Evolution of Earthquake Science with Space Geodesy

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There is no doubt about that the earthquake science has been evolving along with geodesy. Reid (1910) proposed the *Elastic Rebound Theory* based on the data of triangulation before and after the 1906 San Francisco earthquake. In Japan, the Land Survey Department of Army (the predecessor of the Geospatial Information Authority, Japan; GSI) repeated triangulation and leveling surveys and left invaluable information on the mechanics of faulting such as the 1923 Kanto and 1946 Nankai earthquakes etc. However, these techniques require much labor and long time to obtain significant displacements or strains, because of short line of sight. Consequently, it took more than 80 years to reveal horizontal crustal deformation over the entire Japanese islands.

Development of space geodesy could overcome these drawbacks to conventional geodetic techniques. Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) directly measured distance between continents and detected motion of plates in 1980’s, which validated plate tectonics. Thanks to the successes in several experiments of Global Positioning System (GPS), GSI started to deploy a nation-wide continuous GPS network in Japan (GEONET). 4 days after the start of GEONET in 1994, a M8.2 earthquake hit eastern Hokkaido. The retrieved deformation was amazing, because the entire Hokkaido shifted eastward up to 44 cm. Later in the same year, another M7.6 earthquake occurred off the Sanriku coast, northeastern Japan, and was followed by a slowly decaying movement toward the Pacific ocean; postseismic transients. In 1996, some GEONET sites in southern Kanto shifted slowly oceanward with no large earthquakes accompanied. This discovery of slow-slip ignited a worldwide hunt for slow-slip with GPS. Now, we know a wide variety of characteristics of slow-slip. Daily coordinates are accurate enough to give interseismic deformation within a decade. Spatio-temporal variations in geodetic coupling have been estimated using time series of coordinates in most subduction zones. Modeling with crustal blocks and their bounding faults has been applied to GPS velocity field in continents and island arcs to estimate slip rate of faults and motion of blocks. These are now the mainstream of seismo-geodesy and their results are being exploited for the hazard evaluation.

In parallel to the research of long-term deformation, movements with higher frequency than 1Hz have been studied utilizing a kinematic technique. A couple of groups showed that kinematic solutions of GPS during the 2011 Tohoku earthquake and found the usefulness to estimate size of rupture of earthquake larger than M8. This technique is expected to make significant improvements to tsunami warning system. Kinematic technique gives us a precise position on the sea surface, which is vital for the GPS-acoustic positioning (GPS/A) under the sea. Recent deployment of GPS/A stations along the Pacific coast of Japan revealed spatial distribution of interseismic coupling.

Spatial resolution depends on the density of distribution of control points that are repeatedly occupied, which prevents us from knowing detailed structure of earthquake faults. SAR Interferometry (InSAR) solved this problem. The first successful example is the 1992 Landers earthquake, whose coseismic displacement Massonnet et al. (1993) derived from ERS-1 images. Since then, observations with SAR sensors have been made and revealed complicated nature of earthquake ruptures. Recent deployment of satellites with a short revisit time and well-controlled orbits enables us to study temporal variations in surface deformation in plate boundary zones and intraplate deforming zones with as high spatial resolution as a couple of meters.

Kuhn (1962) called facts against the paradigm of normal science “anomaly”. He pointed out that accumulation of “anomaly” will force a paradigm shift; scientific revolution. The emergence of plate tectonics was certainly a scientific revolution and changed a view of earthquake. The developments mentioned above definitely deepened our understanding of earthquake generation process and earthquake cycle, but satellite geodesy did not change the view of earthquake in the framework of plate tectonics but verify it. However, we can find “anomalies” that are not easy to fit the leading models. For example, the 2010 Haiti earthquake raised fan delta and lowered its adjacent mountains. Sequence of earthquakes in New Zealand from Darfield to Kaikoura is astonishing. The Gorkha, Nepal, earthquake ruptured only a part of fully coupled zone of the Main Himalayan Thrust. On the other hand, the Tohoku earthquake was out of scope of long-term forecast in Japan. In late 2016, we observed that a fault ruptured with only 6 years interval in eastern Japan. At least, a simple recurrence model such as “characteristic earthquake model” may not be applied to these examples. These events may force us to reconsider the present model in mainstream. Is minor revision of model enough? Or do we need to replace it with other idea? We should seek answer to these questions. If these observations are real anomalies, we are now experiencing the revolution of earthquake science. It is exciting, isn’t it?