APPLICATION OF THE MODIFIED JOINT HYPOCENTER DETERMINATION METHOD TO THE 1990 AND 1996 BOHOL EARTHQUAKES IN THE CENTRAL PHILIPPINES AND CORRELATING GPS RESULTS

Nolan C. Evangelista[*] **Supervisor: Nobuo Hurukawa**[**]
MEE10507 **Fumiaki Kimata**[***]

ABSTRACT

The relocation of hypocenters was studied using the method of Modified Joint Hypocenter Determination (MJHD) to improve the location of hypocenters. We conducted a case study of two events that occurred in the central Philippines, which were the 1990 and the 1996 Bohol earthquakes in the southeast and the northwest of Bohol, respectively. This study is to unlock the query of the absolute location of hypocenters, fault planes and the temporal change of seismicity. Seismic phase data were obtained by the International Seismological Centre (ISC) and the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The period from 24 hrs right after the mainshock up to one week period of aftershocks was targeted to identify the fault planes. We identified the fault planes of the 1990 Bohol earthquakes which consisted of two M 6 events with pure reverse faults. The fault plane of the first mainshock of Mw 6.7 was located east of the mainshock and dipped southeastward, while that of the second mainshock with Mw 6.6, which occurred 30 minutes later, was located west of the first mainshock and dipped northwestward. We also found that the fault plane of the 1996 northwest Bohol earthquake (Mw 5.2) dipped northwestward.

The results of the MJHD relocation have a constraint to the aftershocks in the studied area and showed the lineaments of the existing faults such as strike slip and reverse faulting. In addition to the hypocenter relocation, we analyzed the GPS data surveyed in the Central Philippines. The result indicated that SOLK station in Bohol Island moves northward relative to Manila, which is in agreement with the P-axis of the 1996 northwest Bohol earthquake. It was consistent with the fault mechanisms of the earthquake. All of these findings are useful for seismic hazard assessment in the study area.

Keywords: Relocation of Hypocenter, Modified Joint Hypocenter Determination, 1990 Bohol Earthquake, 1996 Bohol Earthquake, GPS

1. INTRODUCTION

The Philippines is situated in the west margin of the Pacific. Much of its activity is related to the westward subduction of the Philippine Sea Plate along the boundary of the Philippine Trench (Acharya & Aggarwal, 1980). The eastward subduction of the Eurasian Plate along the Manila Trench and Negros Trench has shown complexity and has contributed seismicity in the western Philippines.

---

[*] Philippine Institute of Volcanology and Seismology.
[**] Building Research Institute.
[***] Research Center for Seismology,Volcanology and Disaster Mitigation, Nagoya University.

This compressional regime played a major reaction that processes different tectonic structure inside the Philippine Mobile Belt. It does exhibit a mixture of faulting such as reverse fault and strike slip fault. Thus, it is necessary to enhance the country's disaster mitigation approach to counter seismic hazards by earthquakes and secondary effects such as tsunami.

We considered a wider area first from 8.5°N- 12.0°N Latitude / 121.0°E-128.0°E Longitude, to reckon the general features of seismic activity in the studied region (Figure 1). The relocation focused on the vicinity of Bohol and nearby Islands from 8.6°N-11.3°N Latitude / 123.0°E-125.2°E Longitude. In 1981, an earthquake of M 5.4 occurred as a reverse fault (global CMT (GCMT)) in the southeast of Bohol. Then 9 years later on February 8, 1990 a strong Mw 6.7 occurred, in just 30 minutes later on the same date, another large event of Mw 6.6 took place still on the southeast of the island (or second mainshock?). All those succeeding events from 1981 fall into a reverse type of faulting (GCMT). By year 2000 along this area southeast of Bohol, repeated earthquakes were triggered by different fault mechanism of strike slip on the edge of the island, which were parallel to the 1981 and 1990 seismic activities. In another venue of seismic activity with same characteristics such as a reverse faulting, located northwest of Bohol, southwest of Cebu City, a moment magnitude Mw 5.2 occurred in 1996.

