# Statistical test of the Load-Unload Response Ratio (LURR) signals using the Lattice Solid Model (LSM): implication to tidal triggering and earthquake prediction

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## Abstract

**Following from previous simulations of LURR using the Lattice Solid Model, statistical tests of LURR signals are carried in order to verify statistical robustness. In each test, 24 samples with the same macroscopic parameters but different random arrangements of particles are studied. Results of uniaxial compression experiments show that before the normalized time of catastrophic failure, the ensemble average LURR value rises significantly. In shearing tests, a dimensionless parameter (size of peak "tidal" perturbation rate relative to rate of "tectonic" loading) is found to control the correlation between earthquake occurrence and tidal stress. When this parameter is very small, nearly no correlation is found. However, when it becomes larger, the peak in the earthquake frequency probability density function shifts from being correlated with the peak in stress rate towards the peak in stress of the tidal perturbation. After removing the average triggering effect, statistics of LURR signals in shearing tests suggest that the larger events are more likely to occur when LURR is high than the smaller events, supporting the LURR hypothesis.**

## Introduction

For several decades, many researchers sought to find a correlation between earth tides and earthquakes. However, no significant correlation is observed (Vidale et al, 1998).

The Load-Unload Response Ratio hypothesis (LURR) views this problem from a different perspective. According to LURR, tidal forces do not trigger earthquakes all the time, only when the system approaches a critical point and a large earthquake is approaching is the system susceptible to minor perturbations such that correlations can occur. Some successful observations and practical predictions using LURR suggest that intermediate-term earthquake forecasting may be possible by this method (Yin et al, 2000).

The preliminary simulations of LURR using the Lattice Solid Model (LSM) (Mora et al, 2002) reproduce signals with a high LURR value followed by a sudden drop prior to macroscopic failure of the sample suggesting that LURR provides a predictor for catastrophic failure in elastic-brittle systems. These simulations need to be tested for statistical robustness and against parameter sensitivity. Statistical robustness is tested in the following by conducting ensemble averages of results obtained using models with different random particle configurations.

## Statistical test of LURR under uni-axial compression by ensemble averaging

As in the previous study (Mora et al, 2002), the system is initialized as a heterogeneous 2D block made up of random sized particles, subjected to uni-axial compression until catastrophic failure occurs. As a simple form of periodic changes, a sinusoidal stress perturbation is added to the constant loading rate of "tectonic" stress build-up to simulate the periodic loading and unloading cycles induced by tidal forces

$$\Delta\sigma_{zz} = A\cos(2\pi t/T), \tag{1}$$

where $A$ and $T$ are amplitude and period of tidal stress. LURR is calculated using

$$LURR = E^{+}/E^{-}, \tag{2}$$

where $E^{+}$ and $E^{-}$ respectively denote the cumulative seismic energy release during loading and unloading within a given time window. Loading and unloading are defined by $\frac{d\sigma_{zz}}{dt} \geq 0$ and $\frac{d\sigma_{zz}}{dt} < 0$ .

In this test, simulations are conducted using 24 samples with the same parameters (amplitude, period of tidal perturbation and tectonic loading rate etc) but different configurations of random particles. LURR values are calculated for each sample in the same way as in previous work and subsequently an ensemble average is computed. Due to sample specificity (Xia et al, 1996), the fracture pattern and catastrophic failure time are different for each sample, so time in each simulation is normalized by the failure time prior to computation of the ensemble average LURR value. Fig.1 (left) shows plots of average LURR computed from the 24 samples versus normalized time for the same parameters used in the previous study. One can see that the averaged LURR begins to rise from $t$ = 0.5, and reaches its peak at $t$ = 0.9 and then drops just before the main event at $t$ = 1.0. An apparent acceleration in energy release is observed just before the main fracture (Fig.1 right). This accelerating sequence fits a power law time-to-failure function ( $E(t) = A + B(t_f - t)^m$ , Bufe et al, 1993) well, but with low curvature ($m$=0.6).

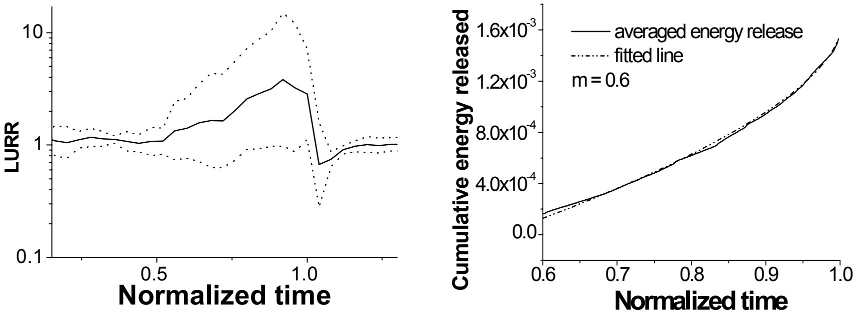

Figure 1 Evolution of ensemble average LURR computed from 24 samples (left) and ensemble average cumulative energy release (right). Dotted line is fitted time-to-failure function, tf is set to 1.0. Parameters are: k = 30 MPa/100,000 time steps, T = 4000 time steps and A = 0.96 MPa.

