

Simulation of Load-Unload Response Ratio using the Lattice Solid Model

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Abstract

The Load-Unload Response Ratio (LURR) method is an earthquake prediction approach that has shown considerable promise. Both the high values of LURR and the observed accelerating seismic moment release (AMR) prior to most large earthquakes mean the focal region tends to an unstable or critical state suggesting intermediate-term earthquake prediction is possible. In order to study the underlying physical mechanism for LURR observations, numerical simulations of uniaxial compression are conducted using the particle based Lattice Solid Model (LSM). The preliminary results show high LURR before catastrophic failure of the sample which provides encouragement for continued study of the LURR mechanism and earthquake forecasting research.

Introduction

The main idea of LURR is that when a system is in a stable state, the response to a small loading is nearly same as the response to unloading, but when the system is near failure or in an unstable state, they are quite different (Yin et al, 1995[9]; 2000[10]). LURR is defined according to this difference. Suppose P and R are the load and response of a system, if P has a small change ΔP and R has ΔR , then

$$X = \lim_{\Delta P \rightarrow 0} \frac{\Delta R}{\Delta P}, \quad (1)$$

can be defined as the response rate, and LURR is defined as

$$LURR = \frac{X^+}{X^-}, \quad (2)$$

where X^+ and X^- are response rate during loading and unloading. When a system is in a stable or linear state, $X^+ \approx X^-$ so $LURR \approx 1$. When a system lies beyond the linear state, $X^+ > X^-$ and $LURR > 1$. Hence, LURR can be used as a criterion to judge the degree of stability of a system.

In earthquake prediction practice using LURR, loading and unloading are decided by calculating the effective shear stress induced by the tidal forces along certain fault orientations or tectonic stress directions, and LURR is often defined as ratio of Benioff strain release during loading compared to unloading periods:

$$LURR = B^+ / B^- . \quad (3)$$

where B^+ and B^- respectively denote the cumulative Benioff strain release during the loading and unloading cycles. In retrospective studies, high values of LURR have been observed a few months or years prior to most of events (Yin et al, 2000[10]). Some intermediate-term earthquake predictions have also been made using this method.

In recent years, accelerating seismic moment release (AMR) prior to many large earthquakes has been observed (Bufe and Varnes, 1993[2]; Bowman et al, 1998[1]). Both AMR and high LURR may have a similar origin or may be due to critical sensitivity before catastrophic events (Wei et al, 2000[8]). To study the physical mechanism of LURR, numerical simulations are conducted using the particle based Lattice Solid Model (LSM) (Mora and Place, 1994[3]; 1998[4]; Place and Mora, 1999[6];2000[7]).

The Lattice Solid Model was developed to provide a basis to study the physics of rocks and the non-linear dynamics of earthquakes. The LSM consists of a lattice of interacting particles. Intact material is modelled as particles linked by elastic-brittle bonds which can break if the separation exceeds a given threshold and frictional forces are applied to unbonded particles that come into contact. The numerical integration is based on a modified velocity Verlet scheme which accurately captures discontinuities such as bond breaking or the transition between static and dynamic frictional contact. Using this model, fracture, shearing of rock, stick-slip behavior and wave propagation are simulated with relative simplicity. Fault gouge self-organisation has been simulated and recent results have provided a comprehensive potential explanation for the Heat Flow Paradox provided (Mora and Place, 1998[4];1999[5]). A modular approach has been developed to allow different micro-physics to be easily added in the model. The LSM has also extended to enable 3-D and random lattices to be modelled (Place and Mora, 2000[7]).

Results

In the present study, the model is initialized as a heterogeneous 2D block made up of random sized particles with diameters ranging from 0.2 to 1. The system is subjected to uniaxial compression from rigid driving plates on the upper and lower edges of the model. Two snapshots from a typical simulation are shown in Figure 1.

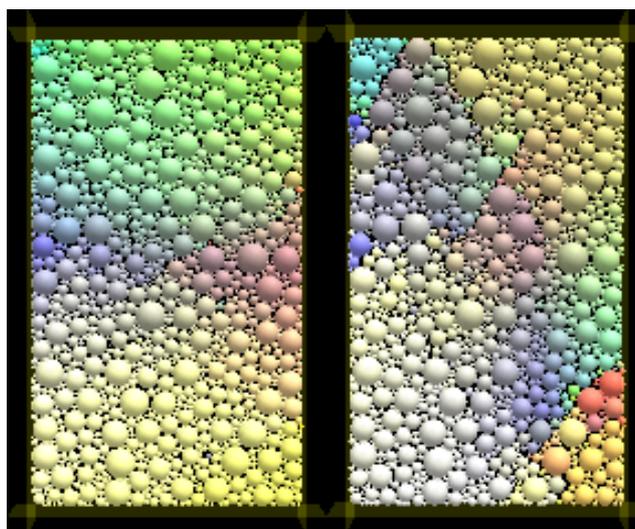


Figure 1: A typical random lattice model. Left: before fracturing. Right: After fracturing.