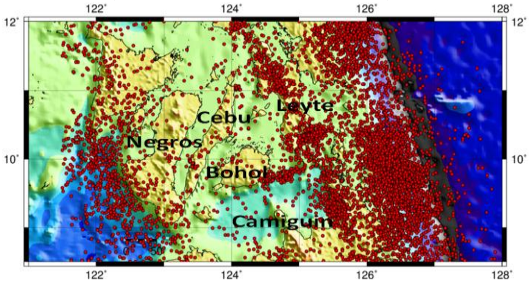

Figure 1. Shallow earthquakes by ISC

2. METHODOLOGY

The concept of relocation of hypocenters was the generalization from Geiger in 1912. Additional parameter was added for station correction by Douglas (1967) and Freedman (1967). Station corrections remove the effects of lateral heterogeneity and reflect a travel-time difference between the assumed velocity structure and the actual one. This method, joint hypocenter determination, calculates hypocenters of a group of earthquakes and station corrections simultaneously, as express in equation (1):

$$(O-C)_{ij} = (t_{ij} - To_j) - T_{ij} = \frac{\partial t_{ij}}{\partial x_j} dx_j + \frac{\partial t_{ij}}{\partial y_j} dy_j + \frac{\partial t_{ij}}{\partial z_j} dz_j + dTo_j + dS_i \ldots\ldots 1).$$

Where $(O-C)_{ij}$ is the travel time residual of the j-th event at i-th station , O is the observed travel time. C is the calculated travel time, t_{ij} the arrival time of j-th event at i-th station, T_{ij} the calculated travel time of the j-th event at the i-th station, dS_i correction to the station correction at the i-th station, To_j is the origin time, $dx_{j,} dy_{j,} dz_j$ and dTo_j are correction of trial hypocenters of j-th event. However, the approach is unstable if the media are too heterogeneous and there is large trade-off between station corrections and focal depths. Therefore, Hurukawa and Imoto (1990, 1992), for local events and Hurukawa (1995), for teleseismic events, modified the method by adding additional constraints that the station correction is independent of the distance and azimuth from the center of the studied region to the station. Although actual hypocenters are sacrificed, it can justify the effectiveness of relocation and even those less events are recorded at some stations. These added parameters as express in equation (2), enable us to relocate the precise location of hypocenters of earthquake which we applied in this study.

$$\sum_{i=1}^{n} S_i D_i = 0 \quad \sum_{i=1}^{n} S_i \cos\theta_i = 0 \quad \sum_{i=1}^{n} S_i \sin\theta_i = 0 \quad \sum_{i=1}^{n} S_i = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where S_i is the station correction at i-th station, D_i is the distance between the i-th station and the center of the region, θ_i is the azimuth of the i-th station from the center of the region and, n is the number of stations.

3. MJHD APPLICATION TO THE 1990 BOHOL EARTHQUAKE

The 1990 Bohol earthquake (Mw 6.7) was located at 1 km depth (ISC). The aftershocks are concentrated at 33 km and deeper from the crustal depth boundaries (Figure 2). This large gap between mainshocks and aftershocks cannot directly represent the real activity of these events for some anomaly of depth location of hypocenters. Fault plane solution from GCMT of two possible nodal planes described no relation of those clusters of aftershocks from the mainshock with respect to depths. The GCMT solution described the first mainshock (Mw 6.7) as a pure reverse fault (Figure 2). Then second mainshock (Mw 6.6) occurred 30 minutes later near the first mainshock. In these events people had experienced the intense ground shaking, observed ground rupture and receding of the sea water hundreds of meters away from the normal tide mark along the coast (Umbal et al; QRT Report 1990). This phenomena could prove and describe the assumption that the 1990 Bohol earthquakes were crustal earthquakes and not beyond the boundary of crustal depths or mantle earthquakes.

First step, we gathered the immediate aftershocks of 24 hrs from the 1st mainshock (Mw6.7). Fourteen events including one foreshock and 12 aftershocks were used originally from ISC database. The MJHD results have 12 events and 29 stations as plotted in Figure 3.

