2013 SCEC Project Report

"Spatio-temporal evolution of seismic clustering in southern California"

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MAJOR RESEARCH FINDINGS

- Development of statistical methodology for robust identification of earthquake clusters. The technique is softly parameterized (i.e., it does not have tuning parameters) and is shown to be very stable with respect to its parameters, magnitude completeness, and earthquake location errors.
- Classification of earthquake clusters in Southern California into three classes: burst-like, swarm-like, and singles. The statistical characteristics of clusters within each class are tightly related to the heat flow and other properties governing the effective viscosity of a region.
- Demonstration of statistical increase of earthquake clustering in the spatio-temporal vicinity of events with $M \geq 6.5$ in southern California according to the relocated catalog of *Hauksson et al.* [2012] during 1981-2011. **(Figure 1)**
- Demonstration of statistical increase of earthquake clustering in the vicinity of the M7.1 Duzce 1999 earthquake according to a unique near-fault catalog [*Seeber et al.*, 2000; *Ben-Zion et al.*, 2003b] that was compiled from data recorded by a temporary network of 10 stations located in close proximity to the hypocenter of the 1999 M7.1 Duzce event.
- Demonstration of statistical changes in general earthquake clustering properties prior and during the swarm of 2010-2011 in Arkansas, US. This swarm occurred after the fluid injection associated with oil and gas production, and led to a maximal event of magnitude $M = 4.7$.

ABSTRACT This project is focused at revealing stable evolutionary patterns of seismic clusters and their relations to the occurrence the largest earthquakes. The project is based on the PI's results on detection and classification of seismic clusters, and the new waveform-relocated catalog of southern California (both obtained within recent SCEC projects). The project directly addresses two of the SCEC4 fundamental problems of earthquake physics. The novelty of this project is in systematic uniform analysis of thousands of robustly detected seismic clusters of small-to-medium magnitude events, as opposed to the handful of largest clusters analyzed in most cluster studies. The previous SCEC projects by the PIs have established the existence of three types of earthquake clusters (burst-like, swarm-like, and singles) of small-to-medium magnitude in southern California, and demonstrated that the cluster type is tightly related to the heat flow and other properties governing the effective viscosity of a region. This project focused on spatio-temporal evolution of earthquake clustering and its relation to large earthquakes. We analyzed data from southern California, Turkey, and Midwestern US. The project results demonstrate increase of seismic clustering in the spatio-temporal vicinity of large events ($M \geq 6.5$) in southern California during 1981-2011 and the Duzce, M7.1, 1999 earthquake in Turkey. Furthermore, we show that cluster properties of seismicity in Arkansas, US, have significantly changed prior and during the swarm of 2010-2011. The results contribute to studies of earthquake predictability and to better understanding of the detailed structure of seismic catalogs in relation to physical properties of the crust.

INTELLECTUAL MERIT The study combines novel approaches to earthquake cluster identification/classification and high quality earthquake catalogs from different environments toward improved understanding of seismicity in relation to large events and human-induced earthquakes. An ability to track the evolving response of the crust to different loadings may be used to monitor the build up of stress in a region. The developed tools and results can have transformative impact on analysis of seismic hazard in active tectonic environments, oil and other production areas, and regions containing both, such as California.

BROADER IMPACT The addressed problems on natural/induced seismicity and seismic anomalies preceding large events have critical societal and economic importance. The developed cluster framework can be applicable to other processes that develop in space-time-energy domains (e.g., river/subsurface flows, aerosol dynamics, chemical reactions, and fires).

