# Load-Unload Response Ratio, Accelerating Moment Release, and Earthquake Prediction

Xiang-chu Yin[1,2], Peter Mora[3], Keyin Peng[1], Yucang Wang[2], and Dion Weatherley[3]

(1) Center for Analysis and Prediction, China Seismological Bureau, Beijing, 100036, China (e-mail: xcyin@public.bta.net.cn).

(2) Laboratory of Nonlinear Mechanics, Chinese Academy of Sciences, Beijing, 100080, China.

(3) QUAKES, Department of EarthSciences, The University of Queensland, Brisbane, Australia (e-mail: mora@shake2.earth.uq.edu.au; weatherley@shake2.earth.uq.edu.au, phone: +61-7 3365 2128; +61-7 3365 4853, fax: +61-7 3365 3474).

## Introduction

According to the critical point hypothesis (Sornette and Sammis, 1995 [4]; Bowman *et al.*, 1998 [1]), the Earth's crust is not perpetually in a critical state. The occurrence of a large or great earthquake in a region appears to dissipate a sufficient proportion of the accumulated energy to remove the crust from a critical state. Subsequently, tectonic loading drives the crust back towards the critical state. During the establishment of criticality, seismic moment release accelerates in the region surrounding the epicenter of the ensuing large or great earthquake. The Accelerating Moment Release (AMR) sequences may be identified by fitting cumulative moment release prior to a large or great earthquake to a power-law time-to-failure relation (Bufe and Varnes, 1993 [2]; Jaumé and Sykes, 1999 [3]). Such a fit provides an intermediate-term prediction of the time of occurrence of the large or great earthquake.

It has been suggested that the acceleration in seismic moment release is due to the establishment of long range correlations in the regional stress field. Such long range correlations prepare the region for a large earthquake. Once in the critical state, only a very small stress perturbation, such as that caused by Earth tides, may be sufficient to trigger earthquakes. Assuming Earth tides are sufficient to trigger earthquakes, especially moderate earthquakes, a parameter called the Load-Unload Response Ratio (LURR) may be used as a measure of the proximity to criticality (Yin and Yin, 1991 [5]; Yin, 1993 [6]; Yin *et al.*, 1994 [7]; Yin *et al.*, 1995 [8]; Yin *et al.*, 2000 [10]).

## LURR as a predictor of large or great earthquakes

From the viewpoint of Fracture Mechanics, the preparation process for an earthquake is the deformation and damage process of the focal media. LURR has been proposed as a measure of this process. LURR is typically defined as the ratio of Benioff Strain release during loading cycles compared to unloading cycles on optimally oriented faults as induced by Earth tides. High LURR values (greater than unity) indicate that a region is prepared for a large or great earthquake. In previous years, a series of successful intermediate-term predictions have been made for strong earthquakes in mainland China and other countries using the LURR parameter (Yin and Yin, 1991 [5]; Yin, 1993 [6]; Yin *et al.*, 1994 [7]; Yin *et al.*, 1995 [8]; Yin *et al.*, 1996 [9]; Yin *et al.*, 2000 [10]).

At the "International Workshop on Solid Earth Simulation and ACES Working Group Meeting" (17 - 21 January, 2000, University of Tokyo, Japan), Yin *et al.* (2000) [11] predicted that *in the beginning of this century, the seismicity in Japan, Korea, and their periphery should raise remarkably . . . strong earthquakes will occur there.* The actual seismicity in Japan during 2000 has verified this prediction. Further study of LURR in Japan since January, 2000, in collaboration with scientists from the Japan Meterological Agency (JMA), supports the prediction made at the International Workshop.

## A test for a common physical mechanism for LURR and AMR

A relationship between the magnitude of a large or great earthquake and the size of the region where a power-law time-to-failure function best fits cumulative moment release has been noted (Jaumé and Sykes, 1999 [3]). This suggests that a physical mechanism underlies AMR (e.g. critical point behaviour). In the results which follow it is shown that by computing the LURR anomaly for multiple region sizes for a given large event, an optimal radius which maximises LURR may be obtained. A favourable comparison between the optimal AMR region size and the optimal LURR region size would tend to indicate a common physical mechanism underlying the two prediction methods.

To study this possibility we conducted a retrospective examination of several magnitude $5 - 5.7$ Australian earthquakes including the Newcastle earthquake which occurred in 1989. For each event, both LURR anomalies and best fit power-law time-to-failure functions are computed using data for a range of distances from the epicenter. Figure 1 shows typical power-law fits and LURR anomalies for the 1997 $M = 5.0$ Burra earthquake and the 1989 $M = 5.7$ Newcastle earthquake. Good power-law fits both with and without log-periodic fluctuations are obtained for the AMR sequences. Prior to each event there is a sharp increase in the LURR anomaly indicating that a large earthquake is imminent in that region. This data suggests a correlation between the occurrence of AMR and LURR anomalies.