In the first numerical experiment, loading is strain controlled and a constant driving rate is applied to the upper and lower edges of the model. In a second experiment, stress control is used in which stress on the upper and lower edges is increased linearly and slowly until the sample fails. In both cases, a sinusoidal disturbance to stress or driving rate is applied as the system is loaded in order to simulate the loading and unloading induced by tidal forces. LURR values are calculated according to Equation (3) but using the cumulative energy release instead of cumulative Benioff strain release (i.e. $LURR = E^+/E^-$ where E^+ and E^- respectively denote the cumulative energy release during the loading and unloading cycles). Figure 2 shows stress, kinetic energy and LURR value versus time step for the strain control experiment. The spikes of kinetic energy correspond to dynamic fracturing involving breaking of bonds and/or slip along fracture surfaces. These represent events in the simulation. Due to an artificial viscosity that is applied to damp energy from the system, kinetic energy soon dies after each event. The energy lost to this viscosity during a given interval of time provides a measure of the total kinetic energy released by events

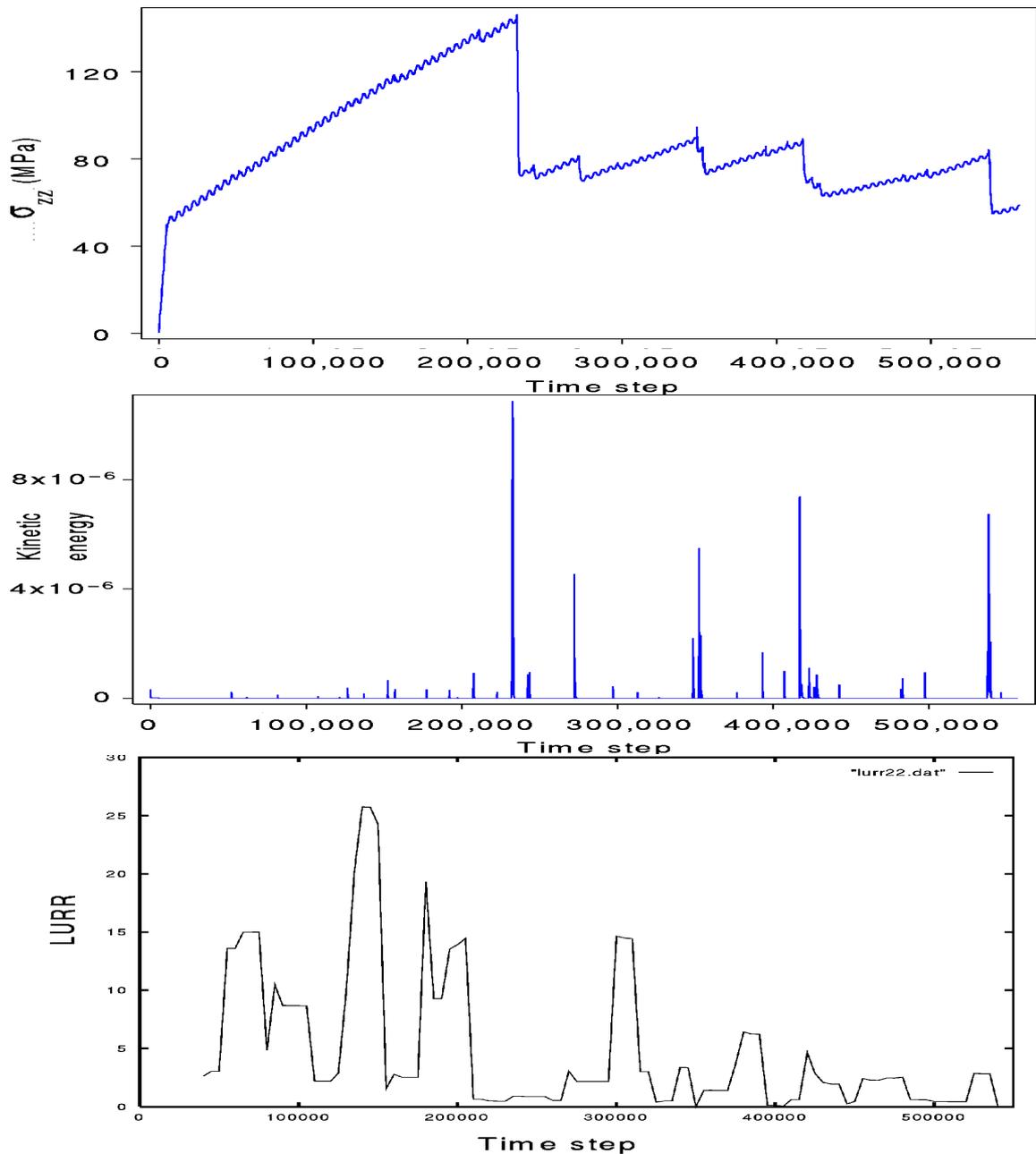


Figure 2: Strain controlled test. **Top:** Stress. **Middle:** Kinetic energy. **Bottom:** LURR value.