TECHNICAL REPORT

1. Background

The results of this project are based on our previous findings on earthquake cluster identification and classification supported by SCEC during 2011-2012 [*Zaliapin and Ben-Zion*, 2011, 2013a (ZBZ13a), 2013b (ZBZ13b)]. In short, in these previous projects we developed a statistical framework for identification of statistically significant individual earthquake clusters based on ideas in [*Baiesi and Paczuski*, 2004; *Zaliapin et al*, 2008]. A multi-event cluster is called a family. The first earthquake with the largest magnitude in a family is called mainshock. All events in a family that occurred after the mainshock are called aftershocks. All events that occurred prior to the mainshock are called foreshocks. This terminology closely resembles the one commonly used in the literature. These definitions lead to two basic clusters – singles and families (to be separated further below into two fundamental types) and 3 types of events within families – mainshocks, aftershocks, and foreshocks. We have demonstrated that the seismicity clusters in the southern CA earthquake catalog of *Hauksson et al.* [2012] can be represented as a combination of clusters of three main types: (i) *Singles* – clusters consisting of one event; a significant part of singles cannot be explained by catalog artifacts (incompleteness, existence of the lowest reported magnitude, etc.) and may reflect certain crustal processes and conditions such as stress heterogeneities, (ii) *Burst-like* clusters characterized by a small number of offspring generations, decreased foreshock and aftershock productivity, and smaller spatio-temporal extent, and (iii) *Swarm-like* clusters characterized by a large number of offspring generations, increased foreshock and aftershock productivity, and higher spatio-temporal extent. The cluster type can be quantified by a simple scalar measure – average topological depth $<d>$ of the leaves in the tree that represents the cluster in the time-space-energy domain. The clusters of different types have distinct preferred geographic locations. Burst-like clusters occur predominantly within areas with decreased levels of heat flow and fluid content and thicker seismogenic zone. Overall, these regions can be characterized as predominantly brittle with high effective viscosity. Swarm-like clusters occur predominantly in the areas with increased levels of heat flow and fluid content, high geothermal activity, and thinner seismogenic zone. Overall, these regions are likely associated with mixed brittle-ductile rheology having decreased level of effective viscosity.

2. Increase of seismic clustering in the vicinity of large events

2.1 Premonitory changes of clustering in Southern California

The results below demonstrate that earthquake clustering in the spatio-temporal vicinity of events with $M \geq 6.5$ in southern California is statistically different from that at other times and locations. We use the relocated catalog of *Hauksson et al.* [2012] in southern California during 1981-2011. There are five such events in the examined catalog: Superstition Hills, 1987, M6.6; Landers, 1992, M7.3; Northridge, 1994, M6.7; Hector Mine, 1999, M7.1; and El Mayor Cucapah, 2010, M7.2.

