AIRCURRENTS

EARTHQUAKES IN EUROPE: THE CASE FOR KINEMATIC MODELING

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EDITOR'S NOTE: Next month, AIR will release a major update to its earthquake model for the pan-European region, adding 24 countries to the existing model domain. Europe's moderate overall seismicity calls for the use of kinematic modeling techniques—a physical approach to understanding earthquake risk, and one that effectively augments the sparse available historical data. AIR Principal Scientist Dr. Bingming Shen-Tu explains what kinematic modeling is and how it is used in the pan-European model.

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A WORLD IN MOTION

"Everything moves, nothing stands still," said the Greek philosopher Heraclitus 2500 years ago. Perhaps Heraclitus had a certain advantage in the shaping of his insight. He lived in Asia Minor, today's Turkey, where historically some of the most destructive earthquakes in all of Europe have taken place.

Heraclitus was speaking philosophically, of course, not seismically. He would not have understood how literally true his statement is. In fact, almost no one did until 50 years ago. The modern understanding of plate tectonics—the realization that the earth's land masses, rigid plates that make up the earth's crust both above the oceans and below them, are in constant motion and tension with respect to each other—was confirmed only in the 1960s.

The movement of these plates, however, is slow. The approach of the African plate north towards Europe, for example, is just six millimeters a year. But the movement is relentless. After eons, the result is the configuration of the earth's surface as we know it today. Europe's Alps are the jumbled remnants of a 200 million year-old primordial sea floor that the advancing African plate has torn up and pushed forward like a bulldozer. The Mediterranean Sea, six million years ago, was dry.

Despite the ages-long timescale of plate motion, it nonetheless impacts the otherwise fleeting experience of human beings: through earthquakes, tsunamis, volcanoes, and their effects. In the tectonic play of irresistible forces, eventually something gives, or breaks, or moves aside. The earth quakes.

MODELING EARTHQUAKE OCCURRENCE

In the mid-afternoon of September 7, 1999, a magnitude 6.0 earthquake struck just 17 kilometers southwest of Athens, Greece. Tens of thousands of buildings were damaged and nearly 100 buildings collapsed entirely. Seventy thousand families were left homeless, several thousand people were injured, and more than 140 people were killed. It was the deadliest natural disaster in Greece in almost a half century and the costliest in more than 100 years.

Earthquake models are used to help anticipate and mitigate such disasters by providing estimates of where, how big, and how often earthquakes are likely to occur in the future. Modeling the seismicity of Europe, however, is extraordinarily complex, not least because the movement north of the African plate is complicated by the additional and simultaneous movement against the Eurasian plate by three other smaller plates, the Arabian plate and the Anatolian and Aegean microplates (Figure 1).

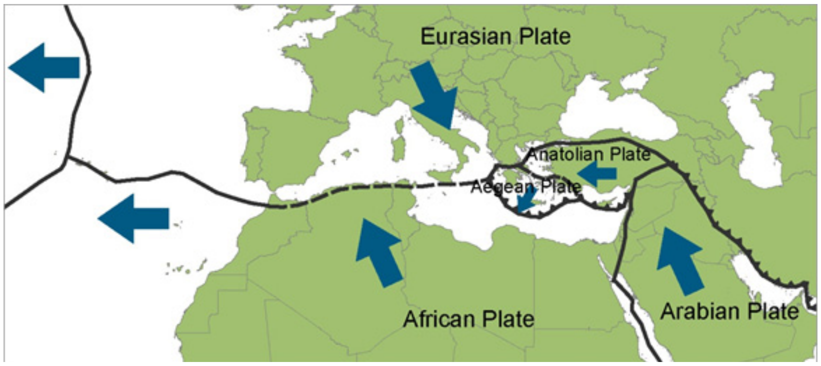

Figure 1. With the interplay of four distinct plates, the tectonic setting of Europe is a particularly complex one. (Source: AIR)

An even bigger challenge is the scarcity of information on past earthquakes. For example, the 1999 Athens earthquake described above took place in an area where until then there had been no record of an earlier earthquake having occurred and where no fault had been mapped; the earthquake's epicenter was in an area thought to be seismically inactive.

