RELOCATION OF LARGE EARTHQUAKES ALONG THE PHILIPPINE FAULT ZONE AND THEIR FAULT PLANES

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ABSTRACT

We relocated large magnitude (Mw ≥ 7.0) earthquakes that have occurred in the Philippine Fault Zone (PFZ) from 1900 to 2012 using the modified joint hypocenter determination (MJHD) method. In order to obtain their precise hypocenters and identify fault planes of the large earthquakes, we used P-wave arrival times at stations worldwide. We confirmed that seven earthquakes (Mw ≥ 7.0) among ten relocated large earthquakes have occurred along the PFZ, they are 1911 (Mw 7.7), 1937 (Mw 7.4), 1941 (Mw 7.0), 1947 (Mw 7.0), 1948 (Mw 7.0), 1973 (Mw 7.4) and 1990 (Mw 7.7) earthquakes. Due to the limited number of data we were unable to relocate the 1901 (Mw 7.5) earthquake. We have confirmed that the August 30, 1924 (Mw 7.1) earthquake does not belong to the PFZ, although previous studies suggested that this event had been generated by the PFZ. Referring to the epicenters of aftershocks, damaged distributions and intensity reports, we estimated the fault plane of each earthquake. In the northern PFZ, the 1990, 1937, 1901, and 1973 ruptured all part of the PFZ. In the central PFZ, only three Mw 7.0 earthquakes in 1941, 1947 and 1948 occurred. Furthermore, five 6.0 ≤ M < 7.0 earthquakes including the 2003 Masbate earthquake occurred along the PFZ. In the southern PFZ, we have only the 1911 Agusan Valley earthquake in the northern Mindanao Island.

Keywords: Philippine Fault Zone (PFZ), Modified Joint Hypocenter Determination (MJHD) Method, Relocation of Hypocenters.

1. INTRODUCTION

The Philippines is located on the western rim of the Pacific Ocean. It is also situated between the two converging major tectonic plates, the Philippine Sea plate and the Sundaland plate. The angular velocity rate measured and estimated by Mid-Ocean Ridge Velocity (MORVEL) is 96 mm/yr (DeMets *et al.*, 2010). The Philippines is also bounded by many trenches.

The Philippine Fault Zone is situated on the borders of two opposing movements of the Philippine Trench and the Manila Trench (Acharya, 1980). The Philippine Fault Zone has a total length of 1200 km and transects the whole Philippine archipelago from north western part of the Luzon region down to the southern part of the Mindanao region. The Philippine Fault Zone is a major left lateral strike slip type of faulting (Allen, 1962; Acharya, 1980; Acharya and Aggarwal, 1980). The average displacement rate of the PFZ is about 20 to 25 mm/yr (Duquesnoy *et al.*, 1994).

Since the country is bounded by the numerous trenches and an active inland faults, the Philippines is considered highly vulnerable to large earthquake hazards and other earthquake related disasters that affect many citizens and also have effects on economic development. This paper will be helpful in developing for disaster mitigation measures. The Modified Joint Hypocenter Determination method (Hurukawa, 1995) is one powerful tool to locate the precise hypocenters of earthquakes and determine the fault planes and this will lessen the number of lives being taken if a strong earthquake

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occurs and if government officials, engineers will have knowledge about earthquake location and their fault planes, this will lead them to have an effective and well-planned disaster mitigation program.

2. METHODOLOGY

We used the Modified Joint Hypocenter Determination (MJHD) method in relocation of large earthquakes along the Philippine Fault zone. The MJHD method was developed by Hurukawa and Imoto (1990, 1992) and Hurukawa (1995) from the Joint Hypocenter Determination (JHD) method. The JHD method (Douglas, 1967; Freedman, 1967; Dewey, 1972), calculates hypocenters of a group of earthquakes and station corrections (SCs) simultaneously. SCs remove the effects of lateral heterogeneity and reflect a travel-time difference between the assumed velocity structure and the actual one. The JHD method uses SCs that remove the effects of lateral heterogeneity. However, since there is a trade-off between location and SC especially when the station coverage is limited, the solution becomes unstable and unreliable. Hurukawa and Imoto (1990, 1992) overcome this problem in the JHD method with adding constraint as follows. SC is dependent of distance and azimuth from the center of the source region to each station, which minimizes their absolute values.