and is used to calculate the LURR value. To avoid violent fluctuations due to poor statistics (ie. too few events during a single load-unload cycle), the LURR values are computed from the energy release during loading and unloading summed over several load-unload cycles (5 cycles in this case). In the strain controlled experiment (Figure 2), the LURR values are high before the main fracture which occurs at around time step 230,000 and become lower after this event. However, the high LURR values do not occur only immediately prior to the main event but in much of the preceding sequence. This is possibly related to the intact nature of the sample and relative paucity of events.

Figure 3 shows kinetic energy and LURR value for the stress control experiment. Since it is easy to failure catastrophically in such a case, we are interested only in the period before the main failure. The kinetic energy plot in Figure 3 suggests that the catastrophic failure is around 260,000 time steps. This is preceded by high LURR values between 160,000 and 210,000 time steps. Again the high LURR values are not precisely prior to the failure event at 260,000 time steps. However, the magnified view of the kinetic energy plot (Figure 4) shows that the initiation event for the catastrophic failure actually occurs at around 212,000 time steps, immediately after the high LURR values. Following this initiation event, the kinetic energy does not drop to zero

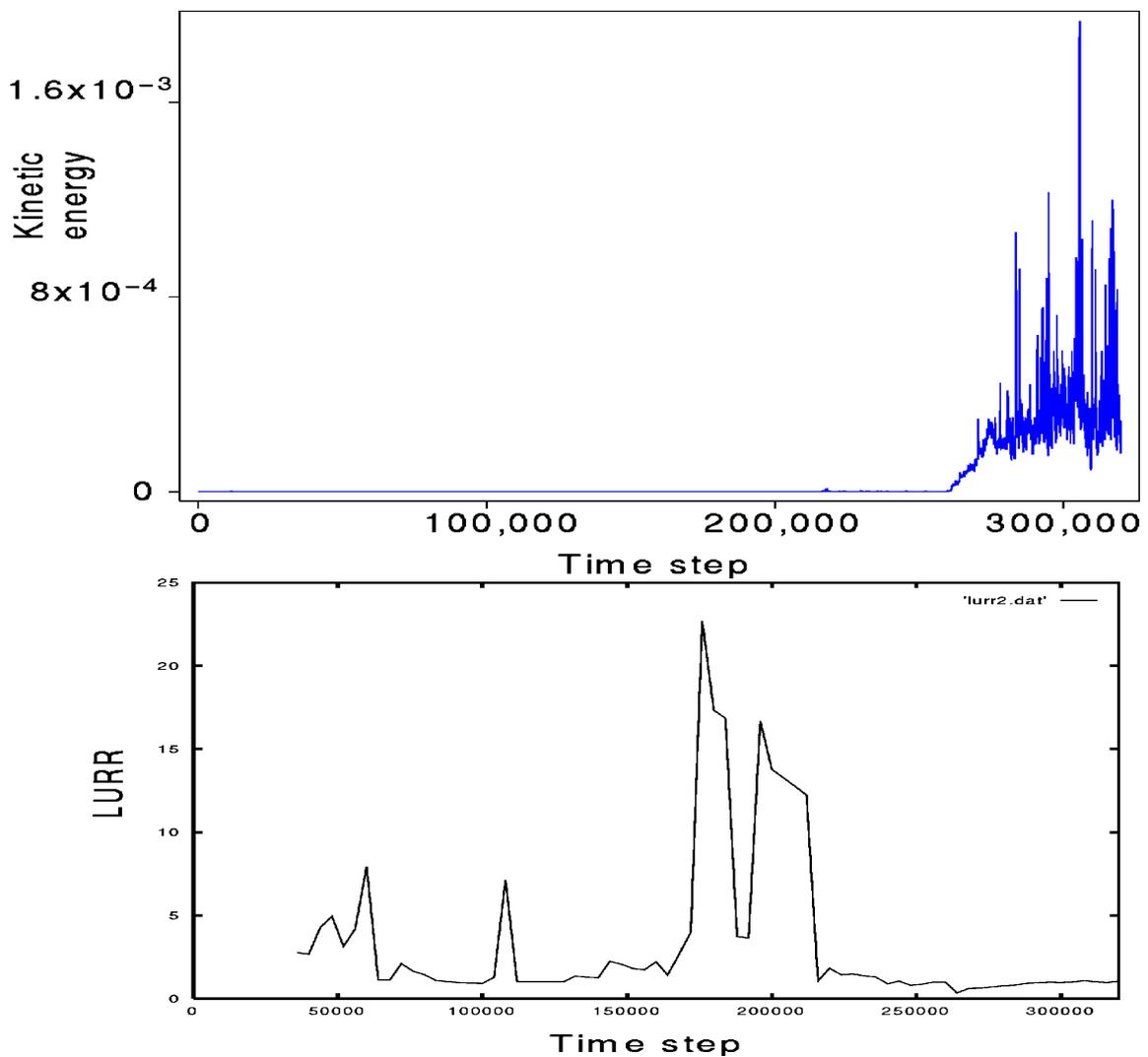


Figure 3: Stress controlled test. **Top:** Kinetic energy. **Bottom:** LURR values versus time.

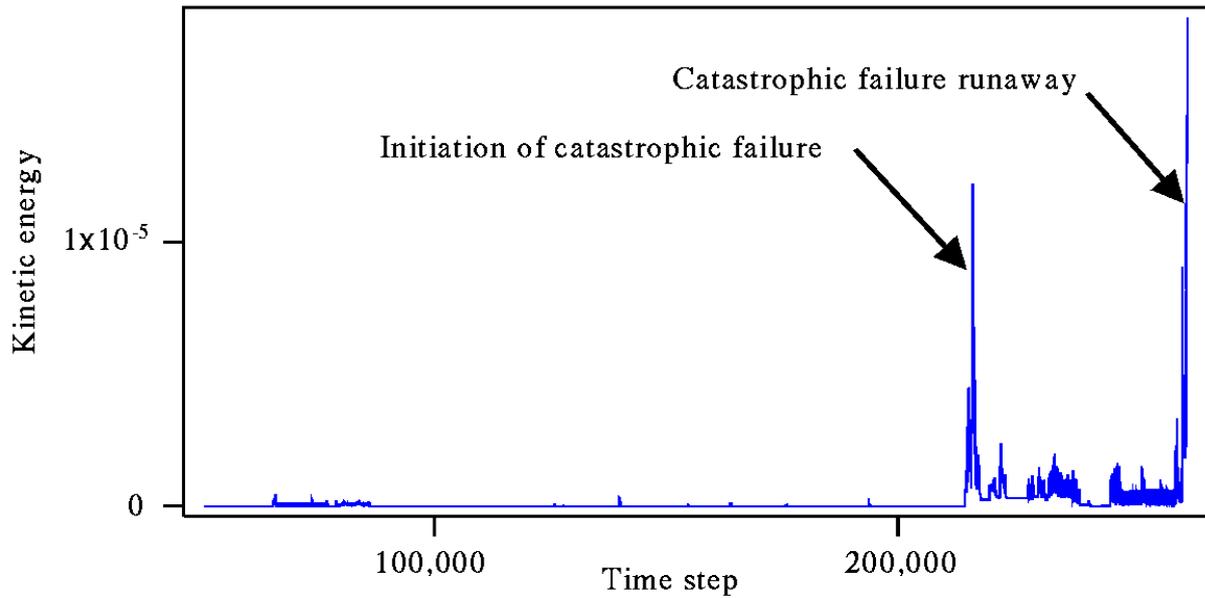