Earthquakes, however, are thought to rupture most commonly along active faults at regular time intervals, and the magnitude of each recurring rupture is thought to be roughly the same—that is, a magnitude that is "characteristic" of that fault. This regularity results from the unremitting pressure produced by the movement of the tectonic plates, which remains essentially the same over time. Thus, after a fault ruptures, the amount of time it will take for sufficient energy to build up before the next rupture will be about the same for each recurrence.

In the case of the Athens earthquake, the build-up period could have been 400 or 500 years—or longer. An earthquake probably *did* occur along the same fault near Athens some hundreds of years ago—but in the turmoil of later history, whatever account may have been made of it, was lost. This has been the experience throughout Europe and indeed many other regions of the world: incomplete records, inadequate information about important earthquake characteristics (magnitude, length of a fault, movement along the fault, etc.), or no records at all. Indeed, the largest earthquakes usually have the longest recurrence intervals, lasting even thousands of years—to before the invention of writing.

The AIR earthquake Model for the Pan-European Region makes use of the available historical catalogs and the mapped locations of more than 330 active faults and fault segments. For about half of these (located mostly in Israel, Turkey, Greece, and Italy), there is some usable information on slip rates (which determine how fast seismic energy or stress is accumulating along the fault) and on the return periods of characteristic earthquakes—key factors needed to assess seismic hazard.

Augmenting the historical record, researchers can also make use of paleoseismic information—data about pre-historic earthquakes derived from such activities as fault trenching. However, the paleoseismic record is considerably sparser than the historical record.

KINEMATIC MODELING—A PHYSICAL APPROACH

Fortunately, data helpful to overcoming the limitations of scarce historical and paleoseismic data has become available in recent years through the application of new technology. The movement by an entire land mass of just six millimeters a year may be too little and too slow for human beings to perceive, but for instruments on board satellites in orbit, it is not. By using the Global Positioning System (GPS) and other geodetic tools (world-surveying systems, usually from orbit) to precisely monitor and probe specific locations on the earth's surface over time, the movement of different parts of land masses relative to each other can be measured.

Enter kinematic modeling, a daunting term that describes a relatively simple concept. Kinematics is the branch of classical mechanics that describes the motion of objects. Indeed, plate tectonics—the large-scale movement of the earth's lithosphere—is a kinematic model, albeit a coarse-resolution one.

At a considerably finer resolution, Figure 2 shows the relative velocities, or deformation, of the earth's crust in the eastern Mediterranean as determined from GPS data. The length of the arrows is indicative of the speed of motion (relative to the benchmark 20mm/yr arrow shown in the legend), while the orientation of the arrows indicates direction of movement. As can be seen, the deformations in this region are quite complex.

Through kinematic modeling, these physical measurements can be used to augment the sparse historical record and greatly enhance our understanding of earthquake occurrence within the crustal layer (within the top 20-50km).

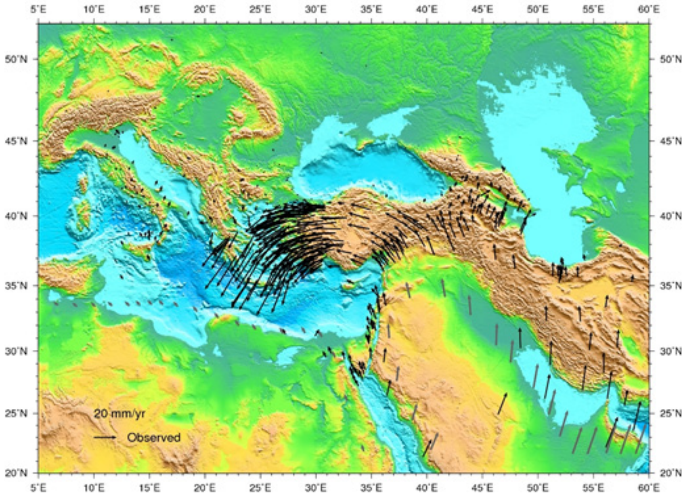

Figure 2. Plate movement and velocities for the eastern Mediterranean as determined from GPS data reveal the complexity of deformation. Source: AIR

ALTERNATIVE STRATEGIES, AND A CLEAR WINNER

There are two widely-used approaches to kinematic modeling. The first is based on the assumption that the seismic actors are rigid fault blocks and that crustal deformation takes place only along block (or, on a larger scale, plate) boundaries. Thus its implementation is simple and direct—but, it relies on assumptions about where the faults (the block boundaries) are located. When the assumed fault locations deviate from actual locations, the model can produce unreliable results. Kinematic block models also necessarily simplify the dynamics of regional tectonics.