3. DATA

We selected large events, which were located near the Philippine Fault Zone (PFZ), by the ISC-GEM (Storchak *et al*., 2013) from magnitude 6.0 or larger with shallow depths ($Z \leq 60$ km) during 1900-2012. We used data from British Association for the Advancement of Science Society Committee (BAASSC), International Seismological Summary (ISS) and International Seismological Centre (ISC).

To calculate the MJHD hypocenters, two parameters must be defined: the minimum number of stations (MSTN) that observed each earthquake and the minimum number of events (MEQ) observed at each station. In this relocation we set the parameters of MSTN and MEQ to 6 and 6, respectively. Phase data with an absolute value of P-wave travel-times residual (O-C, observed minus calculated time) of ≥ 12 s were excluded. We only use initial P-wave arrival time which is very reliable in hypocenter determination. The depth (Z) was fixed to 15 km to reduce the number of unknowns and can help to the accuracy in relocation of epicenters.

4. RESULTS AND DISCUSSION

We were able to relocate ten $M \geq 7.0$ earthquakes for the period after 1911. However, since travel-time residuals of P-arrival times of the 1901 (M 7.5) earthquake were too large and limited number of stations only had recorded this event, the 1901 earthquake was excluded from the MJHD relocation. Furthermore, we relocated 13 events from $6.0 \leq M < 7.0$ earthquakes including the 2003 Masbate (Mw 6.2) earthquake and three immediate aftershocks of the 1990 Luzon earthquake and one immediate aftershock of the 1973 (Mw 7.4) event.

Seven events among ten earthquakes were relocated on the Philippine Fault Zone (PFZ) (Table 1). Other three events are not events on the PFZ based on our result in MJHD relocation. The August 30, 1924 (Mw 7.1) and the June 13, 1929 (Mw 7.2), they behave differently among the other event in the relocation their mainshocks and aftershocks are scattered around the southern PFZ. The April 14, 1924 (Mw 8.0) earthquake, which is known as the Mati earthquake, was relocated very near the Mati segment of the PFZ. The earthquake was describe as violent but not destructive and had caused more damages on the ground than damages on the infrastructure (SEASEE, 1985). Therefore, further studies are needed to this earthquake before we decide if this event belongs to the PFZ.

Since we need to determine the fault length corresponding to the earthquake magnitude in order to establish the history of large earthquakes along the PFZ and to obtain possible seismic gaps, the fault length of magnitude ≥ 7.0 are estimated by the equation for large earthquakes in Sagaing Fault in Myanmar (Hurukawa and Maung, 2011).

Table 1. List of hypocenters of M ≥ 7.0 earthquakes along the Philippine Fault Zone since 1900.

Date (y/m/d)	Time (h:m)	Origin Time (s)	Longitude (°E)	Latitude (°N)	Z (km)	Mw	Source of hypocenter
1901/12/14	22:57	-	122.0	14.0	-	7.5	BAASSC
1911/07/12	04:07	47.96 ± 2.57	125.86 ± 0.55	09.35 ± 0.40	15	7.7	This study
1937/08/20	11:59	18.30 ± 0.48	121.80 ± 0.60	14.74 ± 0.07	15	7.4	This study
1941/11/05	17:38	53.76 ± 0.65	123.60 ± 0.15	12.90 ± 0.11	15	7.0	This study
1947/06/07	18:47	53.11 ± 0.67	124.56 ± 0.14	11.27 ± 0.12	15	7.0	This study
1948/09/02	23:34	54.02 ± 0.59	125.06 ± 0.14	10.43 ± 0.10	15	7.0	This study
1973/03/17	08:30	46.16 ± 0.16	122.78 ± 0.04	13.47 ± 0.03	15	7.4	This study
1990/07/16	07:26	34.28 ± 0.13	121.08 ± 0.03	15.73 ± 0.02	15	7.7	This study

Z = depth (fixed for earthquakes after 1911).

Mw: Moment magnitude by ISC-GEM (Storchak *et al*., 2013).

