Dynamic Triggering of Earthquakes: Symmetry-Based Geometric Analysis

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Abstract

It is known that seismic waves from a remote earthquake can trigger a small local earthquake. Recent analysis has shown that this triggering occurs mostly when the direction of the incoming wave is orthogonal to the direction of the local fault, some triggerings occur when these directions are parallel, and very few triggerings occur when the angle between these two directions is different from 0 and 90 degrees. In this paper, we propose a symmetry-based geometric explanation for this unexpected observation.

1 Formulation of the Problem

Dynamic triggering of earthquakes: a phenomenon. When a seismic wave from an earthquake hits a distant fault – completely unrelated to the fault involved in the original earthquake – this sometimes triggers a minor earthquake and/or other seismic activity at the distant fault's location – either almost immediately, or after some delay; see, e.g., [1, 2, 3, 5, 7, 8, 9, 10, 11, 12, 14] and references therein.

Somewhat unexpected feature of dynamic triggering. Interestingly, it turned out that triggering strongly depends on the angle between the direction of the incoming wave and the direction of the fault; see, e.g., [3, 6]. The vast majority of triggerings occur when these direction are (almost) orthogonal to each other. There is another spike of triggerings – mush smaller one – when the direction of the incoming wave is practically parallel to the direction of the fault. Very few triggerings occur when the angle is different from 0 and from 90 degrees.

Why this happens is not clear.

What we do in this paper. In this paper, we provide a symmetry-based geometric explanation for the above feature of dynamic triggering.

2 Symmetry-Based Geometric Explanation

Let us use symmetries. In physics, symmetries – in particular, geometric symmetries – are an important tool that helps analyze and explain many physical phenomena; see, e.g., [4, 13]. In view of this, let us consider geometric symmetries related to dynamic triggering of earthquakes.

Symmetries: no-faults case. In an area without faults, all physical properties are the same at different locations and at different directions. So, if we shift in any direction, or rotate, the situation remains the same. In addition to these continuous symmetries, we can also consider discrete symmetries:

- reflections over any line and
- reflections in any point.

Also, many physical properties do not change if we re-scale the area, i.e., change the original coordinates (x, y) by re-scaled values $(\lambda \cdot x, \lambda \cdot y)$, for some $\lambda > 0$.

Which symmetries remain in the presence of the fault? Locally, most faults are straight lines.

Thus, when there is a fault, the resulting configuration is no longer invariant with respect to all the above geometric transformations. For example, there is no longer invariance with respect to rotations, since rotating the configuration will also rotate the direction of the fault – and thus, make the configuration different.

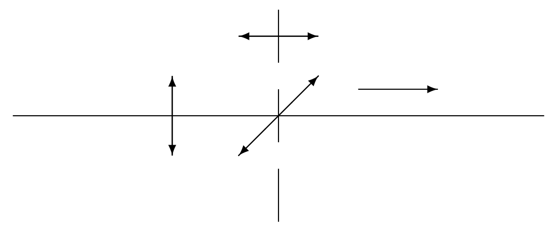
The only remaining symmetries are:

- shifts in the direction of the fault $x \to x + a$;
- reflection over the fault line;
- reflections over any line orthogonal to the fault; and
- scalings $(x, y) \to (\lambda \cdot x, \lambda \cdot y)$ and reflections in any point on the fault.

This configuration and its symmetries are described in the picture below:

- shifts in the direction of the fault are marked by a horizontal one-directional arrow;
- reflection over the fault line is marked by a vertical bi-directions arrow;
- a line orthogonal to the fault is marked as ia dashed line, and the reflection over this line is marked by a horizontal bi-directions arrow; and

- scalings and the reflection in a point on the fault are marked by a slanted bi-directional arrow.



Symmetry matching and resonance: general reminder. To describe how symmetries influence the physical effect, let us consider a simple example: a pendulum with period T. The periodicity of a pendulum means that if we shift the time by T, i.e., consider a moment $t + T$ instead of the original moment t, the state of the pendulum will remain the same. Similarly, the pendulum remains invariant if we shift all the moments by time $k \cdot T$, for some integer k.