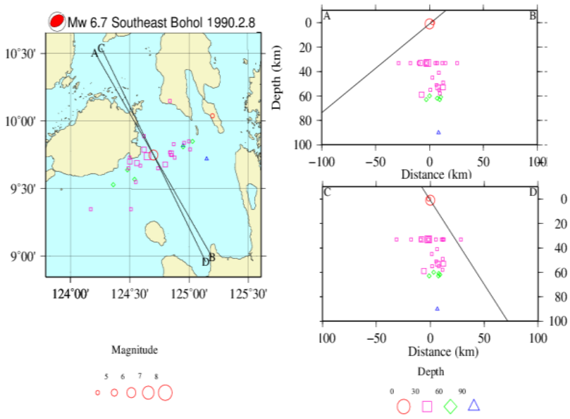

Figure 2. Epicentral distribution and depth cross-sections along A–B and C–D for foreshock, mainshock and immediate aftershocks located by the ISC. The GCMT solution of the mainshock (Dziewonski *et al*. (1981) and later updates) is also shown. Strike A-B and C-D are perpendicular to the strike of two nodal planes of the GCMT.

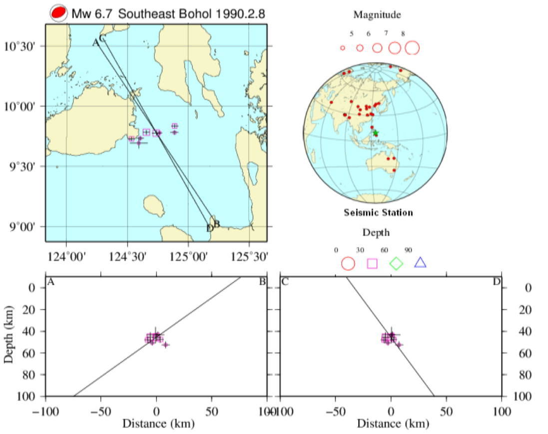

Figure 3. Relocation results of 24 hrs and distribution of station

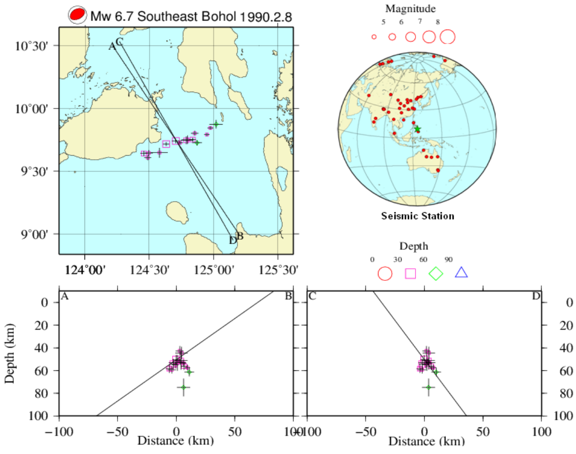

Figure 4. Relocation results of one week and distribution of station

The fault plane of the GCMT solution agrees with the new relocated events of aftershocks. However the mainshock location was pulled down to deeper position. One observation of such effects was due to insufficient number of local stations used in the process and this gave a biased location of hypocenters to deeper location. Only 2 regional stations of PHIVOLCS were used in the process. Probably it needs also another velocity structure model that can agree with a finer result. In 24 hrs relocation of aftershocks, the fault plane is still not clear in which slope makes. It seems that both fault planes shown in two cross sections A-B and C-D have activity along the slope. We extended the duration of aftershocks to one week. Twenty-nine events and 43 seismic stations were used. The results are shown in Figure 4, in which two clusters of activities are distributed along the nodal planes in A-B and C-D cross sections.

The hypocenters were well constraint at the depths of 40 km to 60 km location. This activity is much complex than that of a usual fault plane with reverse characteristics of faulting. The west activity from the two mainshocks (Figure 4) shows hypocenter location migrated nearer to the mainland. Dipping direction might be changing from its sequence of activity.

In order to study the detail of the aftershock distribution, we split the activity into two; eastern group from Mw 6.7 (Fig.5) and western group from Mw 6.6 (Fig.6). Almost all events were located along the nodal plane shown in the C-D cross section in the eastern group.

