The physics of earthquakes: Is it a statistical problem?

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Abstract

The physics of earthquakes covers a broad range of topics. Some are quite well understood and some are not. The surface displacements associated with an earthquake can be used to deduce fault displacements using static elastic dislocation theories. This approach is quite successful and the deduced displacement fields are generally quite reasonable. The time history of displacements on a fault can be deduced from inversions of the recorded seismogram. Again, this approach is reasonably successful, but there are discrepancies. The spatial distributions of inferred displacements are much more heterogeneous than those determined geodetically.

The general origin of earthquakes is well accepted. Earthquakes occur repetitively on preexisting faults. The rupture of faults is controlled by friction. Stick-slip behavior on a fault is associated with a velocity weakening frictional rheology. It is generally accepted that an earthquake converts stored elastic energy into radiated elastic wave energy and frictional heating on the fault.

Although some aspects of the physics of earthquakes are well understood, others are not. We begin with the initiation of rupture on a fault. It is accepted that rupture initiates when the stress on a fault excedes the static friction. An important question is whether faults also “heal”. Are faults “cemented” between earthquakes. The static frictional force is generally expressed in terms of a coefficient of friction. Many laboratory studies of the static coefficient of friction have been carried out. These studies give values that are much higher than values deduced from field observations. A second anomaly between laboratory studies and real faults is the origin of rupture on faults. Generally, rupture is initiated at the base of the seismogenic zone where the frictional stress would be expected to be a maximum.

Is the static failure stress lower that that predicted in laboratory experiments? If it is, what is the reason? Is it due to high fluid pressure, or is it due to fault zone complexities such as stress heterogenieties and/or fault structure?

Another anomalous fact that must be explained is the virtually complete absence of seismicity on a fault prior to the initiation of a major earthquake. Foreshocks do occur, but they are generally on other faults. It appears that once a rupture of any observed magnitude occurs on a fault (or fault segments) the entire fault (or fault segment) ruptures. Can this be attributed to fault healing.

The physics of rupture initiation must also explain the occurrence of aftershocks. A working hypothesis is that these result from the redistribution of stress associated with the

main shock. But why is there a time delay? Is there an essential time dependence of the rupture initiation process? An experimental Arhenius time dependence of failure is a standard approach to the failure of engineering materials.

Once rupture is initiated, dynamic rupture propagation occurs. According to theory, rupture should accelerate to the appropriate seismic wave velocity. In fact rupture occurs at a fraction of this wave speed. Can this be attributed to fault zone roughness and/or to rupture zone branching?

There appears to be systematic differences between the fault-zone displacements obtained from seismic inversions (synthetic seismograms) and geodetic studies. Seismic inversions give very heterogeneous displacement fields on the fault whereas geodetic inversions give much more uniform displacement fields. Can these discrepancies be attributed to variations in propagation speeds associated with fault zone roughness?

Do Heaton pulses exist? If they do, why? What are the implications with regard to fault zone healing?

Another important aspect of the physics of earthquakes is the complexity of seismic wave propagation. Resonant amplification plays an essential role in the localization of severe damage. Focusing of seismic waves also can localize damage. Generation of acoustic fluidization and other mechanisms of enhanced displacements in soft sediments are also important.

The simplest approach to the seismic cycle is to assume that each fault experiences a seismic cycle independent of all other faults. One consequence of this hypothesis is the uniform accumulation of strain on a fault with periodic earthquakes. Although this approach has long been rejected on secondary faults due to fault interactions, it remains one approach to the understanding of the seismicity on a major fault such as the San Andreas. It leads to the concept of "characteristic" earthquakes and seismic gaps. The studies of paleoseismicity on the southern section of the San Andreas Fault indicate periodic earthquakes are, at best, a poor approximation. The failure of the Parkfield experiment on the San Andreas Fault is a further nail in the coffin of "characteristic" earthquakes. The earthquakes on this section occur on a 25 year cycle, the event predicted for 1989 is now some 10 years overdue.

The characteristic earthquake model could be considered a "classical physics" approach to the earthquake problem. A single fault is embedded is a uniform elastic half-space. Although this model works very well when determining the displacement field associated with an earthquake, it fails when applied to earthquake cycles.

An alternative approach to regional seismicity arises from statistical physics. And in particular from the concept of self-organized criticality (SOC). From this point of view the earth's crust is a thermodynamic system. Background seismicity is equivalent to thermal fluctuations in a nonequillibrium driven medium. The Guttenberg-Richter frequency-magnitude distribution of earthquakes is a fractal relation between the number of earthquakes and their rupture area. This fractal relation for driven SOC systems is equivalent to the Boltzmann distribution in equilibrium statistical mechanics. Further confirmation of this approach comes from induced seismicity. Wherever the earth's crust is loaded, i.e. the filling of a reservoir, earthquakes are induced. The earth's crust is always on the brink of failure. This is a characteristic of SOC systems.

The Burridge-Knopoff slider-block model has been considered a simple model for earthquakes for more than thirty years. A pair of slider-blocks exhibit classic chaotic behavior with the period-doubling route to chaos and exponentially diverging adjacent solutions (positive Lyapunov exponent). Large slider-block arrays exhibit classical SOC behavior. Small slip events satisfy fractal power-law frequency-area statistics with the power law near unity. Adjacent solutions have a power-law divergence.

The behavior of the slider-block model can be understood in terms of a cascade model. A metastable slider-block is a block with a net force that exceeds the dynamic friction but is less than the static friction. Metastable block clusters are clusters of blocks that satisfy this condition (considering the dynamic implications of a rupture event). A rupture event initiates where the net force on a block exceeds the static friction. The subsequent rupture spreads over the associated metastable cluster of blocks.

Small metastable clusters of blocks coalesce to form larger clusters. Rupture events sample the population of cluster sizes but significant numbers of metastable blocks are lost only from the largest clusters. The cascade of coalescing clusters generates the fractal (power-law) scaling and this scaling is terminated by the large events in which large numbers of metastable blocks are lost.

It must be noted that slider-block models are models for the behavior of a single fault. They are not models for interacting faults. Thus the results cannot be directly applied to the earth's crust. The earth's crust appears to be made up of a fractal distribution of blocks. This is consistent with the comminution model for the tectonic disruption of the crust. A tectonic zone behaves like a grinding mill. It is the interactions between the associated fractal distribution of faults that results in the observed seismicity.

The chaotic behavior of slider-block models is strong evidence that the behavior of the earth's crust is also chaotic. This implies that exact predictions are not possible. But it does not imply that earthquakes cannot be predicated (forecast) with considerable accuracy. Weather is also a chaotic system. Hurricane paths cannot be predicted exactly, but in many cases the paths can be forecast with considerable accuracy. Thus we should not give up on earthquake prediction (forecasting). Pattern recognition techniques that have been successful in predicting El Nino should be applied to earthquakes. Log-periodic increases in regional seismicity have been verified before some earthquakes. Levels of intermediate level seismicity appear to increase prior to a major earthquake and patterns of aftershock activity change. These precursory patterns of seismic activity certainly merit future studies.

The chaotic behavior of the earth's crust also has important implications for modeling studies. The direct implication is that phenomena over large ranges of scales interact. This is also the case for atmospheric dynamics. Although global circulation models (GCM's) are useful, they do have severe limitations. They fail to predict the variability statistics (noise) of climate. Similarly finite element and other numerical approaches to tectonic problems will also have severe limitations. Despite these limitations it is timely to initiate major numerical studies of earthquakes and regional seismicity.