4.1. Fault Planes of M ≥ 7.0 Earthquakes from 1911 to 2012

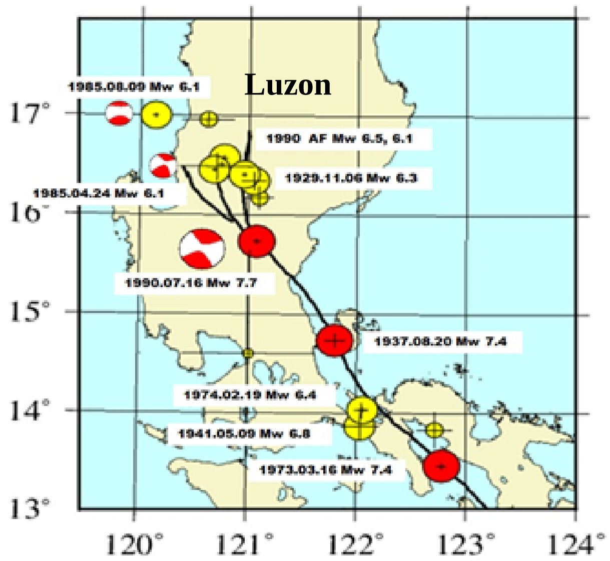

Figure 1. MJHD relocated events in the northern PFZ. Global CMT solutions are also shown (Global CMT catalog, 2013). Large red, middle yellow and small yellow circles indicate M ≥ 7.0, 6.0 ≤ M < 7.0, and M < 6.0 earthquakes, respectively. Cross indicates standard error of an epicenter. Solid lines indicate the PFZ configuration (Allen, 1962).

In this study, large earthquakes with M ≥ 7.0 that have occurred along the PFZ were relocated. Large earthquakes from 1911 to 2012 were relocated simultaneously mainshocks and their immediate aftershock using only the initial P wave arrivals. We divided the PFZ into three regions to explain the seismic activities of each region and show the detailed characteristics of the PFZ, such as the Northern PFZ where large earthquakes occurred, the Central PFZ where the M ≤ 7.0 earthquake occurred, and the Southern PFZ where the largest earthquake in the Philippines occurred.

4.1.1. Northern Philippine Fault Zone

The 16 July 1990 Luzon earthquake (Mw 7.7) was generated by a left-lateral faulting in the central Luzon Island. Ground rupture was observed along a linear trace extending to a 125 km (Nakata *et al*., 1996; Tsutsumi, 2005). The maximum horizontal offset as measured on the fault was 6 meters. The global Centroid Moment Tensor (CMT) solution from the surface waves represents almost pure left lateral strike-slip faulting (Figure 1). The location of the mainshock and three largest aftershocks was consistent with the 120 ~ 125 km rupture length of the previous studies (Yoshida and Abe, 1992).

The 20 August 1937 (Mw 7.4) earthquake was located by ISS with the coordinates of 122.0° E and 14.1° N and is near the south end of Alabat Island near the Calauag Bay. This event was relocated to 121.80°E and 14.74°N. It moves to 0.5° in the north and 0.02° in the east from the first location by ISS and sits on top of the PFZ (Figure 1).

The 17 March 1973 Ragay Gulf earthquake (Mw 7.4) was relocated in the middle of the Ragay Gulf which is very close to the ISC location (Figure 1). Ground breakages were seen along the segment of the PFZ, from west coast of Ragay Gulf to Calauag Bay, a stretch of about 30 km. The fault traces exhibited mole track features with ground fissures arranged in echelon to one another in an E-W trend. Ground displacement exhibited left lateral (Morante, 1974). The MJHD relocation result improves the location only by slight number and the expected fault length that corresponds for an Mw 7.4 is 113 km.

