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Absence of Remotely Triggered Large Earthquakes: A Geometric Explanation

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Abstract

It is known that seismic waves from a large earthquake can trigger earthquakes in distant locations. Some of the triggered earthquakes are strong themselves. Interestingly, strong triggered earthquakes only happen within a reasonably small distance (less than 1000 km) from the original earthquake. Even catastrophic earthquakes do not trigger any strong earthquakes beyond this distance. In this paper, we provide a possible geometric explanation for this phenomenon.

1 Formulation of the Problem

Triggered earthquakes: original expectations. It is known that seismic waves from a large earthquake can trigger earthquakes at some distance from the original quake; see, e.g., [1, 2, 3, 4, 5, 6, 8, 9]. At first glance, it seems reasonable to conclude that the stronger the original earthquake, the stronger will be the triggered earthquakes, so that catastrophic earthquakes will trigger strong earthquakes even far away from the original location.

Unexpected empirical fact. Somewhat surprisingly, it turned out that no matter how strong the original earthquake, strong triggered earthquakes are limited to an about 1000 km distance from the original event. At larger distances, the triggered (secondary) earthquakes are all low-magnitude, with magnitude $M < 5$ on Richter scale; see, e.g., [7].

Why? At present, there is no convincing explanation for this empirical fact.

What we do in this paper. In this paper, we provide a possible geometric explanation for the observed phenomenon.

2 Geometric Explanation

Main idea. Our explanation is based on a very natural idea: that if we have a phenomenon which is symmetric – i.e., invariant with respect to some reasonable transformation – then the effects of this phenomenon will also be invariant with respect to the same transformation. For example, if we have a plank placed, in a symmetric way, over a fence – so that we have the exact same length to the left and to the right of the fence, and we apply similar forces to the left and right ends of this plank, we expect it to curve the same way to the left and to the right of the fence.

What are reasonable transformations here? All related physical processes do not change if we simply shift from one place to another and/or rotate the corresponding configuration by some angle. If we describe each point x by its coordinates x_i, then a shift means that each coordinate x_i is replaced by a shifted value $x'_i = x_i + a_i$, and rotation means that we replace the original coordinates x_i with rotated ones $x'_i = \sum\limits_{j=1}^{n} r_{ij} \cdot x_j$ for an appropriate rotation matrix r_{ij}.

In addition, many physical processes – like electromagnetic or gravitational forces – do not have a fixed spatial scale. If we scale down or scale up, we get the same physical phenomenon (of course, we need to be careful when scaling down or scaling up). This is how, e.g., airplanes were tested before computer simulations were possible: you test a scaled-down model of a plane in a wind tunnel, and it provides a very accurate description of what will happen to the actual airplane. So, to shift and rotation, it is reasonable to add scaling $x_i \to \lambda \cdot x_i$, for an appropriate value λ.

What is the symmetry of the propagating seismic wave? In a reasonable first approximation, the seismic waves propagates equally in all directions with approximately the same speed. So, in this approximation, at any given moment of time, the locations reached by a wave form a circle with radius r equal to the propagation speed times the time from the original earthquake.

When we are close to the earthquake location, we can easily see that the set of all these locations is not a straight line segment, it is a curved part of a circle. However, as we get further and further away from the original earthquake location, this curving becomes less and less visible – just like we easily notice the curvature of a ball, but it is difficult to notice the curvature of an Earth surface; for most experiments, it is safe to assume that locally, the Earth is flat (and this is what people believed for a long time, until more sophisticated measurements showed that it is not flat). So:

- in places close to the original earthquake, the set of locations affected by the incoming seismic wave can be approximated as a circle's arc – a local part of a circle, while
- in places far away from the original earthquake, the set of locations affected by the incoming seismic wave can be well approximated by a straight line segment.

It is important to emphasize that the difference between these two situations depends only on the distance to the original earthquake location, it does not depend on the strength of the earthquake – it is the same for very weak and for very strong earthquakes.

What is the effect of these two different symmetries? Out of all possible symmetries – shifts, rotations, and scalings – a circle is only invariant with respect to all possible rotations around its center. Thus, we expect the effect of the resulting seismic wave to be also invariant with respect to such rotations. Thus, the area A affected by the incoming wave should also be similarly invariant. This means that with each point a, this area must contain the whole circle. As a result, this area consists of one or several such circles. From the viewpoint of this invariance, it could be that the affected area is limited to the circle itself – in which case the area is small, and its effect is small. It can also be that the area includes many concentric circles – in which case the affected area may be significant, and its effect may be significant.