If we perturb the pendulum at random moments of time, it will be affected, but overall, not much: randomly applied pushes will cancel each other, and the overall effect will be small. The largest possible effect can be obtained if we apply perturbations that have the exact same symmetry – i.e., if at the same moment of time during each period, we apply the exact same small push. This is how the kids play on the swings.

For the pendulum and other time-shifting situations, this phenomenon is called a *resonance*, but the same phenomenon occurs in other situations as well, when symmetries are not necessarily related to time: e.g., the largest effect of a wave on a crystal is when the wave's spatial symmetry is correlated with the symmetry of the crystal.

If some symmetries are preserved, we still get some effect: e.g., we can still affect the swings if we push at every other cycle (thus keeping it only invariant with respect to shifts by $2T$), or at every third cycle, etc.

In all these cases, the more symmetries are preserved, the larger the effect; see, e.g., [4, 13].

Symmetries of a configuration involving a seismic wave. From this viewpoint, let us consider the dynamic triggering of earthquakes. The seismic wave generated by a remote earthquake usually lasts for a short time. So, at any given moment of time, what we see is the front line corresponding to the current location of the seismic wave. Locally this line is also a straight line.

The triggering happens when the seismic wave affects the fault, i.e., when the two lines intersect. Thus, from the geometric viewpoint, we need to consider a configuration in which we have two intersecting lines:

- the line corresponding to the fault, and

- the line corresponding to the current position of the seismic wave.

As we have mentioned, the more symmetries are preserved in comparison with the original configuration in which there is only the fault (and no seismic waves), the stronger will be the effect (in this case, the triggering effect). So, to find out which configurations of the two lines lead to a larger effect, we need to describe the symmetries of the resulting two-line configuration.

A simple geometric analysis shows that the symmetries of the two-line configuration depend on the angle between the two lines. Namely, depending on the angle, we have three different cases that we will describe one by one.

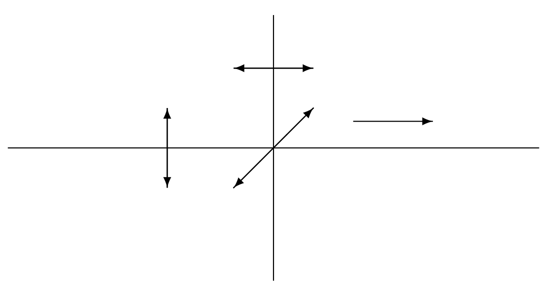
Case when the two lines coincide. The first case is when the front line of the seismic wave coincides with the fault line at some point. Since the front line is orthogonal to the direction of the seismic wave, this case corresponds to the case when the direction of the seismic wave is orthogonal to the fault. In this case, the two-line configuration simply coincides with the fault-only configuration. Thus, in this case, all the symmetries of the fault-only configuration are preserved.

This is this the case when the largest number of symmetries are preserved – thus, the case when we expect the strongest triggering effect. This is indeed what we observe.

Case when the two linear are orthogonal. The front line of a seismic wave orthogonal when the direction of the seismic wave is parallel to the direction of the fault.

In this case, we no longer have invariance with respect to shifts in the direction of the fault. However, we still have invariance with respect to:

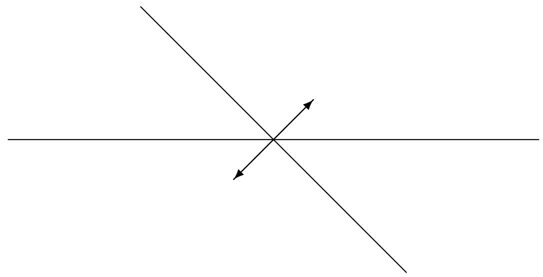
- scaling $(x, y) \to (\lambda \cdot x, \lambda \cdot y)$,
- a reflection in an intersection point $(x, y) \to (-x, -y)$, and
- reflections over each of the two lines.



Remaining case when the two lines are neither parallel not orthogonal. In this case, the only remaining symmetries are:

- scalings and
- reflection in an intersection point $(x, y) \to (-x, -y)$.

We no longer have invariance with respect to reflection over any line.



Conclusion. Our analysis show that:

- the largest number of symmetries are preserved when the direction of the seismic wave is orthogonal to the fault;
- somewhat fewer symmetries are preserved when the direction of the seismic wave is parallel to the fault;
- and in other configurations, we have the smallest number of preserved symmetries.

