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Developments and Challenges with Earthquake Detection, Prediction and Protection

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Abstract

Earthquakes have influenced life on Earth since civilization began. With urbanization and increased population densities across the globe, earthquakes pose a high threat to life and infrastructure alike. Although as a society, we have not yet developed a consistent method of earthquake prediction, developing technologies that are fundamentally based on different fields should allow us to attack this problem from multiple fronts. Research into the rapidly growing field of geosciences, specifically geophysics, is more important now than ever. In this review, the history of humanity's documentation of earthquakes is explored, such as early earthquake quantification methods and seismograph development. Currrent detection methods and data analysis research into earthquake modeling are also reviewed here as they are currently our only means of prediction, and reveal the hopeful directions improved prediction in the future. Lastly, an interesting branch of earthquake prediction is explored, which involves animal behavior and the corresponding electric field phenomena correlated with earthquakes.

Keywords: Earthquakes, Earthquake Prediction, Earthquake Detection, Geophysics, Geosciences, Earth Science

1. Introduction

In the Chilean earthquake of 1960 that cost $4.8 billion in damage and thousands of lives, seismic waves were recorded around the entire earth for multiple days (Encyclopedia Britannica). Each year 500,000 detectable earthquakes occur, 100 of them causing damage (USGS, Cool Earthquake Facts), and so it follows that religious, cultural, and political infrastructure developed around them, some of which can even be traced back to the ancient Egyptians. Once believed to be works of supernatural beings, earthquakes have become ingrained into human knowledge as both unpredictable and powerful. Although earthquakes have affected society since ancient times, effective detection and prediction of earthquakes remains shockingly minimal. This review will discuss what is known about the science of earthquake detection and prediction, and explore current research efforts in this important field. Currently, large systems of seismometers provide large and connected databases to document earthquakes across the globe. This data then is used to fuel research in unearthing predictive signals- such as recognizing changes in the atmosphere or unearthing complex patterns in ambient seismic fields. These research efforts are unfortunately, still fairly incomplete, therefore the limitations and challenges of this important field will be explored below.

Many historic interpretations of earthquakes were based on religion, the first modern scientific conjecture of the cause of earthquakes was made in 1760 by John Mitchell, who proposed that "shifting

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masses of rock miles below the surface" release the waves of motion that are understood as earthquakes, which ripple across the conductive surface of the Earth (USGS, Cool Earthquake Facts). As it is understood today, earthquakes occur when a build-up of seismic stress along tectonic plates of rock release, causing the blocks to violently move relative to each other.

Current solutions to reduce damage of earthquakes include developing resistant architecture that can withstand the shaking force during an earthquake strike. There has been evidence of earthquake-resistant structures in what is now Iran from around 600 BCE, which demonstrate the isolation of different floors to help reduce damage when earthquakes hit (Patowary, 2019), and structures in earthquake-active Peru utilized dry-stone walls to disperse vibrations that might prove otherwise harmful to buildings at around the 13th century (Patowary, 2019). Earthquake engineering however, did not begin as a branch of Civil Engineering until the second half of the twentieth century (Reitherman, 2012). This period of time saw a number of catastrophic earthquakes, including the notable 1906 earthquake in San Francisco California (History.com, 2009). With modern times came more complex problems that drove engineering to minimize risks of downed wires, cracked gas lines, and broken stoves that have had a visible effect on appliances and architecture today.

The general public has also been trained on how to respond in case an earthquake does happen, but the truth is, humans still have very little power over an earthquake's effects. What makes earthquakes so devastating is that earthquake prediction, the ability to tell us when one will hit and how strong it will be, is still a long way from being achieved. Therefore, traditional methods of evacuation fail in this type of disaster, which plays a significant role in the loss of life it brings. Until earthquakes can be accurately predicted, their dangers will remain as a considerable threat to society therefore, it is important for the current challenges and progress to be carefully explored.

2. History of Earthquake Documentation

Our grapple against the ground began with the oldest written records of earthquakes; these can be traced back to over three thousand years ago (USGS, Earthquakes in History). While man has likely always wondered why earthquakes occurred, notable progress was made in 132 BCE China with the invention of the first seismograph (Figure 1)(Kids Discover, 2014). The design was a vase with eight dragon heads in a circle that was sensitive to tremor direction by its eight sides (Figure 1). When slight tremors passed by, the device would drop balls in different directions (Figure 1). This device was a crucial step on the offensive: it was the first recorded mechanism to record the direction and magnitude of an earthquake.

Figure 1. A photograph of one of the first documented seismometers from China (Photo: Houfeng Didong) (Gillan, 2019).

