Revisiting the Tidal Activation of Seismicity with a Damage Mechanics and Friction Point of View

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Abstract

Do Earth tides activate seismicity? Since the peak semi-diurnal tidal stresses are as large as the expected tectonic stress changes over a month's time, they would easily activate seismicity <u>if it were a simple threshold process</u>. The better question to ask might be, "why don't we see a very obvious tidal correlation?"

Could it be that the rate of tectonic stress accumulation is not uniform, but remains quite low until a rapid increase occurs shortly before the earthquake? Or could it be that a self-driven nucleation process occurs on a time scale longer than the diurnal tide, thus destroying the expected synchronization. If there is any nonlinear response to tides, then this purely cyclic loading will follow a hysteresis loop. If tectonic loading is added to the cyclic load, then damage, or seismic response should occur only during that portion of each cycle when the load exceeds the previous maximum. This is known as the Kaiser effect in laboratory studies of acoustic emissions. In the case of Earth tides, this effect should produce a periodicity of roughly 15 days. If there are departures from a strictly linear tectonic loading rate, then the tidal effect on seismicity will not even be periodic, and thus not easily detected with spectral methods.

Although the weight of evidence does not support a <u>general</u> correlation between seismicity and tides, it is still possible that this correlation may develop locally before a large earthquake as proposed by Yin et al.,1995[8]. Dubbed the Load/Unload Response Ratio (LURR) effect, it proposes that seismicity in a region surrounding a future earthquake becomes significantly more active during periods of tidal loading than that during periods of tidal unloading in the year or so before the event based on the non-linearity of stress-strain behavior near macroscopic failure.

Because of the important implications for the predictability of large earthquakes we undertook a re-analysis of 5 major earthquakes in California for which significant LURR effects had been previously published. We also performed sensitivity studies of the parameters that must be specified in the LURR method. We found that fluctuations in the LURR function were primarily controlled by a small numbers of moderate earthquakes, that the results were not robust with respect to choices of area or time interval, and that the choice to plot the LURR ratio on a linear scale biases the display of results.

It is our opinion that the reported anomalous behavior of LURR prior to large earthquakes is of no predictive significance beyond confirming that foreshocks often precede large earthquakes. We make no inference regarding the appearance of LURR anomalies in the numerical modeling experiments of Wang et al (2000). It may be that, in the Earth, time dependent failure processes preclude tides from having a significant effect on earthquake occurrence. At that point in time the Lattice Solid Model did not yet include time dependent failure, and thus might be expected to show some effect of the sinusoidal stress perturbation that was imposed.

Introduction

Yin *et al*, 1995[8] proposed the basic rationale for the Load-Unload Response Ratio (LURR) theory. It is based on the idea that the Earth's crust is in a critical state near the time of an earthquake, thus the sensitivity of its response to incremental loads such as Earth tides is likely to be much greater than at other times. They suggest quantifying this effect through the calculation of the average seismic energy release in a region surrounding the earthquake during periods when the effective tidal stress on the fault plane is positive, divided by the energy release during periods when it is negative. They reported this calculation for a number of earthquakes in China, Australia, and California and suggest that this ratio has a significant increase prior to the large earthquakes that they studied. The time period over which this increase occurs appears to be several months to a year or two.

Recently, Yin *et al*, 2001[9], provided examples illustrating that the largest and best-defined anomalies in LURR seem to occur when the choice of the region over which seismicity is averaged follows the scaling law developed from accelerating moment release, (Bowman *et al*, 1998[4]). That scaling law comes from treating the earthquake as a critical phenomena and fitting a power law in “time to failure” to the cumulative seismic energy release. In a related development (Wang *et al,* 2000[7]), experiments with the Lattice Solid Model in which sinusoidal perturbations to the loading force were applied in numerical modeling experiments. The results appeared to confirm that anomalous values of LURR occurred prior to large events in the model. These recent results seem to be important confirmations of the critical point model of earthquakes, and suggest that there may be some common underlying physics behind both the power law buildup and the LURR phenomenon. Because of the importance of this conclusion, we undertook an independent test of the LURR hypothesis.

Tidal Stresses

The premise is that tidal forces may activate faults that are near their critical stress by adding a small increment to the existing tectonic stress. Since tidal forces can produce both shear and normal stress changes on a fault, we look to the effective stress as a measure of how important the tidal contribution might be to inducing motion on the fault. Effective stress is $\sigma_e = \sigma_s \cos(\psi) - f\sigma_n$ where σ_s is maximum shear stress, ψ is the slip angle, σ_n is the compressive stress across the fault plane, and f is the friction coefficient. Note that the traditional definition of effective stress by Coulomb has been modified to account for the specific slip direction, which can be anticipated given knowledge of the regional tectonic stress field. In what follows we use a local Cartesian coordinate system x y z corresponding to east, north, and up.