Figure 2 is a plot of the goodness of a power-law fit to the AMR sequences prior to the 1986 $M = 5.0$ Canberra, Newcastle, and Burra earthquakes for various critical region sizes. For small region sizes, the data shows considerable scatter. This is due to the paucity of seismic data for regions of these sizes. For the largest region sizes considered, cumulative moment release is not well represented by a power-law relation. However, for radii in the range $125 < r < 150$ km there is a clear minimum in the curves for the three earthquakes. The critical region size based upon AMR for these three earthquakes is $r \approx 125$ km.

Like the best power-law fits in AMR, the LURR anomaly was optimal (maximised) using data within a certain epicentral distance for the Canberra and Newcastle earthquakes (see Figure 3). The data prior to the Canberra earthquake shows a clear maximum in LURR value for regions in the range $100 < r < 150$ km. This compares favourably with the critical region size obtained using power-law fits to AMR. Due to a lack of seismic data, it was not possible to obtain LURR anomalies for $r < 150$ km for the Newcastle earthquake. However, the trend of the data available suggests that the optimal LURR region for the Newcastle event is $r \approx 150$ km. Once again, this result compares well with the results for AMR.

## Discussion and conclusions

The results presented here are quite preliminary, however they indicate that size of the region for an optimal power-law fit to AMR is similar to the optimal region for which LURR is maximised. Too few earthquakes over a too limited magnitude range have been studied
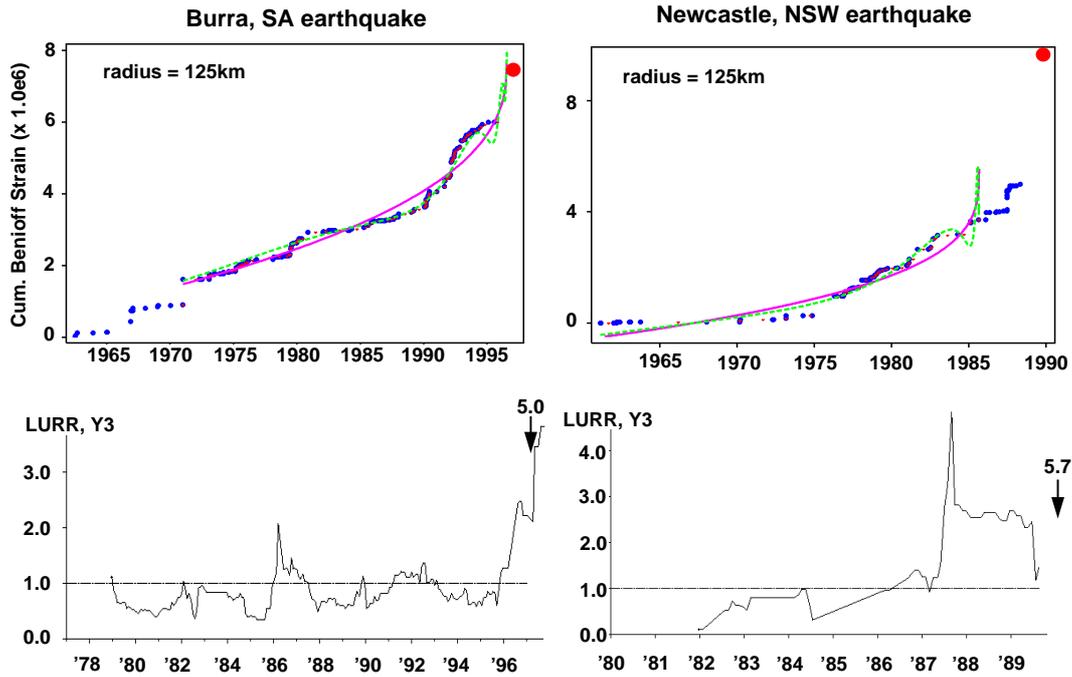
Figure 1: Power-law fits, both with and without log-periodic fluctuations for the Burra and Newcastle earthquakes, using a region size of $r = 125$km. Below the power-law fit for each earthquake, the LURR anomaly for the same earthquake is shown. There is a clear increase in the LURR value prior to the occurence of the two large earthquakes terminating each sequence.
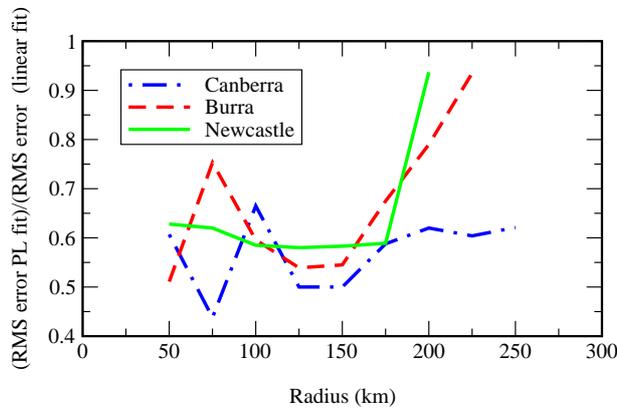