Further progress would be made in terms of analysis, but the semblance of modern measures would only begin in 1889. In that year, German astronomer Ernst von Rebeur-Paschitz, while measuring gravitational attraction caused by other planets with a large pendulum, noticed a seemingly spontaneous and regular swinging unaccounted for by the planets (Berkeley, 2010). The cause of this force was unknown until he had read a report on a massive earthquake months later. Although his pendulum was based in Germany, it had recorded an earthquake all the way from Japan (Berkeley, 2010). Thus, Rebeur-Paschitz had accidentally laid the foundation for seismograms for centuries to come. Today, a three-story tall spring-pendulum design can still be found functioning in Mexico City (Figure 2). Ultimately, research towards future predictions of earthquakes have all utilized data generated by seismograms, making this tool fundamental to making progress towards enhanced prediction.

Figure 2. A spring pendulum that is suspended three stories above from the roof of the Cathedral Metropolitana in Mexico City (Photo Credit: Diego Delso, License: https://creativecommons.org/licenses/by-sa/3.0/) (Wikiwand).

The 1906 San Francisco earthquake was a turning point for driving the scientific study of the San Andreas fault system in California. While significantly behind earthquake research from Japan and Europe, the first U.S. seismographs were installed in 1887 (USGS. 1906 Marked the dawn of the Scientific Revolution). Catastrophic earthquakes ultimately led to the first government-funded scientific investigation into earthquakes, the State Earthquake Investigation Commission, which published a report in 1908 that compiled knowledge from over twenty researchers and serves as a basis for what is now known about earthquakes. To this day, the Lawson report is still held in high regard.

3. Detecting Earthquakes Today

While knowledge of earthquakes has grown a lot since the first seismometer was invented, the basic tools used to detect earthquakes haven't changed a great deal. Seismometers today still utilize Ernst's principle of oscillating pendulums sensitive to ground movement. There are differences, though; since now it is understood that earthquakes consist of four waves with different directions of movement, modern seismometers now include three axes of measurement, modeled by three different pendulums. A Z-component measures vertical motion, while two E/N components measure northern, eastern, western, and southern movement (British Geological Survey).

Another advancement is the presence of easily transportable seismometers today (Figure 3) that can be found at different locations across the globe help pinpoint the epicenters of earthquakes. Reduced cost and internet access have also given rise to many "public seismograph networks", one of which is funded by the U.S. government – the United States Geological Survey (USGS). Larger arrays have also been developed to map the interior of the Earth in terms of capturing wave speed and transmissivity.

Figure 3. Modern seismometer used at the USGS (Public Domain) (USGS).

There are thousands of seismometers now scattered throughout the world creating a network of databases of seismic data. The USGS is just one organization that cooperates with international partners such as the National Science Foundation, to generate an expansive public database of seismic events. Known as the Incorporated Research Institutions for Seismology (IRIS), this database offers data from even the early 1900s (USGS. Earthquakes in History). The ubiquitous nature of the internet also gilds these databases with an important function in early warning systems, where monitoring systems can immediately send electronic signals to damage-prone areas minutes before damage may be done (Japan Meteorological Agency). This is based off of the principle that seismograms gather two types of wave data. The first is the longitudinal and comparatively harmless P-wave, or pressure wave, and the second is the more dangerous S-wave, or shear wave, which measures transverse movement. The p-wave of an earthquake travels about 67% faster than the dangerous S-wave, therefore the p-wave can be used to estimate the center of an impending shock, and areas that will be hit can be notified instantaneously (USGS, Body Waves Inside the Earth). Countries such as Japan have used these signals to broadcast expected earthquakes through TV and radio (Center for Public Impact). While this has made some level of evacuation possible, it would be valuable to increase the evacuation time to provide more effective evacuation of heavily populated areas and of citizens that require more time, leaving earthquakes as a substantial threat today.

4. Modeling Future Earthquakes

Global databases and systems of seismograms have allowed researchers internationally to conduct advanced studies of earthquakes in order to uncover novel methods to predict them. One particular area of research involves analysis of patterns in Earth's tremors has led to fascinating new insights. One study from Stanford examined how the ambient seismic field could hint at moderate-level earthquakes (Denolle et al., 2013). This study, as well as others (Ma et al., 2008) (Prieto et al., 2011), extracts impulse response functions over time between two measuring stations, then modifies and solves this system of differential equations to get useful information relating ambient seismic field patterns and larger seismic events. This is part of a larger effort to analyze earthquakes; however, it has been concluded that additional sensitive seismograph data would be needed to generate more accurate, and useful, functions. In another example, a group from UCLA analyzed strain data to determine appropriate models for earthquake impacts (Snieder 2006). More recently, an effort by the Bulletin of the Seismology Society of America compared station-to-station velocity models to actual data to analyze flaws in Green analysis (Paul et al., 2020).

Another approach that characterizes earthquakes is the analysis of the earthquake aftershock. Such is the tendency of a large earthquake to induce a series of smaller earthquakes on the same fault, an effect of the "readjustment process" of tectonic plates (USGS. What is the difference between Aftershocks and Swarms?). The Epidemic Type Aftershock Sequence (ETAS) model proposed by Ogata in 1988 (Ogata, 1988) is a popular stocastic model for seismicity, but despite decades of research this model lacked the ability to link individual seismic events. Therefore an alternative approach has arisen, known as the "earthquake productivity law", which is defined as the exponential distribution of related earthquakes independent of magnitude (Baranov, 2019). To measure "earthquake productivity" data trees are generated for related earthquakes and the number of "neighbors", or related events, for each earthquake, is graphed (Shebalin, 2020). An alternative model for earthquake aftershocks based on this has been developed and verified in light of other laws, and potential methods to estimate the magnitude of the largest aftershock of an event have been reviewed (Baranov, 2022).