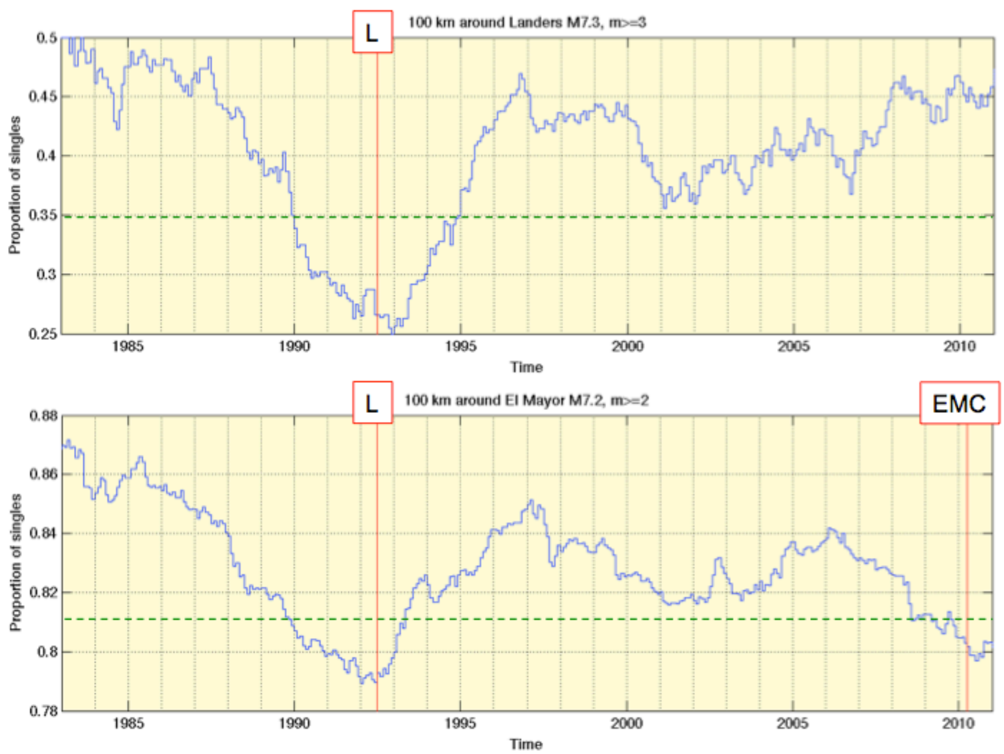

Figure 1: Proportion of singles among the clusters with $m>3$ within a circle with radius of about one rupture length (100 km) around Landers (top) and El Mayor-Cucapah (bottom) epicenters. The proportion drops significantly in the vicinity of large events. This suggests increased homogeneity of the stress field (since heterogeneity can enhance the formation of singles) and increased tendency of earthquakes to cluster (form multi-event families).

Static approach (ND zones): Consider the spatio-temporal volume $\boldsymbol{S}$ to be analyzed (southern California during 1981-2011). We define the X-zone for a large event as the spatio-temporal cylinder with radius R around the event's epicenter and within time T_X after its occurrence. Let $\boldsymbol{X}$ denote the union of all X-zones. The D-zone is defined as the intersection of the spatio-temporal cylinder with radius R around the event's epicenter within time T_D prior to its occurrence and the space-time volume outside of the X-zones: $\mathbf{S}\backslash\mathbf{X}$. Let $\boldsymbol{D}$ denote the union of all D-zones. The $\boldsymbol{N}$-zone is finally defined as the rest of the space-time: $\boldsymbol{S}\backslash\boldsymbol{X}\backslash\boldsymbol{D}$. We perform statistical comparison of various cluster properties between $\boldsymbol{D}$ and $\boldsymbol{N}$ zones. Our initial findings include the following: (i) The average leaf depth $<d>$ for all clusters with $m>3$ is significantly larger in $\boldsymbol{D}$-zones. (ii) The average leaf depth $<d>$ for large families (number of events $N>20$) with $m>3$ is significantly larger in $\boldsymbol{D}$-zones. These two results indicate preference of preceding small events to occur in relatively hot and/or deeper regions. (iii) The proportion of families among all $m>3$ clusters is significantly larger in $\boldsymbol{D}$-zones. (iv) The proportion of large families ($N>5$) among all families ($N>1$) with $m>3$ is significantly larger in $\boldsymbol{D}$-zones. These results suggest that the *clustering increases in the vicinity of a large earthquake*, possibly reflecting acceleration of aseismic processes in regions with relatively low viscosity and near the bottom of the seismogenic zone that lead to the nucleation of large ruptures. This is consistent with physical expectations and the recent case studies of *Bouchon et al.* [2011, 2013] and *Kato et al.* [2012].

Dynamic approach: We find that earthquake clustering is changing in time around the epicenters of selected impending large events, within regions of linear size comparable to that of the earthquake rupture length. **Figure 1** shows the proportion of singles among all clusters with magnitude $m>3$, in a 5-years moving window with a step of 1 month, in a circle with radius of about one rupture length (100km) around the epicenters of Landers (top) and El Mayor-Cucapah (bottom) earthquakes. A prominent drop of the proportion is observed (i) around the Landers event in both experiments, and also (ii) around El Mayor event, in the analysis focused on the El Mayor region. These results may reflect progressive smoothing of large-scale stress heterogeneities before large events as seen in model simulations of evolving seismicity on a large heterogeneous fault [*Ben-Zion et al.* 2003a; *Zöller et al.,* 2005]. Furthermore, we have shown that (i) the average leaf depth is significantly increasing around the times of the Superstition Hills and El Mayor-Cucapah events when examining the seismicity of the San Jacinto fault zone, (ii) the number of topologically deep ($d>1$) and large ($N>5$) families within the Salton Trough region is increasing around the time of Superstition Hills and Hector Mine events. These results are again consistent with increasing aseismic or partially aseismic deformation that lead to the nucleation of the large events.