If the parameters are changed within a specified range (e.g. a factor of 5 larger or smaller for A and k), similar results are observed. This suggests that our previous results are statistically robust.

## Statistical test of LURR under shearing tests

### Model description

In this test, the model consists of a central fault sandwiched between elastic regions which are attached to rigid driving plates at their outer boundaries (Fig. 2). A simple frictional force with magnitude proportional to the normal force is employed (Place and Mora 2001; Mora and Place, 2002). Similarly as in previous tests, a small sinusoidal perturbation is added to the slow tectonic loading.

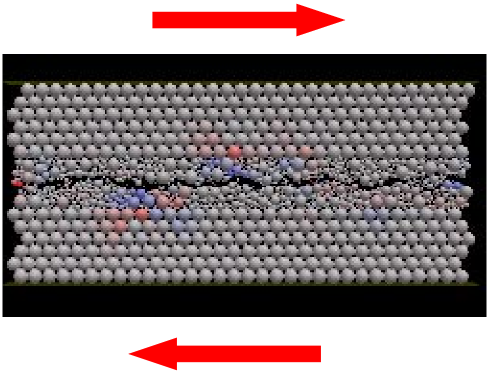

Figure 2 Snapshot of a shearing test. Boundary conditions are circular in the horizontal direction. A constant normal stress of 150MPa is applied at the upper and lower rigid driving plates.

### Earthquake occurrence sensitivity to parameter variation

To simulate the effect of earth tides on earthquake occurrence, the parameters cannot be chosen arbitrarily, but must be selected according to the following conditions

$$\left|\Delta\sigma_{zz}\right| << \sigma_{zz} \quad \frac{d\left|\Delta\sigma_{zz}\right|}{dt} >> k \quad \text{and} \quad T_e << T << T_L \tag{3}$$

where $T_e$ is the synthetic earthquake rupture duration and $T_L$ is the average time interval between large earthquakes, $k$ is rate of tectonic stress $\sigma_{zz}$.

However, due to limited computer power, it is impossible to use the observed parameters in numerical tests. In this simulation, the basic parameters are: A = 0.96 MPa, T = 4000 time steps. k ~ 3×10 -4 MPa per time step.

To study the effect of tidal parameters such as $A$, $T$ and $k$ on earthquake occurrence, we plot the probability density function (pdf) of events versus phase angle for different parameters in Fig. 3. Here phase angle $\theta \in [-\pi, \pi]$, $\theta + 2\pi n = \frac{2\pi}{T} t$, $n$ is the cycle number and $t$ is event time.

The results show that the pdf curve is mainly sensitive to parameter $k_2 = \frac{d|\Delta\sigma_{zz}|}{dt} \Big/ k = \frac{2\pi A}{Tk}$, not to $A$, $T$ and $k$ individually. For the same $k_2$, the pdf is almost the same. When $k_2$ is small enough (e.g. $k_2 < 0.23$), the pdf is flat indicating that no correlation is observed between earthquake occurrence and phase angle $\theta$. However, when $k_2$ is greater than 0.23, a peak is observed in the pdf curve close to the peak in the perturbation stress rate, indicating a correlation between earthquake occurrence and rate of stress perturbation. With increasing of $k_2$, the peak becomes higher and narrower, and shifts from being close to the peak in stress rate towards the peak of the stress perturbation, indicating an increasing correlation with the perturbation stress value rather than rate.

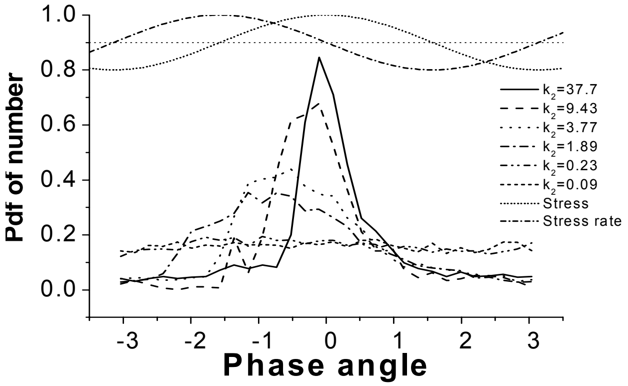

Figure 3 Plots of pdf of events versus phase angle for different parameters. The shapes of stress and stress rate of perturbation are plotted for comparison.