We calculate solid Earth tide deformation using the method of Berger *et al* 1987 [3]. In order to calculate tidal stresses, we first determine the extensions in three horizontal directions, typically at 45^0 intervals, $e_{ns}\, e_{ew}\, e_{ne}$. The strain field is then given by $e_{xx} = e_{ew} \quad e_{yy} = e_{ns} \quad e_{xy} = e_{ne} - \frac{1}{2}(e_{ns} + e_{ew})$.

For shallow earthquakes, the free surface boundary condition requires all vertical components of the tidal stress to be zero. If the tidal stress tensor is T, then the force F acting across a fault plane with normal N is given by

$$F = T \bullet N = \frac{2\mu}{(1-\nu)} \begin{pmatrix} (e_{xx} + \nu e_{yy})\cos(\varphi)\sin(\delta) - (1-\nu)e_{xy}\sin(\varphi)\sin(\delta) \\ (1-\nu)e_{xy}\cos(\varphi)\sin(\delta) - (e_{yy} + \nu e_{xx})\sin(\varphi)\sin(\delta) \\ 0 \end{pmatrix}$$

where μ is rigidity, ν is poison's ratio, fault strike is φ and dip is δ. If the slip vector is given by S, then the tidal Coulomb stress as we have defined it above becomes

$$\sigma_e = F \bullet S + f(F \bullet N)$$

Solid Earth tides largest constituents are the lunar and solar semi-diurnal tides with periods of approximately 12.41 hours and 12.00 hours respectively. The beat between these two closely spaced spectral lines produces a modulation with about a 15-day period. During those times when the two tidal components are nearly in phase, the amplitude is large, the EW and NS components of tidal stresses are nearly equal, and the shear stresses are thus nearly zero. As a result, the effective stress on fault planes of all orientations is controlled by the normal stress. Normal stress is independent of fault strike and slip direction, but does vary with dip, decreasing to zero of course as the dip of the fault approaches zero.

For those times that the tidal components are nearly out of phase, the amplitudes are smaller, and there are significant differences between EW and NS stresses. This does give rise to some shear stress, although it is never comparable in size to the normal stress during the peak times. During these times, the effective stress is weakly dependent on fault orientation.

It has been known for some time that tides in the ocean produce elastic strains in the crust at considerable distances. The Northridge earthquake and the Loma Prieta earthquake analyzed in this study were close enough to the Pacific Ocean that ocean loading effects could be significant. To evaluate this, we used the direct body tide and the ocean load separately in the calculation of LURR for the Northridge earthquake. Programs for these calculations together with databases of ocean tides developed from space geodetic sources were made available by Agnew 1996[1]. In the case of Northridge, local effects in the Gulf of California were included, and in the case of Loma Prieta, the effects of San Francisco Bay were included. For these earthquakes, both within 40 km of the Pacific Ocean, the ocean loading does contribute significantly to crustal deformation. Despite this, the interval times for which Coulomb stress is positive were changed very little. The primary effect of adding the ocean loading was to change the sign of a few smaller earthquakes. We examined all earthquakes of magnitude 5 or greater in the 20-year catalogs and found that there were no changes in the sign of their contribution to the LURR function resulting from the addition of the ocean load. Clearly if a moderate earthquake had occurred during one of the periods where the ocean loading had changed the sign of Coulomb stress, this could have had an important effect on the calculation of LURR.

Test of LURR method

For this test we examined the seismicity over 20-year periods prior to some major earthquakes in California. Three of the events used appeared in both the LURR analysis of

Yin *et al,* 1995[8] and the power law fitting of Bowman *et al,* 1998[4], so the results could be directly compared with the earlier work. The list of events used appears in Table 1 below.

Earthquake	**Date**	**Mag**	**Radius**	**Mechanism**
Landers	June 28 1992	7.3	150km	strike=341 dip=70 slip=-172
Loma Prieta	Oct 18, 1989	7.0	200	strike=123 dip=71 slip=128
Northridge	Jan 17, 1994	6.7	120*	strike=130 dip=53 slip=111
Superstition Hills	Nov 24, 1987	6.6	110*	strike=133 dip=78 slip=178
Coalinga	May 2, 1983	6.7	120*	strike=320 dip=30 slip=87

* Bowman *et al* (1998) best fit of radius and magnitude

Table 1. Earthquakes used in study.

