveras fault since 1850 (Bakun, 2008).

In this paper, I gathered together observed reservoir stage-level observations and seismicity rate changes for the region around Anderson Reservoir, and investigated the level of correlation between the observations. Lastly, I developed a three-dimensional (3-D) finite-element model of Anderson Reservoir stage-level changes in order to investigate the magnitude and spatial distribution of imposed differential stressing.

OBSERVATIONS

Coastal California receives virtually no rainfall between the months of April and November, with most runoff accumulating during winter monsoon months of January and February. This pattern leads to annual cycles of reservoir filling and drawdown (Fig. 1). The annual mean change at Anderson Reservoir is 6.3 m, with a standard deviation of σ = 8 m. California is subject to global El Niño–La Niña patterns that cause multiyear droughts followed by higher-than-average rainfall. Since 1980, the maximum stage-level change was 60 m, which occurred between 1988 and 1992 (Fig. 1).

The Calaveras fault has the most energetic microseismicity in the San Francisco Bay region; it has had 25 moderate-sized (4.0 ≥ M ≤ 6.2) earthquakes since 1968 and ~12 M ≥5 earthquakes since 1850 (Bakun, 2008). Seismicity associated with the Calaveras fault demonstrates mixed strike-slip and convergent tectonics (e.g., Manaker et al., 2005). The post-1980



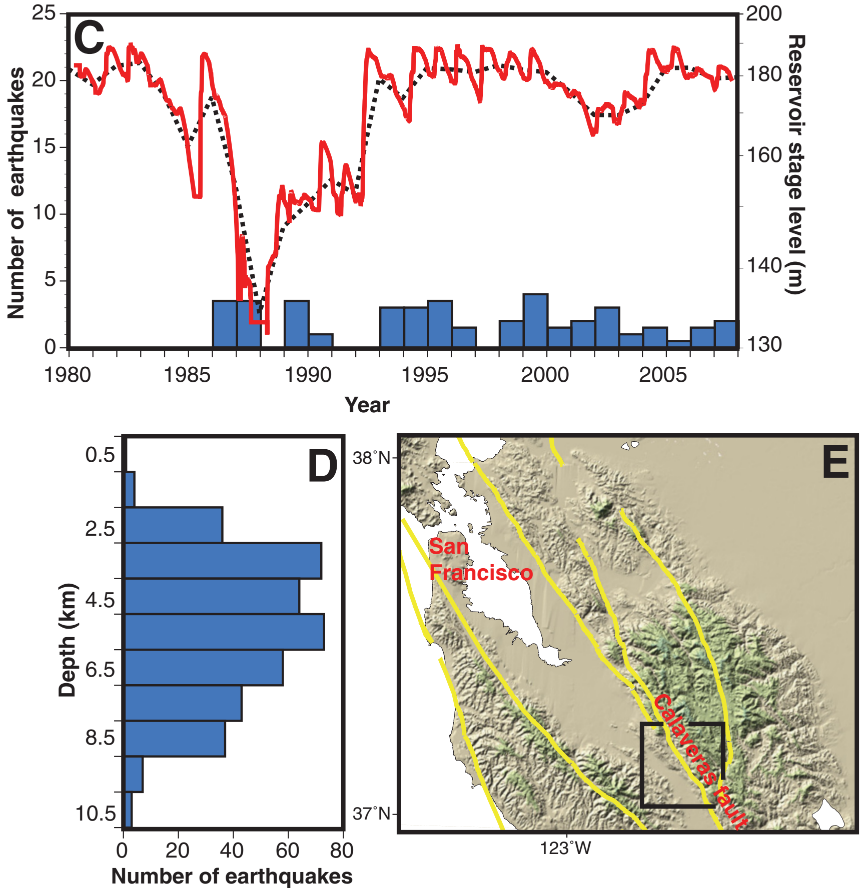


Figure 1. (A) Number of M ≥2 earthquakes per year within 10 km of the geographic center of Anderson Reservoir plotted with the daily reservoir stage level (red line) and annual mean stage level (black dashed line). The yellow curve shows best-fit Epidemic Type Aftershock Sequence model for expected aftershock rate from the M = 6.2 Morgan Hill earthquake. (B) Map shows epicenters and calculated differential stress change from 60 m stage-level change at 5.5 km depth. (C) The same information is displayed as in (A), except earthquake rate is shown with aftershocks removed. (D) Earthquake depth distribution. (E) Regional tectonic setting (inset box corresponds to stress change map in B, and has 30-km-long sides).

catalog is complete above M = 2 (e.g., Parsons, 2007). At one time, it was thought that Anderson Reservoir impoundment might be responsible for a seismic gap on the Calaveras fault beneath it (Bufe, 1976), but the 1984 M = 6.2 Morgan Hill earthquake ruptured that section. Aftershocks from the Morgan Hill earthquake raised seismicity rates significantly above background in the vicinity of the reservoir until 1987 (Fig. 1); Epidemic Type Aftershock Sequence modeling (Ogata, 1988) based on the first year of aftershocks yields the proportion of post-1985 seismicity expected from aftershocks (Fig. 1B). Declining seismicity rates that correlate to a reservoir drawdown are coincidental, being caused by normal Omori law temporal decay. The Morgan Hill event itself occurred 34 yr after impoundment, and its hypocenter was located outside (Hartzell and Heaton, 1986) of the calculated range of reservoir stress effect (calculations discussed in Modeling section).