Figure 4: Magnified view of kinetic energy in the stress control experiment prior to the main event runaway at around 260,000 time steps.

indicating that the fracture is continuing to grow, with slip along the fracture resisted by friction and fracturing processes. Hence, in the second example, the LURR value is high immediately prior to the initiation event for catastrophic failure suggesting the LURR has provided a good predictive parameter for this event. At time step $\sim 262,500$ (the end of the plot), the stress has built up to a level where frictional and surface roughness effects can no longer resist and the fracture runs away catastrophically.

Conclusions

The lattice solid model has been used to simulate LURR in several uniaxial compression experiments. Preliminary results show high LURR values prior to the main failure followed by a drop in LURR values. In an experiment involving stress control, the high LURR values occurred immediately prior to the catastrophic failure initiation event suggesting that LURR provides a good predictive parameter for this event. Although too few simulations have been computed to study statistical significance, the preliminary results suggest that catastrophic failure in elastic-brittle system under compression is preceded by high LURR values. These results are encouraging and motivate continued study of the LURR mechanism and earthquake forecasting research.

Acknowledgments

This research was funded by the National Natural Sciences Foundation of China (Grant No. 19732060), the Australian Research Council (ARC), The University of Queensland, and the ARC International Researcher Exchange Programme 2000 (IREX).

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