In line with the above general physical analysis, we expect that:

- the most triggering effects will happen when the seismic wave is orthogonal to the fault;
- somewhat fewer triggering effects will occur when the seismic wave is parallel to the fault; and
- the smallest number of triggering effects will occur when the seismic wave is neither parallel not orthogonal to the fault.

This is exactly what we observe. Thus, the symmetry-based geometric analysis indeed explains the observed relative frequency of dynamic triggering of earthquakes at different angles.

3 A Possible Qualitative Physical Explanation

General idea. What are the possible *physical* explanations for the observed phenomenon? To answer this question, let us consider a general problem: how do you break some object? Usually, there are two ways to break an object:

- You can apply, to this object, a strong force for a short period of time. This happens, e.g., when a cup falls down on a hard floor and breaks.
- Alternatively, you can apply some force for a sufficiently long time. This is what happens to structures under stress: they eventually start to crumble.

The first type of breaking is most assured: a rare china cup can withstand a fall. The second type of breaking is not guaranteed: many old building stand for hundreds of years without breaking down, but it still occurs – some buildings do eventually collapse if they are not well maintained.

Analysis of the problem. From this viewpoint, to describe when an incoming seismic wave is most probable to trigger an earthquake, we should look at two situations:

- a situation when the time during which the energy of the incoming seismic wave affects the fault is the shortest; in this case, the energy per unit time will be the largest – this will lead to most triggerings, and

- a situation when the time during which the incoming seismic wave affects the fault is the longest – this will also lead to some triggerings.

The wavefront of the incoming seismic wave from a remote earthquake is practically flat. Let us denote:

- the fault length by L,

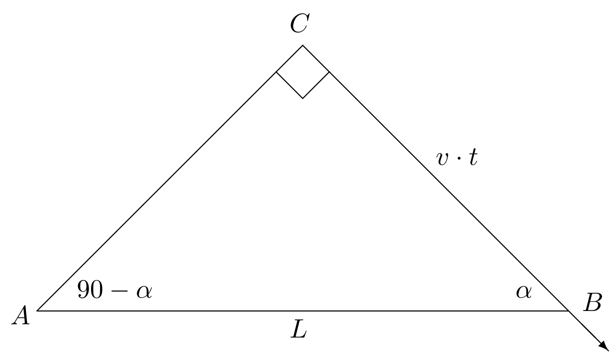
- the speed of the incoming seismic wave by v,

- the angle between the direction of the wave and the fault by α, and

- the time during which this wave affects the fault by t.

The wavefront is orthogonal to the direction in which the wave comes, so the angle between the wavefront and the fault is $90-\alpha$. Let us consider the moment when the seismic wave first hits one of the sides of the fault. Let us denote this point by A, and the other side of the fault by B. Eventually, the wavefront will hit the point B as well. We can trace this hit by placing a line from B to the current position of the wavefront along the direction of the incoming wave. Let us denote the point where this line intersects with the current wavefront by C; this point marks the part of the seismic wave that, in time t, will hit the point B on the fault. The wave travels with speed v, so the distance BC is equal to $v \cdot t$. In the right triangle ACB, the angle $\angle BAC$ is equal to $90 - \alpha$, thus $\angle ABC = \alpha$, and thus, by definition of cosine, $v \cdot t = L \cdot \cos(\alpha)$. Hence, the interaction time is equal to

$$t = \frac{L \cdot \cos(\alpha)}{v}.$$



Resulting explanation. This time is the smallest when $\cos(\alpha)$ is the smallest, i.e., when α is close to 90 degrees (when the cosine is 0). This is indeed when we observe most triggerings.

The interaction time t is the largest when the cosine takes the largest value, i.e., when the angle α is close to 0 (when the cosine is 1). This is indeed when we observe the second (smaller) peak of triggerings.

So, indeed, we seem to have – at least on a qualitative level – a possible physical explanation for the observed phenomenon.

Remaining problem. So far, both the symmetry-based geometric analysis and the physical analysis provide us only with a qualitative explanative explanation of the observed phenomenon. It is desirable to transform this qualitative explanation into a quantitative one – e.g., to be able to predict which proportion of triggerings occurs at different angles.

Acknowledgments

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