Calaveras fault earthquake occurrence within the calculated sphere (~10 km radius) of potential stress-change influence caused by stage-level changes exhibits rate variability. The mean number of post-1987 M ≥2 events is 8.1 yr^{-1}, with a standard deviation of $\sigma = 4.0$, and the mean post-1984 declustered rate is 4.5 yr^{-1}, with $\sigma = 2.8$. This implies a coefficient of variation of ~50%. Stage-level variability was greater during this period, with a coefficient of variation of 127%. The mean annual stage-level change was 6.3 m; seismicity rate correlations have been made with changes as small as 1 m at other locations (e.g., Utkucu, 2005).

While variability in both seismicity rate and stage level is evident at Anderson Reservoir, there appears to be no temporal correlation by inspection (Fig. 1). Given the different nature of the measurements, the approach taken to quantify the degree of correlation is a nonparametric rank order correlation test. In this test, the annual earthquake counts are ordered according to rank, as are the mean annual stage levels. The two rank orders are then correlated (Fig. 2). If there were a link between Anderson Reservoir stage-level and earthquake rates, then some degree of linearity would be evident on the plots of Figure 2. If there were some delayed, or phase-shifted effect, the slope of the regression would be different than 1, but still linear. The correlation coefficient for earthquake rates within a 10 km radius of Anderson Reservoir is $r = -0.07$, and for declustered event rates, $r = 0.09$. In other words, there is no correlation between stage level and Calaveras fault seismicity rates.

MODELING

Hundreds of cases have been reported in the literature linking reservoir stage-level changes to variations in seismicity rates. Cases where no such link exists are less commonly reported, though the reported 20% of Japanese reservoirs associated with seismicity rate changes by Ohtake (1986) gives some inkling. Two primary causes are advanced for reservoir-induced earthquake rate changes: stress changes induced by the weight of the impounded water, and hydrologic effects such as pore-pressure changes within faults (e.g., Talwani, 1997). Here, I focus the discussion by quantifying one of the two potential causes. I concentrate on the stress-change effect because investigation of hydrologic influences requires unavailable/uncertain information about pore-pressure status and permeability state of the Calaveras fault.

I constructed a 3-D finite-element model of the Anderson Reservoir that includes a tabular body shaped from mapped reservoir boundaries that overlies an elastic solid (Fig. 3). The weight of the model reservoir can be varied according to measured water content, and stresses induced in the underlying solid can be calculated. Here, I calculate differential stress change (difference between maximum and minimum principal stresses), which does not require/assume any particular fault orientations or regional stress field (Parsons, 2006).

In Figure 3, the modeled stress change from the maximum stage-level change of 60 m that occurred between 1988 and 1992 is shown at 5.5 km depth, where most earthquakes have occurred (Fig. 1C). In that case, the calculated maximum stress change of 0.04 MPa is more than sufficient to have triggered earthquakes, with the threshold expected to be ~0.01 MPa (e.g., Reasenberg and Simpson, 1992; Hardebeck et al., 1998; Harris, 1998). For maximum stage-level change, the 0.01 MPa stress change radius extends ~10 km from the geographic center of Anderson Reservoir (Figs. 1 and 3). Most stage-level changes were smaller than 60 m, with the average annual mean being 6.3 m ± 8.0 m. These smaller-level changes affect the upper ~2 km beneath the reservoir, with the 0.01 MPa threshold extending over a 10 km radius. Very few earthquakes have occurred at these depths (Fig. 1C).

Modeling results indicate that stage-level changes at Anderson Reservoir have imparted differential stresses into the underlying crust containing the Calaveras and subsidiary faults sufficient to trigger earthquakes. However, no such triggering is evident when seismicity rates and stage-level changes are compared (Figs. 1 and 2).