2.2 Premonitory changes of clustering prior to the Duzce event on the North Anatolian fault

This pilot study demonstrates changes in clustering in the vicinity of the M7.1 Duzce 1999 earthquake. We work with a unique near-fault catalog [*Seeber et al.*, 2000; *Ben-Zion et al.*, 2003b] that was compiled from data recorded by a temporary network of 10 stations located in close proximity to the hypocenter of the 1999 M7.1 Duzce event. The network operated 3 months before and 3 months after the Duzce earthquake. The catalog includes over 26,000 local events preceding and following the Duzce earthquakes with unprecedented detail. Various studies based on this data set provided high-resolution information on the fault zone structure and co/post changes of seismic velocities associated with the Duzce event [*Ben-Zion et al.*, 2003b; *Peng and Ben-Zion*, 2004, 2005, 2006; *Wu et al.*, 2009; *Roux and Ben-Zion*, 2014]. The local seismicity was shown to exhibit clear spatio-temporal changes after the Duzce event [e.g. *Peng and Ben-Zion*, 2005, 2006]. A careful recent study documented a lack of localized accelerated foreshock activity near the hypocenter of the Duzce mainshock [*Wu et al.*, 2014]. However, the overall larger-scale evolution of seismicity before the Duzce mainshock has not been analyzed in detail so far. **Figure 2** shows the evolution of the average leaf depth $<d>$ (top panel) and the proportion of singles (bottom panel) within 60 days prior to the Duzce event. Within 5 days prior to the mainshock, the average leaf depth significantly increases from its steady-state level of $<d> \approx 1$ to about 4. During the same time, the proportion of singles significantly drops. Both the changes indicate increase of clustering similar to that observed in southern California. The results are consistent again with development of partially-aseismic swarm-type behavior and progressive smoothing of stress heterogeneities. We note that the analysis is contaminated by the fact that the examined seismicity includes many aftershocks of the Izmit M7.4 earthquake of 17 August, 1999. Nevertheless, the detailed catalog together with our cluster techniques allow us to identify significant evolving pre-Duzce signals that motivate further detailed analysis.

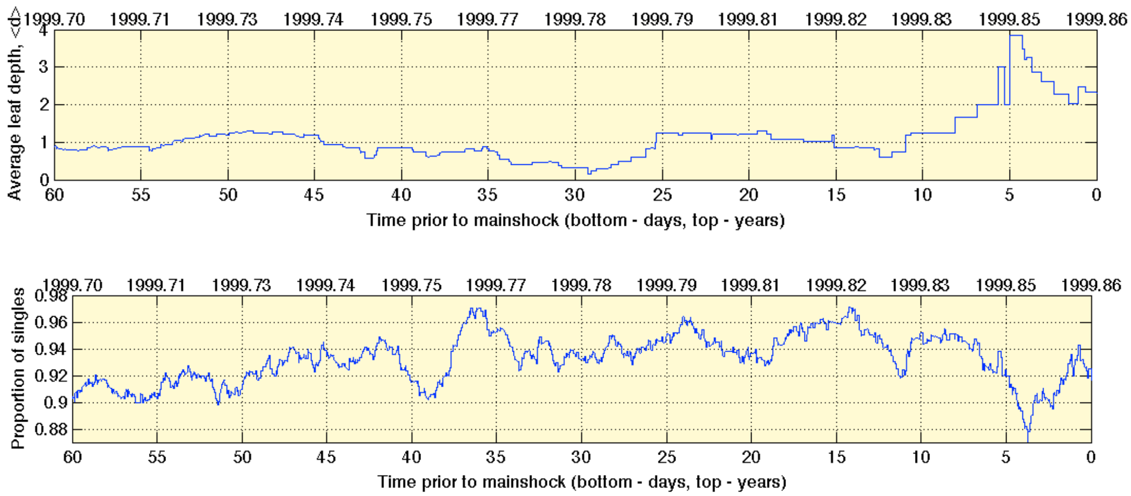

Figure 2: Premonitory changes of clustering prior to Duzce mainshock, 12 November 1999, M7.1. Top panel: Average leaf depth <*d*> in a moving window of 7 days for families with mainshock magnitude $m>3$. Bottom panel: Proportion of singles among all the clusters in a moving window of 3 days.