Similar results are obtained using two parameters to describe the average correlation degree between occurrence of events with stress or stress rate of perturbation (Fig. 4).

$$\alpha_1 = \frac{\text{total number of events in positive stress of perturbation}}{\text{total number of events in negative stress of perturbation}}$$

$$\alpha_2 = \frac{\text{total number of events in positive stress rate of perturbation}}{\text{total number of events in negative stress rate of perturbation}} \qquad (4)$$

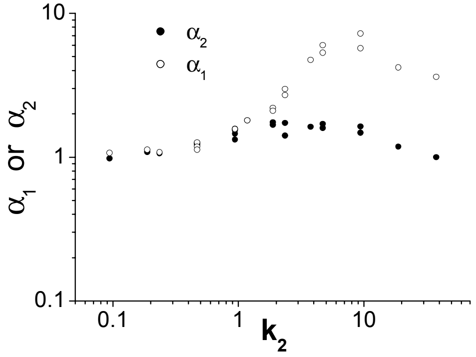

Figure 4. Average correlation between occurrence of events with stress ($\alpha_1$) or stress rate of perturbation ($\alpha_2$) for different $k_2$.

## Statistics of LURR

Considering the observation of a strong correlation between simulated earthquake occurrence and the periodic stress perturbations when $k_2$ is large, the averaged triggering effect should be removed in order to investigate the temporal variation of LURR. Hence, the LURR is calculated using

$$LURR = \frac{\sum E^+ / \sum E^-}{\alpha_1} \tag{5}$$

where loading and unloading are defined by $\sigma_{zz} \geq 0$ and $\sigma_{zz} < 0$. Figure 5 shows the pdf versus LURR for all events generated from 8 simulations. One observes that the pdf for all events (dotted lines) is nearly centered about LURR=1. However, the pdf distribution for the 10% largest events (solid line) is more peaked and is shifted to the right (ie. centered at LURR>1) indicating that the larger events tend to occur when LURR is high and less likely to occur when LURR is low. Except for several cases with very large $k_2$ (e.g. $k_2 > 3$ and $\alpha_1 \sim 5$) when very few events are found in unloading cycles and hence LURR cannot be calculated, similar results are observed in all other cases. These results suggest that the large events are more likely to occur when LURR is high although there is no apparent correlation between simulated earth tides and simulated earthquake activity if all events are counted.

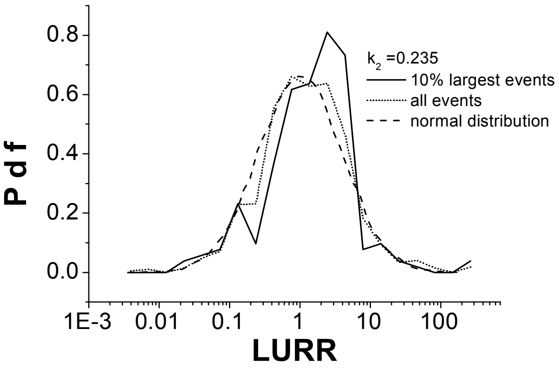

Figure 5 Pdf versus LURR for all events (dotted), the largest 10% of events (solid), and a Gaussian curve centered at LURR=1 for comparison (dashed).

## Conclusions and discussions

The statistical studies presented in this paper verify statistical robustness of previous results in which LURR values rose prior to catastrophic failure in numerical uni-axial compression experiments. Within our parameter ranges, a dimensionless parameter $k_2$ (the ratio of tidal stress rate to tectonic stress rate) was found to control the correlation between earthquake occurrence and tidal stress perturbations. For low $k_2$, earthquake occurrence tends to be correlated with stress rate of the perturbations. When this parameter becomes larger ($k_2$>10), the occurrence of events becomes more correlated with the tidal stress value. If this conclusion can be extrapolated to the case of real earthquakes ($k_2$=10-1000), then nearly all earthquakes would be expected to occur during high and positive tidal stress. However, this is not observed raising the question: What is the main reason for the absence of earthquake correlation with tides? Vidale estimated that the pre-seismic stress rate is much higher (1000 times) than long-term tectonic rate (Vidale et al, 1998), so the effect of tides is lessened. Our simulations seem to support this idea since the high pre-seismic stress rate (low $k_2$ in our study) implies a low correlation between earth tides and earthquake occurrence. A mechanism for delayed failure has been suggested to explain the observations (Lockner, 1999) and such a mechanism should be incorporated into the simulation model in future work.

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