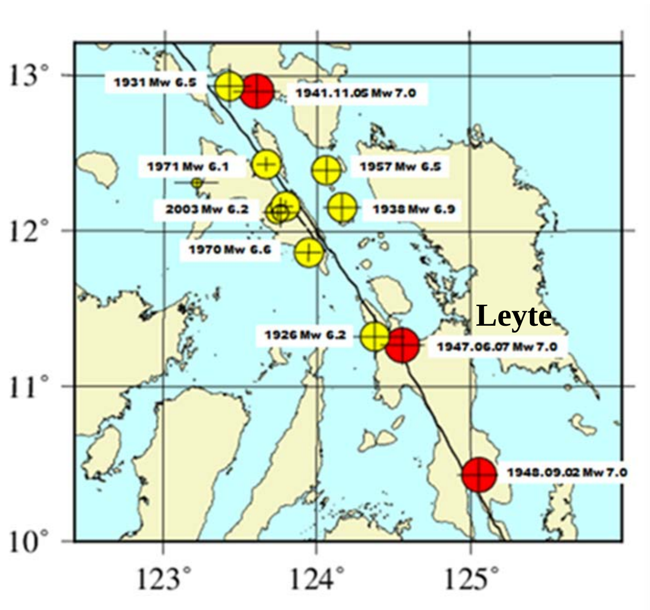

Figure 2. MJHD relocated events in the central PFZ. Symbols are as in Figure 1.

4.1.2. Central Philippine Fault Zone

The 05 November 1941 earthquake (Mw 7.0) was also generated by the PFZ and this earthquake was located by ISS at 123.5°E and 12.5°N. After the relocation the new hypocenter of this event suggested that the fault plane of this event is main PFZ segment in the central part of the PFZ.

The 07 June 1947 earthquake (Mw 7.0) was located by ISS at 124.7°E and 11.3°N. The results of MJHD relocation improves the initial location by ISS and confirms that this event was generated by the central region of the PFZ and its fault plane is the northern part of the Central Leyte fault segment of the PFZ (Figure 2).

The 02 September 1948 earthquake (Mw 7.0) was located by ISS located in the Pacific Ocean about 100 km east of the PFZ. The ISC-GEM also located this event approximately 50 km near the PFZ. Therefore we relocated this event to determine if this event is generated by the PFZ, and our results on MJHD relocation confirms that this event is generated by the PFZ. Based on our results the fault plane of that this event is the southern part of the Central Leyte Fault, a segment in the central region of the PFZ. Seven $6.0 \leq M < 7.0$ earthquakes occurred in this region (Figure 2).

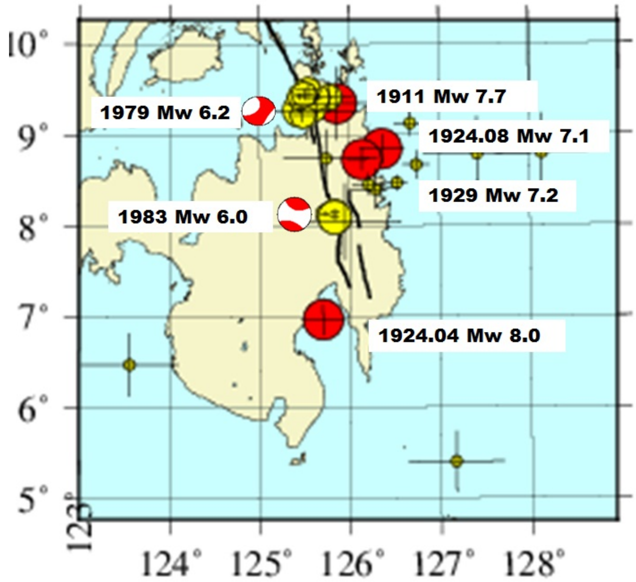

Figure 3. MJHD relocated events in the southern PFZ. Symbols are as in Figure 1.

4.1.3. Southern Philippine Fault Zone

The 12 July 1911 Agusan Valley earthquake (Mw 7.7) was located at the Pacific Ocean with the coordinates of 127.1°E and 8.5°N by ISS while ISC-GEM located it on the northeast tip of the Mindanao Island. The MJHD results relocated this event very near the northern part of the Mindanao fault segment of the Philippine Fault Zone (Figure 3). Since we have only few data and limited worldwide seismological stations recorded this event and the quality of data is less accurate so we have large but acceptable (O-C) residuals. We could relocate this event from offshore to inland earthquake close to the northern part of the Mindanao fault segment.