3. Cluster anomalies of induced seismicity in the Midwestern US

Here we focus on cluster properties of seismicity in Arkansas, US, prior and during the swarm of 2010-2011. This swarm occurred after the fluid injection associated with oil and gas production, with maximal event of magnitude $M = 4.7$. *Llenos and Michael* [2013] argued that the significant increase in the background rates and aftershock productivity might indicate that the swarm is comprised of human-induced earthquakes. While the evidence presented by *Llenos and Michael* is strong, their analysis involves fitting a five-parameter ETAS model, which is known to be somewhat unstable. Namely, it has been shown [*Sornette and Werner*, 2005; *Veen and Schoenberg*, 2008; *Wang et al.*, 2010] that estimation of the ETAS model parameters is affected by the catalog's lowest magnitude cutoff, which may lead to a serious bias in the estimated parameter values. This is particularly important for analyzing the seismicity of Arkansas, where the detection threshold decreased significantly since the 80s, possibly biasing the results based on ETAS model. In addition, the ETAS model does not account properly for swarms [ZBZ13b]. In the initial analysis below we corroborate the results by *Llenos and Michael* with our cluster technique that is not sensitive to the magnitude cutoff, and provide more robust comparative analysis of periods with different quality of catalogs.

Panels (a) and (b) of **Fig. 3** compare the joint distribution ($\log T$,$\log R$) of the rescaled space and time components of the nearest-neighbor distance η. The top white line is the same in both panels, for easy visual comparison. Two observations are noteworthy. First, the distribution in panel (b) is located closer to the origin with the average nearest-neighbor distance being $\eta \approx 10^{-6}$ vs. $\eta \approx 10^{-4}$ prior to 2009 in panel (a); this reflects the overall *increase in seismicity rate* after 2009. We emphasize that a shift towards the origin *cannot* be due to a decreased magnitude cut-off, as demonstrated in ZBZ13a; it has to be connected to actual increase of seismic rates at all magnitudes. This property is one of the notable advantages of our cluster technique over the

ETAS-like methods. Second, the distribution in panel (b) is more compact, reflecting a higher degree of earthquake clustering. To support this observation we perform analysis that retains the marginal time and space distributions of the observed seismicity (i.e., preserves the temporal and spatial heterogeneities of the original catalog) but destroys all possible dependent local spatio-temporal structures [ZBZ13a]. Specifically, we randomly reshuffle the occurrence times of observed events and average the 2D joint distribution of ($\log T$,$\log R$) for 100 independent reshuffled catalogs; the results, called *homogenized profiles*, are shown in panels (c) and (d). It is readily seen that seismicity before 2009 fits well its homogenized profile. However, the observed joint distribution of events after 2009 is located almost an order of magnitude closer to the origin than its homogenized profile, and has different overall shape with a branch quasi-parallel to the horizontal axis indicating clustered events. The results indicate that seismicity after 2009 is dominated by local dependent spatio-temporal structures (clusters) that are destroyed by the reshuffled analysis. Hence, the differences that happen after 2009 cannot be explained solely by increase of the seismic rate; they are due in addition to prominent changes of the *clustering style* of seismicity.

