Quasi-static slips before and after large interplate earthquakes inferred from small repeating earthquake data

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Abstract: Many small repeating earthquakes have been found in the northeastern Japan subduction zone. These earthquakes are thought to be caused by repeated rupture of asperities on the plate boundary. Using the small repeating earthquake data, we can infer the space-time distribution of the quasi-static slips on the plate boundary. The obtained distribution shows that most of large interplate earthquakes are followed by large afterslips occurring in the surrounding areas and the afterslips sometimes foster the occurrence of other large earthquakes. Therefore the quasi-static slip distribution is very important to evaluate the possibility of rupture of large asperities.

1. Introduction

Recent friction laws predict that there must be a nucleation process before the occurrence of a large earthquake (e.g., Scholz, 1998). If we detect the nucleation phase, we will be able to make a short-term earthquake prediction. However, the nucleation size is still open to dispute and no modern geodetic instruments such as GPS have succeeded in detecting the nucleation process. Therefore, the earthquake prediction strategy relying on the nucleation process might be hopeless. In this paper, we discuss the possibility of the prediction of large interplate earthquakes based on the recent progress in the study on the property of the plate boundaries.

2. Large asperities on the plate boundaries

Yamanaka and Kikuchi (2004) investigated the source processes of large interplate earthquakes along the northeastern Japan subduction zone using regional seismic data. They found that in some areas large slips had been repeatedly observed for the large earthquakes whose source regions were overlapped. This means that asperities (seismic patches which are strongly coupled in the interseismic periods and show large slips when they are ruptured) are persistent on the plate boundaries and the asperity model proposed by Lay and Kanamori (1980, 1981) is basically correct.

3. Small asperities on the plate boundaries

If the asperities are persistent on the plate boundaries, there should be small earthquakes caused by repeated rupture of an identical small asperity. Such small repeating earthquakes have been actually found in California (Ellsworth and Diets, 1990; Nadeau et al., 1995) and NE Japan (Matsuzawa et al., 2002; Igarashi et al., 2003). Most of the small repeating earthquakes occur periodically but the intervals become shorter when nearby large asperities are ruptured as large earthquakes.

4. Modified asperity model

From the observations mentioned above, the plate boundaries are thought to be composed of asperities (seismic patches) and aseismic areas. The asperities slip seismically as the
earthquakes but they are strongly locked in the interseismic periods. The aseismic areas slip steadily and aseismically in the interseismic periods but their slips are accelerated as afterslips when nearby large asperities are ruptured as large earthquakes. In terms of the rate- and state-dependent friction law, an asperity and an aseismic area respectively correspond to rate-weakening and rate-hardening regions. In the original 'asperity model' proposed by Lay and Kanamori (1980, 1981), the regions other than asperities are treated as 'weak zones'. The model mentioned above is very similar to the original asperity model but explicitly incorporates the area where quasi-static slip (stable sliding; aseismic slip) is dominant.

5. Quasi-static slip distribution estimated from small repeating earthquakes

Cumulative slip at a small asperity must coincide with the cumulative aseismic slip in the surrounding region. Thus we can estimate the cumulative aseismic slip using the rupture history of the small repeating earthquakes (Nadeau and McEvilly, 1999; Uchida et al., 2003). The obtained quasi-static slip distribution clearly shows that most of large interplate earthquakes are followed by large afterslips in the regions surrounding the main source areas (i.e., asperities). Matsuzawa et al. (2004) investigated the space-time distribution of the quasi-static slips in the earthquake swarms off Sanriku, NE Japan and proposed a 'chain reaction model' where seismic slip at a large asperity (earthquake) accelerates the quasi-static slip in the surrounding area (afterslip) and a large afterslip fosters rupturing of the nearby asperities.

6. Implications in long-term earthquake prediction

The modified asperity model mentioned above predicts that if an asperity is isolated from other asperities of similar size or larger, the asperity will generate earthquakes of the same size with a constant time interval. In such a case, long-term earthquake prediction is possible; actually Matsuzawa et al. (2002) successfully predicted a M4.7 earthquake off Kamaishi. Many small repeating earthquakes showing very regular occurrences are found in California and Japan and these are also thought to be the earthquakes occurring on isolated asperities. However, large isolated asperities are not so common and interactions between asperities cannot be neglected. Actually, Yamanaka and Kikuchi (2004) revealed that M8 class events off Sanriku ruptured plural asperities but the combinations of the asperities were not necessarily always the same and the hypocenters (initial break points) were usually located away from the large asperities. Therefore it is very difficult to carry out a deterministic long-term earthquake prediction. However, the asperities related to a target earthquake are usually limited; all we have to do is take finite combinations of asperities into account and evaluate the possibility of each combination to assess the probability of each candidate of the impending large earthquake. In the assessment, we have to consider the possibility that a gigantic earthquake rupturing exceptionally many large asperities (such as the 2004 M9.0 Sumatra-Andaman Islands earthquake) may occur; the possibility would be very small but should not be neglected.

7. Implications in short-term earthquake prediction

As mentioned above, Matsuzawa et al. (2004) showed that earthquake swarms off Sanriku can be explained by a 'chain reaction model'. Uchida et al. (2005) revealed that the afterslip of the 2003 Tokachi-oki earthquake fostered the rupture of a large asperity off Kushiro to generate a M7.1 earthquake. These studies indicate that interactions among asperities and aseismic regions make the deterministic earthquake prediction difficult but the interactions
also make the probabilistic prediction possible in some cases. Of course, we have to know the strain accumulation history of each asperity for one cycle at least to issue a reliable prediction.

8. Conclusion

The possibility of the earthquake prediction based on the 'modified asperity model' is discussed. The model predicts that isolated seismic patches (asperities; rate-weakening regions) surrounded by aseismic (rate-hardening) regions will be regularly ruptured with a constant size and repeating interval. In this case, long-term prediction with a small error is possible. For example, the standard error of the occurrence interval is only around 10% of the averaged repeating interval for the case of the M4.8 off-Kamaishi sequence. In the regions where asperities are closely located, periodicities of the large earthquakes become vague because of the interactions among the asperities and aseismic slips. In this case, however, we can issue a probabilistic prediction to some extent when large seismic and/or aseismic events occur close to the target region.

9. References