The other strategy assumes that the crust behaves like a viscous fluid and models that behavior along a *continuum*. This approach requires making fewer assumptions. For example, estimates of fault locations are not needed, although when such information is available it can be used—along with historical catalog data, fault geometry and slip rates—as additional, powerful input to make the kinematic model more reliable. Indeed, results from the block-based technique can also be incorporated.

AIR seismologists and researchers use the second, continuum-based approach to assist in the development of a catalog of shallow, or crustal earthquakes for the AIR earthquake Model for the Pan-European Region.
The widespread destruction of masonry buildings that the earthquake surveys found initiated the development of technical documents that subsequently have been used to retrofit such buildings and to design new, more resilient ones.

APPLYING KINEMATIC MODELING IN THE AIR PAN-EUROPEAN EARTHQUAKE MODEL

As can be seen in Figure 2, the most active crustal deformation taking place in the pan-European region is at the eastern end of the Mediterranean. It is here that the interplay of the African and Eurasian plates is being additionally impacted by the intrusion of the Arabian plate and the Anatolian and Aegean Sea microplates.

Using the GPS data as primary input, but incorporating all other available data as well, AIR seismologists define and overlay a three-dimensional grid on the model domain. Figure 3 shows the grid from a bird's eye view. Each of the 820 cells of varying size that comprise the grid is defined to capture a crustal volume that exhibits a relatively homogenous deformation pattern. In general, grid cells are smaller in areas where the changes in relative velocities are greater. In order to preserve the homogeneity within cells, they are also smaller where there is considerable variation in deformation patterns. In the case of Italy, for example, we see from Figure 2 only very moderate deformation, yet the patterns of deformation there are highly variable—extension (normal faulting) in the central and south (Central Apennines) , thrust faulting in the east, northeast, and north—and therefore a finer grid is required. In relatively stable areas, a coarser grid is sufficient.

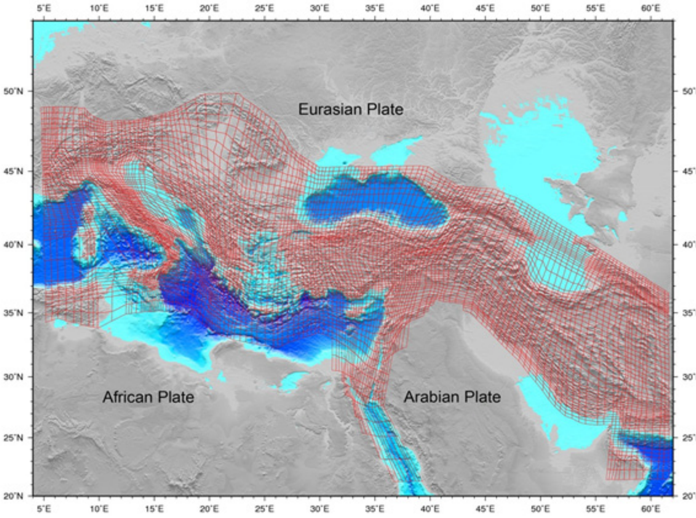

Figure 3. The deformation grid developed for the Eastern Mediterranean. Source: AIR

By applying a mathematical procedure known as inversion, GPS data, plate motion velocities and other available data are converted into a strain rate for each cell. Strain rates captures how quickly the lithosphere is being deformed and therefore how quickly seismic energy is accumulating. Finally, through interpolation, these cell-specific strain rates are converted into a *continuous* strain rate field.

The result is shown in Figure 4. The areas with the highest strain rates—in reds and oranges—are the areas with the highest rates of seismic energy accumulation, those most likely to produce more frequent earthquakes. (Note the low to moderate seismicity in Romania on this map—a country known for its high seismic risk. As stated earlier, the kinematic model is used only for shallow, or crustal, activity; Romania's earthquakes are deep and therefore modeled using a different strategy than the one described in this article.)