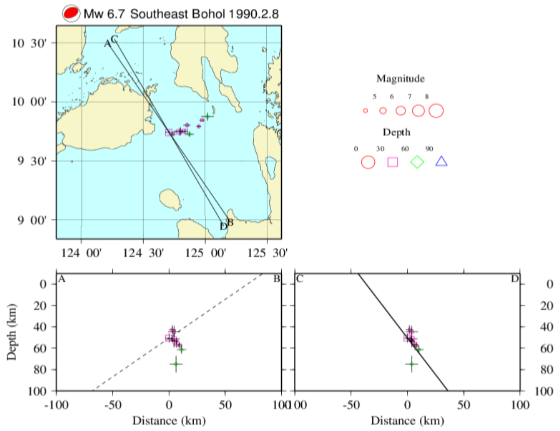

Figure 5. East activity from the 1st mainshock.

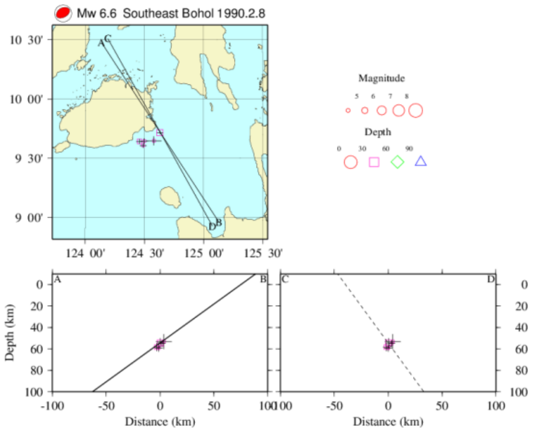

Figure 6. West activity from the 2nd mainshock.

Therefore, the fault plane of the first mainshock is dipping southeastward. On the other hand, earthquakes in the western group were located on the nodal plane in the A-B cross section. Therefore, the fault plane of the second mainshock is dipping northwestward. Although the west is not so conclusive because there are only 5 events available in one week time of relocation. However, it shows different direction from east activity

Furthermore, we relocated longer term from 1964-2008 (Figure 7) and the result established much constraint location than shorter term (Figure 8). The longer term has established an indicator for the shallow location of earthquakes between 124°E to 125°E longitude and 9.5°N to 10°N latitude trending northeast-southwest direction. The approximate length is about 70 km for crustal depth earthquakes in cross section A-B and approximately 20 km in width in cross section C-D (Figure 8). Although deeper earthquakes location beyond the crustal boundaries is constraint at the depth of about 40 km to 70 km, actual depth errors will be much larger than standard errors shown in figure 8.

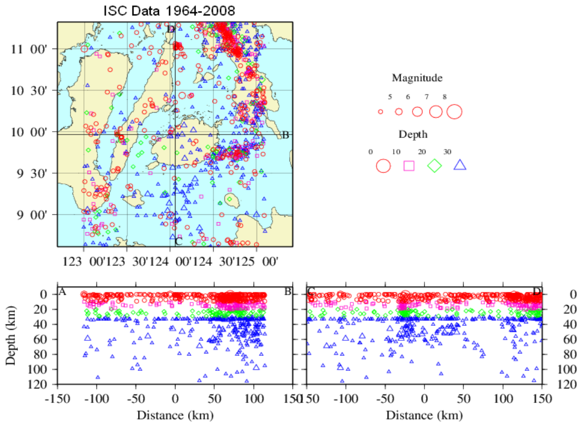

Figure 7. Relocated hypocenters (MJHD method).

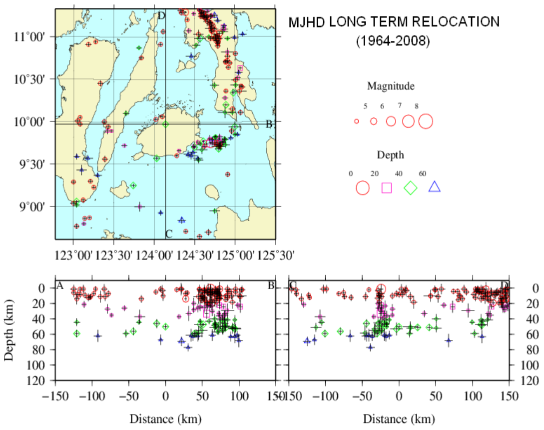

Figure 8. ISC hypocenters before relocation.