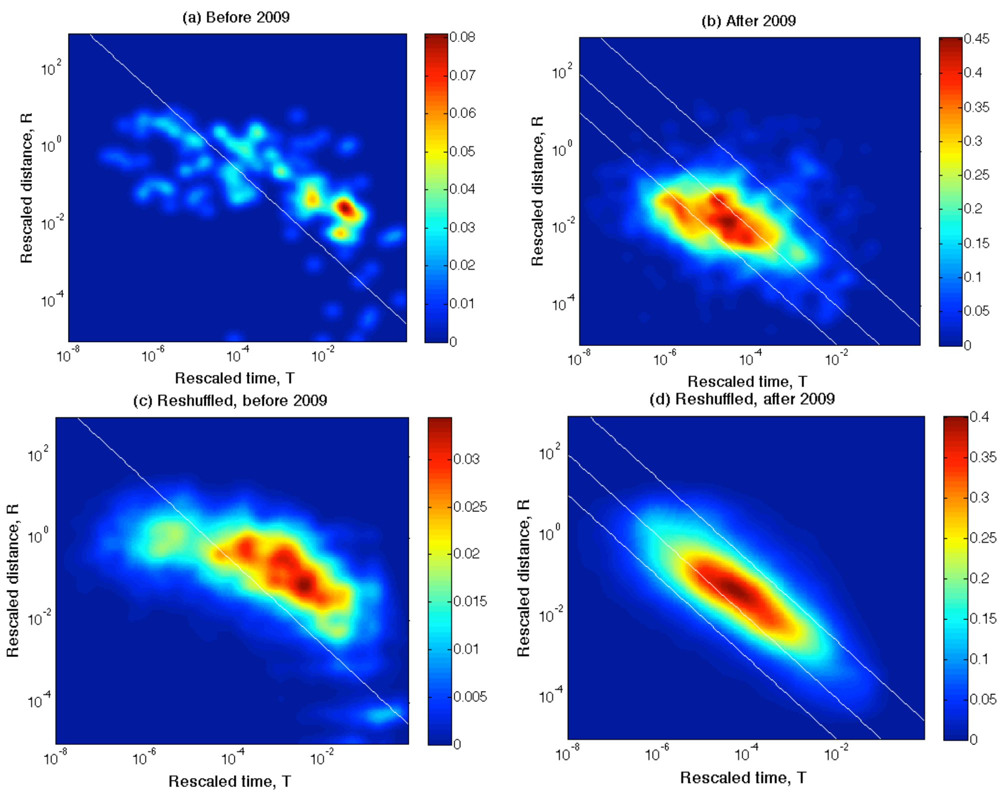

Figure 3: Arkansas sequence – 2D distribution ($\log T$, $\log R$) of the rescaled time and space components of the nearest-neighbor distance η. (a) Observed events before 2009, (b) observed events after 2009, (c) reshuffled catalog using events before 2009, (d) reshuffled catalog using events after 2009. The white line in (a), (c) corresponds to $\eta = 10^{-4.6}$ the white lines in (b), (d) correspond to $\eta = 10^{-4.6}$, 10^{-6}, and 10^{-7}.

PROJECT PUBLICATIONS

1. Zaliapin, I. and Y. Ben-Zion (2013a) Earthquake clusters in southern California, I: Identification and stability. *J. Geophys. Res.*, 118, 2847-2864. doi: 10.1002/jgrb.50179
2. Zaliapin, I. and Y. Ben-Zion (2013b) Earthquake clusters in southern California, II: Classification and relation to physical properties of lithosphere. *J. Geophys. Res.*, 118, 2865-2877. doi: 10.1002/jgrb.50178

PROJECT PRESENTATIONS

1. Zaliapin, I. and Y. Ben-Zion (2013) Spatio-temporal evolution of seismic clusters in southern and central California, Abstract S11B-2378 presented at 2013 Fall Meeting, AGU, San Francisco, California, 9-13 December.
2. Zaliapin, I. and Y. Ben-Zion (2013) Spatio-temporal Evolution of Seismic Clusters in Southern and Central California. Workshop *"Dynamics of Seismicity, Earthquake Clustering and Patterns in Fault Networks"*, SAMSI, October 9-11, 2013
3. Zaliapin, I. and Y. Ben-Zion (2013) Spatio-temporal evolution of seismic clusters in southern and central California, *Proc. of Southern California Earthquake Center (SCEC) 2013 Annual Meeting, Palm Springs, CA, September 8-11, 2013,* Vol. XXIII, p.85, poster 075.

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