Although such research has vastly expanded our understanding of earthquakes, more work needs to be done to leverage that understanding into useful prediction models.

5. Can Animals Predict Earthquakes?

Studies on earthquakes today encompass a far broader range of symptoms that might predict an earthquake and use increasingly novel strategies to do so. In a 2014 study by Hiroyuki Yamauchi, surveys revealed that pets were more restless before the earthquake prior to its occurrence (Yamauchi et al., 2014).

Records of unusual wildlife activity before earthquakes can be traced back to Greece in 373 BC (USGS, Can animals predict earthquakes?), in which centipedes and rats were reported to have left the city for safety. While people have noticed unusual animal behavior before earthquakes in recorded accounts (including a zoo in China that observed zebras banging their heads against walls and elephants wildly swinging their trunks before a large earthquake) little has been done to quantify this phenomenon until recently (Sanderson, 2008). Surveys by Hiroyuki Yamauchi, Hidehiko Uchiyama, Nobuyo Ohtani, and Mitsuaki Ohta published in 2014 found a relationship between both distance and time from the epicenter with pet activity, reporting that "the ratio of total unusual animal behaviors increased in both [cats and dogs]" before a magnitude 9.0 earthquake occurred (Yamauchi et al., 2014).

Figure 4. Frog migrations before an earthquake in China (Mui, 2008).

Whilst the exact reason animals can detect this specific danger is unknown, current hypotheses include changes in "atmospheric pressure, gravity, ground deformation, noise from the formation of microcracks, groundwater level changes, and the emission of gases and chemical substances (Mui, 2008)." A 2017 study confirms the ability of animals to pick up on a large range of abiotic noises (Garstang, 2017). However, it contends that the sounds heard by animals before an earthquake are the result of induced vibrations in metal, the product of a large chain of activity starting with crustal breakage, not sounds directly from the crust breaking (Garstand, 2017). Such studies provide insight into unexpected signals from earthquakes- that alternative signals may be found, not necessarily in seismic vibrations.China, inspired by these findings, launched its own animal monitoring program in 2015 (BBC News, 2015). While no earthquakes have yet been predicted with this program, active analysis of large samples of animals may perhaps save lives in the future.

These efforts prompt the question: What are animals sensing? As seen, one of the hypotheses includes low-frequency sounds outside of human hearing ranges. The answer may be in the sky rather than the ground below. Many studies have noticed correlative observations between earthquakes and electromagnetic wave emission, electric field phenomena, and magnetic field phenomena. A 2018 paper by Friedemann Freund, a NASA researcher, proposes a unifying theory, suggesting that tectonic stresses cause "the activation of electronic charges … via the rupture of peroxy bonds (Freund et al., 2021)". These electronic charges immediately travel fast and far out of stressed zones to trigger a handful of phenomena, including but not limited to those mentioned before, massive air ionization, and increased levels of ozone and carbon monoxide (Freund et al., 2021).

As for animals, Freund says that ionization of air molecules- which may, for example, oxidize water into hydrogen peroxide- as well as the oxidation of organic compounds, may cause unusual reactions within animals (Freund & Stolc, 2013). Whatever the pathway animals use to detect earthquakes, there is clearly more for us to learn from them to understand the subtle symptoms that precede an earthquake.

6. Conclusion

The 1906 San Francisco earthquake shook down $15 billion dollars in infrastructure, ending 3000 lives and leaving 250,000 homeless (History.com, 2009). Models by USGS suggest that such catastrophic earthquakes occur every 200 years in the California region, therefore it is highly likely that California will experience one in the next few decades (USGS, When will it happen again?). Although countries like Japan currently use earthquake data, and specifically p-wave data, for prediction, the amount of advanced warning time could be vastly improved. Likewise, advances in ambient seismic data analysis have revealed valuable insights into moderately-sized earthquakes, however refinement of our current tools are needed for more sensitive measurements to facilitate prediction of larger quakes. New approaches to geophysical research are sure to lead to exciting new models of earthquake prediction, and one of these approaches may be through cluster analysis. For example, tree-based analysis of aftershocks has already lead to new insights into the nature of earthquakes, so as mathematical and computational science continues to evolve, we will develop stronger tools for more sophisticated analysis of seismic data. Lastly, to the more we learn about changes in animal behavior preceeding earthquakes, the clearer the mechanisms will be and more thoroughly explored for further insight, leading us closer to improved earthquake prediction. With urbanization and increased population densities across the globe, posing a high threat to life and infrastructure alike, earthquakes have grown as influential as ever, making these developments all the more important.

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