DISCUSSION AND CONCLUSIONS

This paper was motivated by suggestions that reservoir impoundment in tectonically active regions could represent a hazard because of the

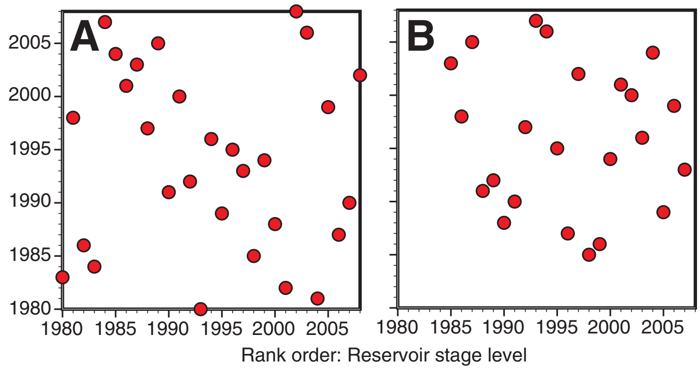


Figure 2. (A) Rank order of annual earthquake rates within 10 km of the geographic center of Anderson Reservoir plotted against rank order of mean annual reservoir stage level. No linear relationship is evident, and the two parameters appear uncorrelated (correlation coefficient *r* = –0.07). (B) Same information as A, except the annual earthquake rates are corrected for expected aftershock rates from the 1984 M = 6.2 Morgan Hill earthquake; no correlation is evident (*r* = 0.09).

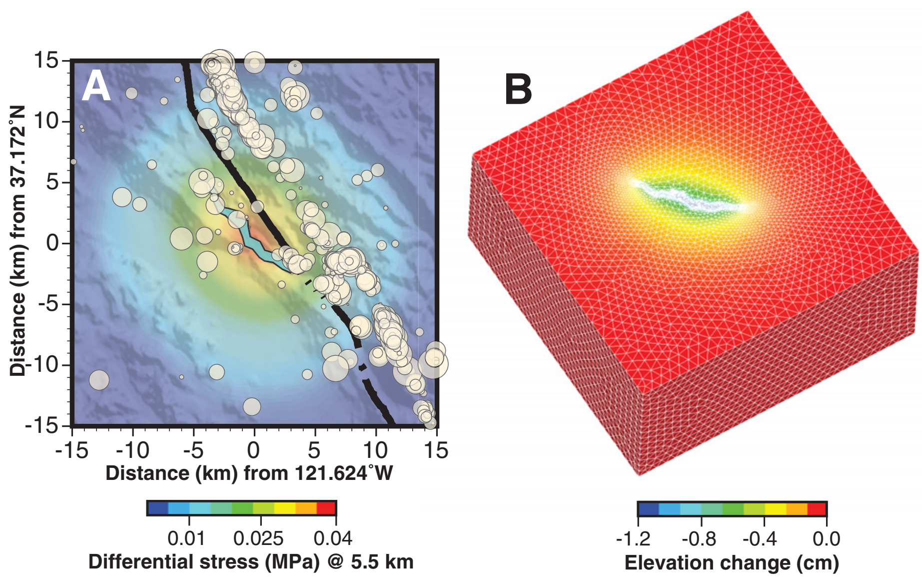


Figure 3. (A) Calculated differential stresses induced by a 60 m stage-level increase at 5.5 km depth beneath Anderson Reservoir. If a 0.01 MPa threshold for triggering is applied, then the maximum stage-level change would have the potential to trigger or suppress earthquakes within a 10 km radius. (B) Finite-element model of the reservoir shaded by calculated elevation change.

potential to trigger large earthquakes. However, neither the stress changes caused by stage-level changes, nor any hydrologic effects from Anderson Reservoir appear to affect local earthquake rates. Calculations show that stress changes would have been sufficient to trigger earthquakes, and it can be assumed that the highly faulted crust associated with the Calaveras fault zone would allow water to interact with faults.

Four potential reasons for the lack of correlation between Anderson Reservoir stage-level and seismicity rate changes can be considered: (1) Stress changes imparted by reservoir loading in high-strain regions might be dwarfed by tectonic strain accumulation. Indeed, many, if not most of the positively correlated case studies presented in the literature (see list in the introduction for examples) are taken from midcontinent or other low-strain settings. (2) The induced stress changes from Anderson Reservoir may not be aligned properly with the tectonic stress field, where the most likely regime for triggering is normal faulting, although strike-slip regimes are also favored somewhat (e.g., Simpson, 1976; Chander, 1997). However, if the induced stresses disfavor triggering, then they might be expected to inhibit earthquakes, for which there is also no evidence at Anderson Reservoir. (3) Stresses imparted by stage-level changes are gradual, taking 6 months to a few years, and it is possible that static earthquake triggering must occur by sudden stress changes. (4) Perhaps the dominant effect from reservoirs is hydrologic, and the Calaveras zone is already completely saturated. It seems unlikely that the faults are impermeable, given that the 1984 M = 6.2 Morgan Hill earthquake occurred recently.

In conclusion, from this blind, single case study, there is not evidence that reservoir impoundment necessarily represents enhanced danger of large earthquake triggering in seismically active zones.

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