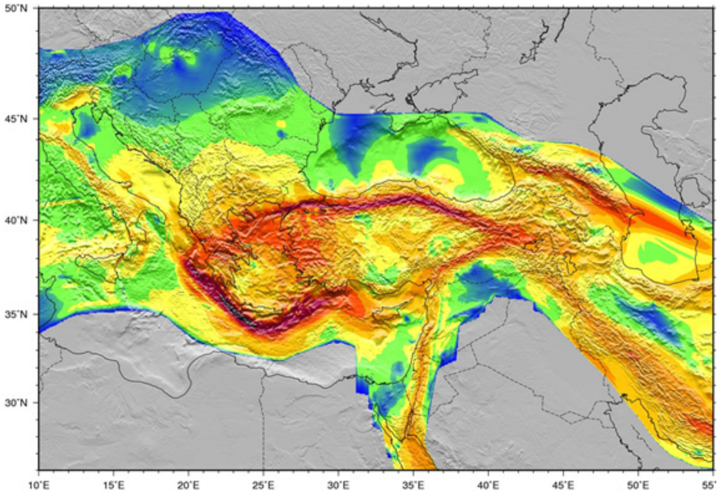

Figure 4. GPS data, plate motion velocities and all other available information is converted into a continuous strain rate field that clearly indicates areas where seismic energy is accumulating at high rates. Source: AIR.

WHERE, HOW BIG AND HOW OFTEN?

In developing an earthquake model for a region, AIR seismologists must estimate not only where potential future earthquakes are likely to occur, but also how often they will occur and how big they will be. The strain rate field depicted in Figure 4 represents the distribution of seismic energy accumulation and is therefore indicative of where crustal earthquakes will occur in the future. But it also represents an energy "budget" to be spent by the occurrence of earthquakes. But will the budget be spent by frequent smaller events or by infrequent larger ones?

The historical record provides guidance on this question. If the historical record—which is dominated by the more frequent small-to-moderate earthquakes—effectively uses up the energy budget, then the historical record can be assumed to be representative of what will happen in the future. That is, the rate of occurrence of future earthquakes can reasonably be estimated based on the rate of occurrence in the historical catalog.

However, if there is an accumulation of energy that remains unspent by earthquakes in the historical record, a seismic "deficit" exists. Such a situation would indicate that, in that area, there is an increased potential for large infrequent earthquakes to take place. In this way, kinematic modeling and the energy accumulation rates it produces provide the guidance necessary to estimate the size and frequency of those large events whose return periods are close to or longer than the historical record.

THE ADVANTAGE OF KINEMATIC MODELING: INSIGHT INTO THE UNKNOWN

Estimating the location and frequency of earthquakes that have long return periods is centrally important to seismic risk assessment. Yet, as outlined above, the historical and paleoseismic records are spotty at best and provide little guidance in the Pan-European region. Kinematic modeling offers a *physically*-based approach to understanding earthquake occurrence. As such, the shortcomings of a purely statistical approach can be effectively by-passed and the occasions when judgment has to be exercised are significantly reduced.

A powerful real-world example is provided by the magnitude 8.0 Wenchuan earthquake that ruptured the Longmeng Shan fault in central China in 2008. The Longmeng Shan fault had produced no event larger than a magnitude 7 in recorded history—that is, in the past 500 years. Consequently, the national seismic hazard map of China had characterized the fault as a low risk zone. However, using kinematic modeling, AIR determined that the strain rate here was much higher than the historical implied—that is, a seismic deficit existed that suggested that earthquakes with magnitudes much larger than historically observed were possible, and even likely. Tragically, the Wenchuan earthquake validated the results of the kinematic modeling and killed an estimated 68,000 people in the process.

Thus kinematic modeling makes for a more robust model that reliably captures the risk from earthquakes—including those large events that have no historical precedent.

ABOUT AIR WORLDWIDE

AIR Worldwide (AIR) is the scientific leader and most respected provider of risk modeling software and consulting services. AIR founded the catastrophe modeling industry in 1987 and today models the risk from natural catastrophes and terrorism in more than 50 countries. More than 400 insurance, reinsurance, financial, corporate and government clients rely on AIR software and services for catastrophe risk management, insurance-linked securities, site-specific seismic engineering analysis, and property replacement cost valuation. AIR is a member of the ISO family of companies and is headquartered in Boston with additional offices in North America, Europe and Asia. For more information, please visit www. air-worldwide.com.