Also some constraints are observed in the neighboring island where the Philippine Fault Zone is located northeast of Bohol and indicating some seismic gap along the Philippine Fault (Figure 8).

The relocated hypocenters are well distributed in space and along the tectonic line (Figure 9), but we cannot say that this line is a major tectonic line in the sense that the dipping direction are on both sides and seismic activities are randomly distributed along the tectonic line. We assumed that this stress release is only due to compression along the fault.

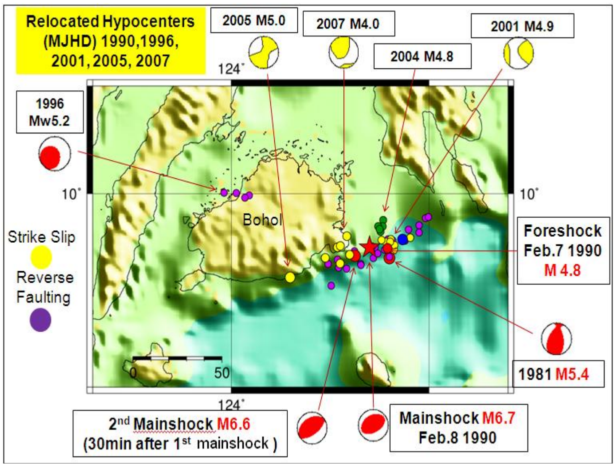

Figure 9. Relocated hypocenters in the southeast and northwest of Bohol for long term (1964-2008)

4. MJHD APPLICATION TO THE 1996 BOHOL EARTHQUAKE

A moderate to strong earthquake occurred in the northwest of Bohol with the depths of 50 km (ISC) and the magnitude was Mw 5.2 (GCMT). Here we relocated the aftershocks recorded by PHIVOLCS from May 27, 1996 until August 2, 1996. The first iteration from 12 events, only 7 events were included in the succeeding iteration. In the final results only four events were utilized to determine the fault plane (Figure 10). Therefore, we concluded that the nodal plane in cross section A-B is the fault plane of this event of 1996 that is dipping north-northwestward.

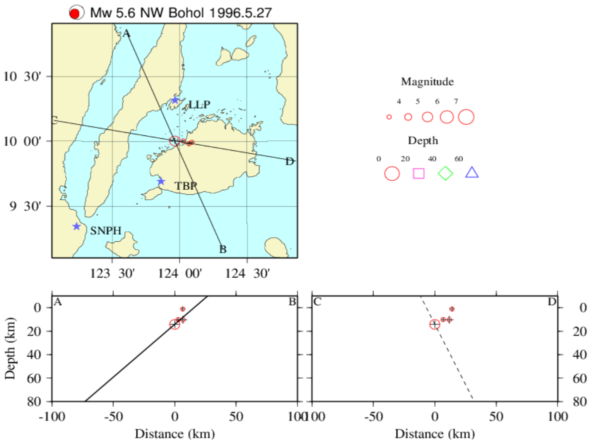

Figure 10. Relocated hypocenters of the 1996 Northwest Bohol earthquake.

5. GPS RESULTS

We processed and analyzed the GPS data and compared to results of the MJHD relocation. This relates some vectors results of SOLK and SOLF stations (Figure 11) generally to north northwest direction with respect to PIMO in Manila. In the previous earthquake event, northwest of Bohol, The focal mechanism (GCMT) showed a compression to northwestward as a reverse fault (Figure 10). This indicates northward movement of Bohol Island that is in agreement with the P-axis of the 1996 northwest Bohol earthquake. The resultant vectors of SOLK, and SOLF has a velocity of 19.51 mm/yr and 19.42 mm/yr, respectively.