Figure 2: Goodness of fit of a power-law fit to the AMR sequences prior to the Canberra, Newcastle, and 1996 Burra earthquakes for various critical region sizes. For region sizes in the range $125 < r < 150$ km, there is a clear minimum in the three curves, indicating that quite good power-law fits were obtained for region sizes in this range.

to determine whether a relation between the optimal LURR area and mainshock magnitude emerges that is similar to that of AMR. However, the observed correlation between the occurrence of LURR and AMR, and the similar of the sizes of the critical regions in the few cases studied suggests that both observations have a common physical origin. Further work may provide clues that yield an understanding of the mechanism underlying AMR and LURR and will potentially lead to a solid foundation for intermediate-term earthquake prediction.
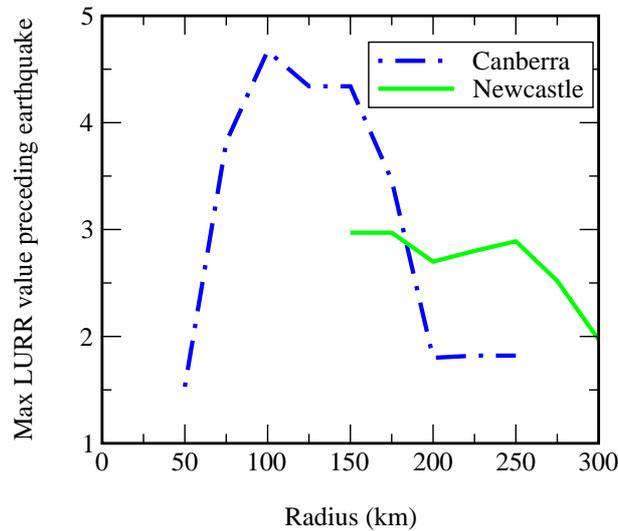
Figure 3: Maximum LURR anomaly for various region sizes for the Canberra and Newcastle earthquakes. There is a clear maximum in LURR value for regions in the range $100 < r < 150$ km surrounding the epicenter of the Canberra event. Paucity of seismic data prevented computation of LURR for the Newcastle earthquake, for region sizes $r < 150$ km. However, the trend of the data suggests that a maximum LURR value would be obtained for $r \approx 150$ km.

## Acknowledgments

## References

[1] Bowman, D. D., Ouillon, G., Sammis, C. G., Sornette, A., and Sornette, D., 1998, *An observational test of the critical earthquake concept,* J. Geophys. Res., **103**, pp. 24359–24372.

[2] Bufe, C. G. and Varnes, D. J., 1993, *Predictive modeling of the seismic cycle of the greater San Francisco Bay region,* J. Geophys. Res., **98**, No. B6, pp. 9871–9883.

[3] Jaumé, S. C. and Sykes, L. R., 1999, *Evolving towards a critical point: a review of accelerating seismic moment/energy release prior to large and great earthquakes,* Pure Appl. Geophys., **155**, pp. 279–306.

[4] Sornette, D. and Sammis, C. G., 1995, *Complex critical exponents from renormalization group theory of earthquake prediction,* J. Phys. I. France, **5**, pp. 607–619.

[5] Yin, X. C. and Yin, C., 1991, *The precursor of instability for nonlinear systems and its application to earthquake prediction,* Science in China, **34**, pp. 977–986.

[6] Yin, X.C., 1993,  *New approach to earthquake prediction,*  PRERODA (Russia's "Nature"), **1**, pp. 21–27 (in Russian).

[7] Yin, X. C., Yin, C., and Chen, X. Z., 1994,  *The precursor of instability for nonlinear systems and its application to earthquake prediction – the Load-Unload Response Ratio theory,*  Nonlinear dynamics and predictability of geophysical phenomena, **AGU Geophysical Monograph 83** (eds Newman, W.I., Gabrelov, A. M., and Turcotte, D.L.), pp. 55–60.

[8] Yin, X. C., Chen, X. Z., Song, Z. P., and Yin, C., 1995,  *A new approach to earthquake prediction – the Load-Unload Response Ratio (LURR) theory,*  Pure Appl. Geophys., **145**, No. 3/4, pp. 701–715.

[9] Yin, X. C., Chen, X. Z., Song, Z. P., and Wang Y.C., 1996,  *The temporal variation in LURR in Kanto and other regions in Japan and its application to earthquake prediction,*  Earthquake research in China, **10**, pp. 381–385.

[10] Yin, X. C., Wang, Y.C., Peng, K. Y., Bai, Y. L., Wang, H., and Yin, X. F., 2000,  *Development of a new approach to earthquake prediction: Load/Unload Response Ratio (LURR) theory,*  Pure Appl. Geophys., **157**, pp. 1923–1941.

[11] Yin, X. C., Wang, Y.C., Peng, K. Y., Zhang, Y. X., and Xia, M. F., 2000,  *New developments of LURR theory and its new application,*  International Workshop on Solid Earth Simulation and ACES WG Meeting, **Abstract vol**.