Statistics and Triggering of Earthquakes

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1 Overview of the Field

Earthquakes and faults exhibit highly complex structures and patterns that follow, within noisy fluctuating signals, persistent spatio-temporal variations. Clustering is a prominent hallmark of seismicity and fault patterns. Clustering in space is exemplified by the concentration of earthquakes along the boundaries of major tectonic plates and regional fault networks. Clustering in time is best seen as a significant increase of seismic activity immediately after large earthquakes, within so-called aftershock sequences. Earthquake swarms, bursts and gaps are the other prominent examples of clustering. Clustering is a particular example of a large variety of structures and patterns of earthquakes, which remains the primary source of information for constraining physical models of earthquake dynamics. Clustering of seismicity can be produced by various physical processes including, prominently, triggering of events over wide ranges of spatio-temporal scales. Triggering contributes to the complexity of earthquake patterns and is responsible for the effects of correlations and memory. Developing a clear understanding of the underlying physical mechanisms behind earthquake clustering and triggering can lead to significant progress in earthquake hazard assessment and forecasting.

2 Recent Developments and Open Problems

One of the immediate problems that requires the development of improved statistical/mathematical and physical approaches is an in-depth understanding of the physical mechanisms responsible for triggering of earthquakes in different situations. Candidates for earthquake triggering by preceding events include static or dynamic stress changes, fluid flow and pore pressure changes as well as afterslip, to name only a few; an important unsolved challenge is to identify which triggering mechanism is dominant in different cases. Solving this problem requires not only the identification of triggering cascades or aftershocks from observational data but also the development of realistic physics-based earthquake models for triggering cascades, which incorporate essential mechanisms and dynamics of earthquake processes. This challenge includes reconstruction of the complex sub-surface geometry of regional fault networks, which cannot be directly observed but largely influences the spatio-temporal properties of seismicity. This highlights the importance of statistical approaches for solving this inference problem.

To make fundamental progress to solve these open problems, it is also important to analyze triggering in different situations of interest. These include earthquake triggering in nature, earthquake triggering in the lab as well as earthquake triggering due to geoengineering activity. The latter is of particular interest in the case of induced seismicity in mines, dams, etc., where an in-depth understanding and quantification of triggering is crucial for any successful earthquake hazard assessment program.

3 Presentation Highlights

To address the problem of identifying triggering cascades and clusters of seismic activity, I. Zaliapin and Y. Ben-Zion as well as J. Davidsen presented a new robust statistical method. The method allows one not only to define aftershocks in an objective way and study their statistical properties but also to derive a comprehensive and accurate classification of clusters of earthquakes. In particular, the specific cluster type seems to be related to physical conditions in the area of their occurrence. This is a promising and innovative approach to the problem of clustering of seismicity and to study the underlying triggering mechanisms.

Recent progress on the effects of static and dynamic triggering due to large earthquakes were reported by X. Meng. This was made possible by new techniques to identify very small earthquakes that are typically not detected. A. Velasco addressed the issues of data collection and identification of remote and possibly delayed triggering due to dynamic stress changes. D. Zigone presented very recent progress concerning dynamic triggering of slow slip events — events that are quite different from "normal" earthquakes but are thought to play an important role in specific geological settings. V. Durand discussed a case study from Turkey highlighting the possibility of triggering even years after the initial event.

The problem of triggering of earthquakes and fractures was addressed from an experimental perspective by P. Johnson and J. Fineberg. This included the effect of perturbations of a stress field initiated by the passage of a transverse displacement field in a laboratory setting. It also included the dynamics of frictional interfaces and its relation to the stress field which is very important for the initiation of earthquake ruptures and, thus, triggering.

The problem of earthquake triggering due to geoengineering activity was discussed by several participants. D. Eaton gave a detailed introduction into the subject of induced seismicity associated with hydraulic fracturing. The presentation also elaborated on the statistical analysis of induced seismicity due to such activity. This type of analysis is critical for mitigation of risks associated with hydraulic fracturing which is a preferred method in modern shale oil and gas extraction. N. van der Elst outlined a detailed study of remote triggering of earthquakes in central US by large world wide mainshocks. The work illustrates the possibility of such triggering and hazard they pose near the sites of active anthropogenic fluid injection. The conducted research demonstrates the importance of fluid migration in the dynamic triggering of earthquakes. M. Naylor discussed the problem of clustering and its relation to induced seismicity associated with CO_2 storage.

4 Scientific Progress Made and Outcome of the Meeting

The format of the workshop allowed to conduct intensive and productive discussions on the above topics and related questions. The setting of the workshop was ideal as it allowed to bring together several established researchers as well as junior scientists and graduate students. Participants expressed their satisfaction and approval of both the format and scientific topics used during the workshop.

As the main goal, the workshop successfully built and strengthened newly emerging links between active research groups in different scientific areas statistics/probability, mathematics, physics, geodesy and seismology/geophysics toward achieving improved understanding of seismicity patterns and statistics and a physical theory for earthquake triggering. Specific examples include new joint efforts on the topic of earthquake triggering due to geoengineering activity and on the topic of earthquake statistics related to potentially scale-invariant triggering processes from picoseismicity and lab experiments to the largest observed earthquakes in the field. These collaborations are evidence of the key role of the mathematical sciences in studying seismicity dynamics as an essential component of this interdisciplinary research endeavor.

We are confident that the workshop will help the participants to advance their current studies related to the topic of earthquake triggering and clustering.

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