On the other hand, a straight line has different symmetries: it is invariant with respect to shifts along this line and arbitrary scalings. Thus, it is reasonable to conclude that the area effected by such almost-straight-line seismic wave is also invariant with respect to the same symmetries. This implies that this area is limited to the line itself: otherwise, if the area A had at least one point outside the line, then:

- by shifting along the original line, we can form a whole line parallel to the original line, and then
- by applying different scalings, we would get all the lines parallel to the original line – no matter what distance, and thus, we will get the whole plane, while the affected area has to be bounded.

Thus, in such situations, the effect of the seismic wave is limited to the line itself – i.e., in effect, to a narrow area around this line – and will, thus, be reasonably weak.

This indeed explains the absence of remotely triggered large earthquakes. Indeed, for locations close to the earthquake, the resulting phenomenon is (approximately) invariant with respect to rotations – and thus, its effect should be similarly invariant. This leaves open the possibility that a large area will be affected and thus, that the resulting effect will be strong – which explains why in a small vicinity, it is possible to have a triggered large earthquake.

On the other hand, in remote locations, location far away from the original earthquake, the resulting phenomenon is invariant with respect to shifts and scalings – and thus, its effect should be similarly invariant. As a result, only a very small area is affected – which explains why, no matter how strong the original earthquake, it never triggers a large earthquake in such remote locations.

Comments.

- It should be mentioned that our analysis is about the geometric shape of the *area* affected by the seismic wave, not about the physical properties of the seismic wave itself. From the physical viewpoint, at each sensor location, the seismic wave can definitely be treated as a planar wave already at much shorter distances from the original earthquake than 1000 km. However, if instead of limiting ourselves to a location of a single sensor, we consider the whole area affected by the seismic wave – which may include many seismic sensors – then, at distance below 1000 km, we can no longer ignore the fact that the front of the incoming wave is curved. (At larger distances from the earthquake, even at such macro-level, the curvature can be ignored.)

- It should also be mentioned that what we propose is a simple *qualitative* explanation of the observed phenomenon. To be able to explain it quantitatively – e.g., to understand why 1000 km and not any other distance is an appropriate threshold, and why exactly the Richter scale $M = 5$ is the right threshold – we probably need to supplement our simplified geometric analysis with a detailed physical analysis of the corresponding phenomena.

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References

[1] E. E. Brodsky, V. Karakostas, and H. Kanamori, "A new observation of dynamically triggered regional seismicity: Earthquakes in Greece following the August 1999 Izmit, Turkey earthquake", *Geophysical Research Letters*, 2000, Vol. 27, pp. 2741–2744.

[2] J. Gomberg, P. Bodin, K. Larson, and H. Dragert, "Earthquake nucleation by transient deformations cause by the $M = 7.9$ Denali, Alaska, earthquake", *Nature*, 2004, Vol. 427, pp. 621–624.

[3] J. Gomberg, P. Reasenberg, P. Bodin, and R. Harris, "Earthquake triggering by transient seismic waves following the Landers and Hector Mine, California, earthquake", *Nature*, 2001, Vol. 11, pp. 462–466.

[4] D. P. Hill at al., "Seismicity in the Western United States triggered by the M 7.4 Landers. California, earthquake of June 28, 1992", *Science*, 1993, Vol. 260, pp. 1617–1623.

[5] S. E. Hough, L. Seeber, and J. G. Armbruster, "Intraplate triggered earthquakes: observations and interpretation", *Bulletin of the Seismological Society of America*, 2003, Vol. 93, No. 5, pp. 2212–2221.

[6] D. Kilb, J. Gomberg, and P. Bodin, "Triggering of earthquake aftershocks by dynamic stresses", *Nature*, 2000, Voll. 408, pp. 570-574.

[7] T. Parsons and A. A. Velasco, "Absence of remotely triggered large earthquakes beyond the mainshock region", *Nature Geoscience*, 2011, Vol. 4, pp. 312–316.

[8] A. A. Velasco, S. Hernandez, T. Parsons, and K. Pankow, "Global ubiquity of dynamic earthquake triggering", *Nature Geoscience*, 2008, Vol. 1, pp. 375–379.

[9] M. West, J. J. Sanchez, and S. R. McNutt, "Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake", *Science*, 2005, Vol. 308, pp. 1144–1146.