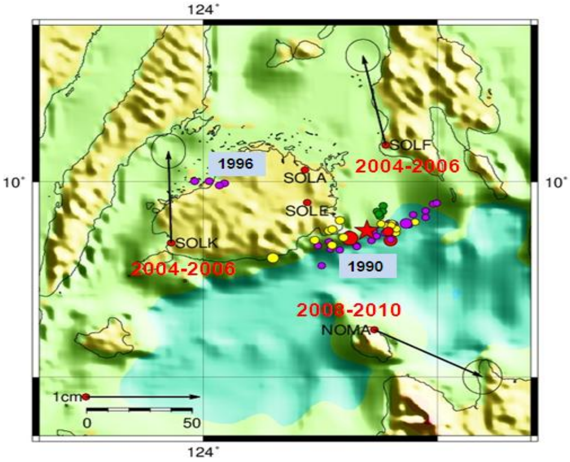

Figure 11. GPS Vector Results

Station NOMA on the other hand is trending east southeast direction with a velocity of 21.5 mm/ yr.

At present, we could not generally conclude whether those vectors could represent the regional or local crustal movement in this studied area in the sense that only few stations have been processed. It needs to place some more GPS sites and more campaign periods in order to be able to derive much finer results in the study area.

6. CONCLUSION

The relocation using the Modified Joint Hypocenter Determination (MJHD) method can constrain precise locations of a group of earthquakes simultaneously. Such precision is necessary to analyze fault planes of large earthquakes, the tectonic structure and migration process of seismic activity. Therefore, we have applied the relocation to the 1990 and 1996 Bohol earthquakes in the central Philippines and obtained the following results: The 1990 earthquake activities were divided into two groups. The eastern group located east from the first mainshock (Mw 6.7) indicated that its fault plane dips southeast, while the western group located west of the second mainshock (Mw 6.6), which occurred 30 minutes after the first mainshock, indicated that its fault plane dips northwest. The temporal change of seismicity was also clear and established a well constraint location of events after the relocation of longer term, which also gave clearer location for the strike slip of faulting and the reverse type of faulting in the southern part of Bohol Island. The fault plane of the 1996 northwest Bohol earthquake (Mw 5.2) is dipping north northwestward. The fault orientations of these two areas, southeastern and northwestern part of Bohol, are generally trending northeast and southwest.

Some segment in the Philippines Fault Zone was also constraint and gave clearer view of its seismic activity, of some segment with a seismic gap. Finally, we analyzed the GPS data in and around Bohol Island relative to Manila. The result indicates northward movement of Bohol Island that is in agreement with the P-axis of the 1996 northwest Bohol earthquake.

ACKNOWLEDGEMENT

My appreciation to Mr. I. Narag and Dr. J. Punongbayan (PHIVOLCS Data Management), Dr. T. Bacolcol (PHIVOLCS-GPS TEAM) and Ms. N. R. Hanifa Gunawan, (Nagoya University) for guiding me to process the GPS data thank you very much. To Dir. R. Solidum Jr., Dr. B. Bautista, Dr. K. Okino (Tokyo University) thank you for the advices during my individual study.

REFERENCES

Archarya, H. K. and Aggarwal, Y. P., Journal of Geophysical Research, Vol.85 No.B6, Pages 3239-3250, June 10,1980

Douglas, A., Nature, 215, 47-48, 1967.

Dziewonski, A. M., T–A. Chou, and J. Woodhouse, J. Geophys. Res. 86, 2825-2852, 1981.

Freedman, H. W., Bull. Seism. Soc. Am., 57, 545-561,1967.

Geiger, L., 1912, (1910 German article) Bulletin of St. Louis University, 8 (1), p. 56-71.

Hurukawa, N. and M. Imoto, M., 1990, J. Seism. Soc. Japan, Ser. 2, 43, 413-429.

Hurukawa, N. and M. Imoto, Geophys. J.Int.(1992) 109, 639-652.

Hurukawa, N., 1995, Geophy. Res. Letters, Vol. 22, No. 23, pp 3159-3162.

Umbal, J.V. et.al, PHIVOLCS QRT TEAM 1990 (Report of Investigation on the February 8, 1990 Earthquake in Bohol Province)