The results showed that the LURR function is highly variable and dependent in detail on the parameters used. The most significant parameters involve the choice of the radius of the region to be analyzed, the length of the time window over which results are averaged, and the upper magnitude cutoff in the catalog used. The choice of seismic activity function, whether energy, square root of energy (Benioff strain), or event count also influenced the result. Only minor effects of the choice of fault orientation were seen. We could only roughly duplicate the parameter choices apparently made by Yin et al, 1995[8]. Our results showed that all of the significant variations in the LURR function were the result of a small number of moderate sized foreshocks, which apparently occurred randomly with respect to the tidal phase. Subsequent discussions revealed that they had used an upper magnitude cutoff, which eliminated most of the moderate foreshocks. Their choice of a cutoff was based on using only the linear segment of the magnitude-frequency distribution. We were unable to find any rationale as to why this procedure should be used. The effect is peculiar since eliminating the larger foreshocks does not remove their influence on the LURR function. These moderate events typically have numerous smaller aftershocks of their own that are included in the LURR calculation.

If there is any nonlinear response to tides, then this purely cyclic loading will follow a hysteresis loop. If tectonic loading is added to the cyclic load, then damage, or seismic response should occur only during that portion of each cycle when the load exceeds the previous maximum. This is known as the Kaiser effect in laboratory studies of acoustic emissions. In the case of Earth tides, this effect should produce a periodicity of roughly 15 days. We constructed a staircase function based on intervals of time when the envelope of the tidal coulomb stress plus the tectonic stress rate exceeded previous maximum values. In calculating the envelope, we averaged over daily intervals to remove the short period tides. We used this function to calculate what we call the SLURR function, with all the other definitions remaining the same as that of LURR.

The results for the Northridge earthquake using both the conventional LURR function and the modified version are shown in figure 1. No precursory behavior can be noted for either. Results from other earthquakes were equally unconvincing. Both the numerator and denominator of LURR are explicitly shown as an aid in interpreting variations in the ratio. It seemed important to us to know if an increase in the LURR ratio was due to increased seismicity during the loading periods or decreased seismicity during the unloading periods. Both circumstances can be observed. In addition, the individual events that contribute to the averages are shown. This allows one to assess, for example, whether an increase in seismic energy during a loading period is due to a single large event or a large number of smaller events. We note several examples where both circumstances occur.

Dieterich, 1987[5] developed a technique to predict seismic activation due to stress changes based on the rate and state friction law. His method suggests that time-delayed nucleation might preclude the detection of tidal triggering effects. Lockner and Beeler, 1999[6], and Beeler and Lockner, 2002[2], present direct evidence that the typical duration of earthquake nucleation is 69-212 days. Their result would explain why correlation of seismicity with tides has never been established. It would also suggest that the staircase function we used in calculating SLURR should have been based on an envelope averaged over a much longer period of time.

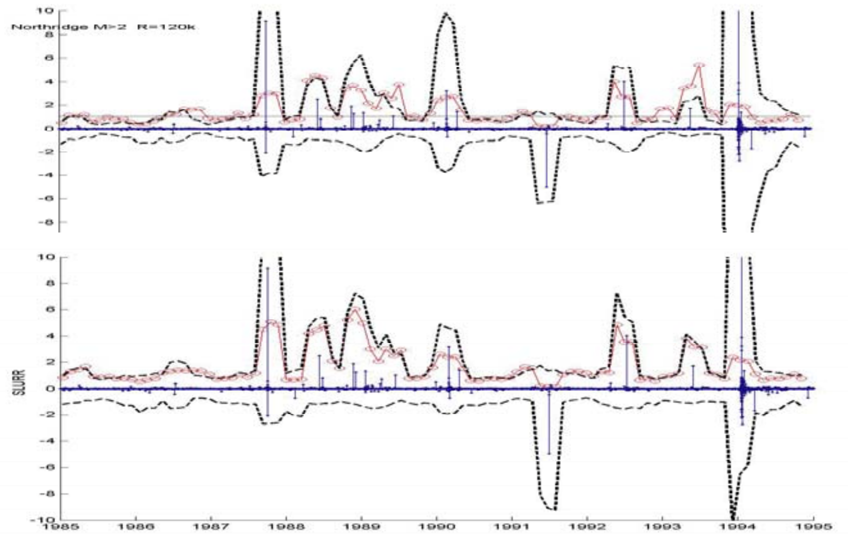

Figure 1: LURR and SLURR functions for the Northridge earthquake. For clarity, both the numerator and denominator of the function are shown, with the resulting ratio shown in red. Benioff strain associated with individual earthquakes is shown as a vertical line. All of the significant variations can be identified with specific moderate earthquakes. In this and other examples calculated, we see no hint that increased tidal activation occurs prior to major earthquakes.

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