5. EARTHQUAKE HISTORY ALONG THE PHILIPPINE FAULT ZONE

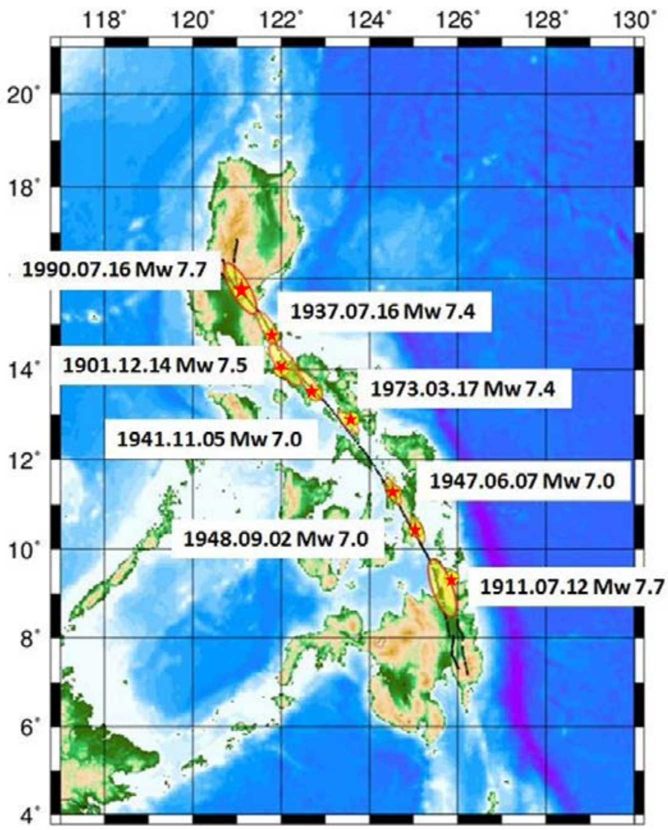

Figure 4. Earthquake history along the Philippine Fault Zone. Red stars indicate the epicenters of M ≥ 7.0 earthquakes during 1900 – 2012. Ellipses indicate their fault planes.

To obtain an earthquake history along the Philippine Fault Zone (PFZ), we plotted the calculated M ≥ 7.0 events (MJHD results) along the PFZ during the period 1901 to 2012 (Figure 4). There are eight M ≥ 7.0 occurred along the PFZ since 1900 (Figure 4 and Table 1). The M ≥ 7.0 earthquakes are as follows: 1901 (Mw 7.5), 1911 (Mw 7.7), 1937 (Mw 7.4), 1941 (Mw 7.0), 1947 (Mw 7.0), 1948 (Mw 7.0), 1973 (Mw 7.4) and 1990 (Mw 7.7). The northern PFZ, where the recent large and damaging (1990 Mw 7.7) and other large earthquakes (1901, 1937 and 1973) had occurred, had been ruptured all parts of the PFZ. The central PFZ was defined by Besana and Ando (2005) as location of large and medium sized events, correlates well with our relocation results particularly the 2003 (Mw 6.2), 1947 (Mw 7.0) and 1948 (Mw 7.0) events. In the southern PFZ, only the 1911 (Mw7.7) earthquake had occurred in the northern part of Mindanao Island and no large earthquake occurred in the southern part of the Mindanao Island.

6. CONCLUSIONS

The Modified Joint Hypocenter Determination (MJHD) method can constraint precise locations of a group of earthquakes simultaneously. Therefore, we have applied the relocation of the large earthquakes that occurred near the Philippine Fault Zone (PFZ) from 1900 to 2012 and identify their fault planes. We confirmed that seven large earthquakes (Mw ≥ 7.0) among the ten relocated large earthquakes have occurred along the PFZ, they are the 1911 (Mw 7.7), 1937 (Mw 7.4), 1941 (Mw 7.0), 1947 (Mw 7.0), 1948 (Mw 7.0), 1973 (Mw 7.4) and 1990 (Mw 7.7). However, we could not relocate the 1901 (Mw 7.5) earthquake due to the limited number of precise arrival-time data. We have also confirmed the August 30, 1924 (Mw 7.1) earthquake does not belong to the PFZ, although previous studies suggested this event was generated by the PFZ. Referring to the epicenters of aftershocks, surface ruptures, damaged distributions and intensity reports, we estimated their fault planes of each earthquake.

I will continue to study on historical earthquakes. I will relocate past large earthquakes in the Philippines by using the Modified Joint Hypocenter Determination (MJHD) method and determine their precise location and their fault planes. The results will contribute in the development of hazard assessments and disaster mitigation in the Philippines.

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